Ethanol to Ethyl Acetate

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Ethanol to Ethyl Acetate

Abstract
Ethyl acetate is a specialty chemical with dominant use as a solvent, and total production exceeding 3.7MMT annually in 2017. Current production methods mainly utilize petrochemical-derived feedstocks of ethanol and acetic acid that undergo Fischer Esterification to produce ethyl acetate. This is traditionally considered to be an unsustainable process. A new startup company, Greenyug, based out of Santa Barbara, CA, has proposed a new design that solely utilizes fermentation ethanol, and, as a result, is considered sustainable. Greenyug describes (in accordance to US Patents US8562921B2, US9079851B2, and US9447018B2) a two-step reaction pathway that first partially dehydrogenates ethanol to acetaldehyde, then utilizes nucleophilic addition of ethanol to acetaldehyde to form ethyl acetate. This novel process makes use of reactive distillation to achieve both high conversion and selectivity in one reaction vessel, which is difficult to achieve with the current production methods. Technical and economic feasibility of Greenyug’s process is investigated in this report.

A plant is designed to replicate Greenyug's newly constructed 50kT/year Columbus, NE facility. The process is composed of three main segments; one in which the main chemistry takes place through reactive distillation, and two in which separations occur. The final product is 99.8% ethyl acetate by mass and meets market purity specifications. The design requires an initial capital investment of $16.9MM, yields a fifteen year net present value (NPV) of $23.08MM, and has an estimated investor’s rate of return (IRR) of 38.73%. The proposed process is expected to break even in Q1 2023. This investigation concludes that Greenyug poses a competitive threat to the ethyl acetate industry, from both a technical and economic standpoint.

Disciplines
Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering
23 April 2019

Dear Dr. Daeyeon Lee and Professor Bruce Vrana,

Enclosed is an analysis into the technical and economic feasibility of the Greenyug process: the sustainable conversion of ethanol to ethyl acetate. The following proposed process produces 50kT of ethyl acetate per year. The plant will be located in Columbus, NE, and in close proximity to the ADM corn plant. This allows for advantageous operation as the ethanol feedstock arrives at this plant via direct pipeline. The ethyl acetate produced has a weight purity of 99.8%, meeting market specifications.

This process makes use of three main unit operations, where the innovative technology stems from the reactive distillation. The ethanol is fed into the reactive distillation column, where it undergoes dehydrogenation, in the reactive zone located at the feed tray of the column. The ethyl acetate produced, along with the aldehyde/ketone byproducts, is fed into a hydrogenation reactor, modelled as a packed bed. This is required to convert the aldehyde/ketone byproducts into alcohol byproducts, as this would allow the byproducts to have a greater boiling point difference from ethyl acetate. This is important to ensure optimal separation of ethyl acetate from the byproducts. A distillation column is used to achieve this separation. One day’s supply of ethanol is maintained and one week’s supply of ethyl acetate remains on site before shipment to customers.

The plant will operate for 24 hours, 330 days a year, with ethanol available at a market price of $0.21/lb and ethyl acetate sold at a market price of $0.42/lb. Our team investigated the economic feasibility of this process by assuming conservative estimates for equipment costs and operating costs. The base case economic model suggests that this process yields a NPV of $23.08MM and an investor’s rate of return (IRR) of 38.73%. This analysis is conservative in its approach as it does not assume the need for a green premium, even though the ethyl acetate produced is sustainable and could warrant the premium. We conclude that this process allows Greenyug to be a viable competitor and threat to the ethyl acetate market, both from an economic and technical standpoint.

Sincerely,

Kerri Heuser
Vinson Liao
Neha Narain
Ethanol to Ethyl Acetate

Kerri Heuser, Vinson Liao, Neha Narain

Faculty Advisor: Dr. Daeyeon Lee
Project Author: Bruce Vrana
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1 Abstract

Ethyl acetate is a specialty chemical with dominant use as a solvent, and total production exceeding 3.7MMT annually in 2017. Current production methods mainly utilize petrochemical-derived feedstocks of ethanol and acetic acid that undergo Fischer Esterification to produce ethyl acetate. This is traditionally considered to be an unsustainable process. A new startup company, Greenyug, based out of Santa Barbara, CA, has proposed a new design that solely utilizes fermentation ethanol, and, as a result, is considered sustainable. Greenyug describes (in accordance to US Patents US8562921B2, US9079851B2, and US9447018B2) a two-step reaction pathway that first partially dehydrogenates ethanol to acetaldehyde, then utilizes nucleophilic addition of ethanol to acetaldehyde to form ethyl acetate. This novel process makes use of reactive distillation to achieve both high conversion and selectivity in one reaction vessel, which is difficult to achieve with the current production methods. Technical and economic feasibility of Greenyug’s process is investigated in this report.

A plant is designed to replicate Greenyug’s newly constructed 50kT/year Columbus, NE facility. The process is composed of three main segments; one in which the main chemistry takes places through reactive distillation, and two in which separations occur. The final product is 99.8% ethyl acetate by mass and meets market purity specifications. The design requires an initial capital investment of $16.9MM, yields a fifteen year net present value (NPV) of $23.08MM, and has an estimated investor’s rate of return (IRR) of 38.73%. The proposed process is expected to break even in Q1 2023. This investigation concludes that Greenyug poses a competitive threat to the ethyl acetate industry, from both a technical and economic standpoint.
2 Introduction

2.1 Background

Ethyl Acetate is a moderately polar solvent with volatile, non-toxic, and non-hygroscopic properties that make it a desirable product. It is commonly used as a solvent or a diluting agent, and can be found in several consumer products, including nail polish remover, paints, adhesives, wines, coffee, and tea. Current global sales of ethyl acetate exceed $4bn/year and are growing at a rate faster than that of global GDP. As of 2016, global demand for this product was 3.7MMT. A degree of excess capacity exists in the ethyl acetate market and is concentrated in the Asia-Pacific.

The current industry standard for the production of ethyl acetate revolves around the Fischer Esterification pathway. One feed material for this process is usually a variation or combination of synthetic and fermented ethanol. The other feed material is synthetic acetic acid, made from carbon monoxide and methanol. Therefore, at this time, the standard production process is not considered to be sustainable. The Fisher Esterification reaction takes place in a reactor, and its products are separated using distillation. An existing challenge is the ternary azeotrope that exists between ethanol, ethyl acetate, and water. To reach market standards, the final ethyl acetate product must meet a specification of 99.8% purity.

2.2 Motivation and Goals

Recent media reports of a company called Greenyug have captured the attention of several well-established companies in the ethyl acetate market. Greenyug is a small, privately-held startup company based in Santa Barbara. This company is commercializing a newly developed ethyl acetate production process that uses fermentation ethanol as its sole feedstock. Using 100% renewable resources makes this process more sustainable than the current in-
dustry standard. Greenyug claims that the process will be cost competitive, or even more economical than the current standard for ethyl acetate production. Though claims from startups are often far-fetched, Greenyug has already demonstrated its technology at a pilot plant in Pune, India, by building and starting up a commercial scale facility at ADMs corn processing plant in Columbus, NE that will produce 50 kT of ethyl acetate per year. The proximity to the ADM corn plant provides a logistical and economical benefit of ethanol supply; Greenyug is able to gain direct access through pipeline and could see a discounted ethanol price. These factors make Greenyugs claims feasible and could prove to be a concern for companies and jobs in this market.

Given the private nature of the company, there is virtually no public information about Greenyug and its process. The basis and majority of the data available is presented in three patents that Greenyug filed in 2012, 2013, and 2014 (Section 27.3). The overall main chemical reaction of this process is available and occurs as follows:

$$2CH_3CH_2OH \rightarrow CH_3COOCH_2CH_3 + 2H_2$$

The patents also indicate the process uses reactive distillation technology to drive this reaction and make ethyl acetate in a simple, low-cost process. The patents also discuss the use of hydrogenation reactions to hydrogenate existing liquid co-products. The patents offer a good starting point for data and engineering design of the production plant, but the available public information is far from complete; this project thus makes a large number of assumptions to model this process.

The goal of this design project is to investigate the feasibility of Greenyugs process from both engineering and economic perspectives. The engineering aspects revolve around using the available information supplemented with several assumptions to reverse engineer the production process that Greenyug is using. From an economic viewpoint, this design project estimates Greenyugs operating and capital costs and estimates what green premium (if any)
Greenyug will need to achieve at least a 15% IRR on their investment. Several other considerations are included, such as side reactions, the possibility of selling produced hydrogen, fluctuating market prices, and start-up, maintenance, and operational costs. The overall aim of this report is to determine if Greenyug will become a viable competitor to an already established company in the ethyl acetate industry.
3 Objective Time Chart

**Figure 1:** Objective Time Chart for Ethanol to Ethyl Acetate Project
4 Innovation Map

N/A
5 Market and Competitive Assessment

5.1 Market Sizing and Applications

The global market consumption for ethyl acetate is currently 2,019,000 tonnes, set to grow at a CAGR of 5.75% between 2019 and 2023. On a global scale, Asia-Pacific is set to lead the market both in production and consumption of ethyl acetate.

The food and beverage segment accounts for the largest market share of ethyl acetate consumption, commonly using the chemical as synthetic flavoring. The widespread use of ethyl acetate across a diversity of flavorings, allows for ethyl acetate to be used in a versatile manner across regions. Analysts expect the general growth of the food and beverage sector to be the most significant driver of the growth of the ethyl acetate market. The food and beverage sector in the US, for example, is set to see revenues increase at a CAGR of 11.0% between 2019 and 2023, resulting in a market volume of $27,300 MM by 2023. Driving significant growth in the food and beverage sector is the increased prevalence of e-retail businesses and online food delivery patterns.

Looking specifically at the North American region, ethyl acetate is increasingly used in the decaffeination process to reduce caffeine in coffee, tea leaves, and cocoa. There has been increased investment in this application, and this points to the increased growth in the market, specifically in the North American region.

Ethyl acetate is also commonly used as a solvent for high-resolution printing inks and laminated adhesives in flexible packaging. Ethyl acetate is used in this application due to its fast evaporating properties. This application of ethyl acetate is significant in pointing towards a continued growth of the market as the manufacturing industry now looks to shift towards the class of flexible packaging. For example, flexible packaging allows for a greater ease of recycling, in comparison to rigid packaging. E-commerce plays a significant role here.

\[\text{Barnes [2018]}\]
\[\text{Statista [2018]}\]
\[\text{Anand, Koshy, and Arora [2018]}\]

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once again, as logistics companies and online businesses turn to flexible packaging options for shipment and delivery of products across the region.

Considering the variety of industries that rely on ethyl acetate and the growing regional demand for the product, the production of ethyl acetate is seen as a strong prospect for a business venture. Although it is without a doubt that the commodity already holds important clout with its customers, existing market leaders have already captured strong market share for ethyl acetate. The most attractive aspect of this process lies in its ability to yield sustainably produced ethyl acetate. The demand for green ethyl acetate is clear, whether the demand stems from regulations that require a sustainable approach, or from consumers who demand a sustainable chemical product. One example where sustainable ethyl acetate may be highly desirable is within the fragrances and perfume industry. This industry has seen consumers continuously search for sustainably produced products that limit environmental damage. The food and beverage industry is no different, with consumers often looking for sustainable ingredients and healthier alternatives.

5.2 Competitive Assessment

The specialty chemicals industry is usually dominated by large players, often those that have been established in the industry as a whole. Successful players in this industry are categorized by their ability to produce a suite of products that have interrelated economies of scale and cost benefits, rather than producing one specific chemical. The barriers of entry to the specialty chemicals industry are often high, limited by the significant capital requirements. For any new business in the industry, a unique value proposition is required, even if the business is able to bypass the capital requirements. In the case of Greenyug, the ability to be a first mover in the industry is key. For Greenyug, the unique value proposition lies in their ability to sustainably produce ethyl acetate. As mentioned above, this is the first commercialized process to produce green ethyl acetate.

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Barnes [2018]
As the sustainably produced ethyl acetate product does not quite have an established market, it falls within the bounds of the current ethyl acetate market, and may have to face competitive forces that exist within this product market. This puts Greenyug at somewhat of a disadvantage, as they attempt to define a new market segment whilst continuously competing against existing giants in the field.

On a global scale, some of the most well known ethyl acetate competitors are INEOS (Switzerland), Celanese (USA), Carbohim (USA) and PT. IndoAcidatama Tbk (Indonesia)\(^6\).

As mentioned previously, it is most likely that Greenyug’s main competitors will be large and well-established chemical companies. As ethyl acetate is a relatively homogeneous product, it is likely that the main competitive metric will be the price.

### 5.3 Green Premium

As this process produces an ethyl acetate product that is considered to be more sustainable than the norm, the process may warrant the application of a green premium for the product. This green premium may bring a competitive edge for Greenyug, and could allow Greenyug to effectively compete against some of the larger players.

Based on a comprehensive study completed by the Nova-Institute, most participants (42%) indicated that the green premium for sustainable and bio-based products lies between 10-20\(^7\). Participants of this study include major sustainable chemical producers located in the EU. It is therefore expected that Greenyug can apply a 15% green premium to the product price.

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\(^6\) Anand, Koshy, and Arora [2018]

\(^7\) Participants of this study include major sustainable chemical producers located in the EU.
6 Customer Requirements

The project objective requires 50kT of ethyl acetate to be produced per year. To compete with industry incumbents, a significantly high purity is required. From considering patent information and industry specifications, the goal purity for the green ethyl acetate product is 99.8%. The hydrogen byproduct in this process is burned for fuel value and this fuel value is assumed to be estimated at the current market price of natural gas. All other byproducts are considered to be waste products.

As mentioned in Section 5.2, Celanese is a major competitor and player in the ethyl acetate market. The purity specification for the ethyl acetate sold by Celanese is 99.7%, with a ethanol wt.% of 0.05% on the higher end. The sales specification sheet for Celanese (Section 27.5) indicates that the odor of the ethyl acetate product is nonresidual. The product is colorless, with a maximum of 10 Pt-Co Units.

The proposed process meets all of these customer requirements, and a detailed product composition can be seen in the ASPEN simulation output in Section 27.7.
7 Presented Innovation Edge

The proposed design provides an efficient process to produce cost-competitive, green ethyl acetate, compared to the traditional production process, outlined in Section 12.1. The traditional design relies heavily on product recycle to both increase conversion and yield, as well as improve separation efficiency in the process. Tweaking this recycle ratio has proven to be the major factor in determining the economics of the traditional process.

Greenyug’s design solely utilizes fermentation ethanol as the feedstock for the process. The plant location has been strategically chosen to be within the vicinity of a corn facility, allowing for a reliable and potentially discounted source for feedstock material.

The process utilizes three major unit operations that can be easily scaled to meet customer demands. The first major unit operation mitigates the issue of low production conversion and selectivity. Reactive distillation shifts the equilibrium by continuously removing products from the reaction zone. The system can easily be scaled up past the current proposed 50kT production as both reaction equilibrium and column separation specifications are well understood for the process. To scale up the process, the column diameter can be increased and the appropriate heating and cooling equipment can be adjusted to account for additional feedstock. The other two major units accomplish the final separation to meet the desired 99.8% purity specification. These processes have been designed to avoid the issues that the traditional production process encounters. These two major unit operations have been designed such that independent scale up for a desired production output can be achieved. For example, there is no longer a need to include a recycle stream. This novel process allows for the creation of a high conversion, flexible, and profitable process that can easily be adapted to meet a variety of customer demands.
8  Critical-to-Quality Variables

N/A

9  Product Concepts

N/A

10 Superior Product Concepts

N/A

11 Competitive Patent Analysis

N/A
12 Preliminary Process Synthesis

12.1 Traditional Chemistry

Ethyl acetate is a specialty chemical product traditionally synthesized via acid-catalyzed Fischer Esterification of acetic acid and ethanol through the following overall reaction:

\[ CH_3COOH + CH_3CH_2OH \rightarrow CH_3COOCH_2CH_3 + H_2O \]

The conventional method uses acetic acid manufactured from syn-gas derived methanol and either petrochemical-derived or fermentation ethanol. The process can be considered "slightly green" due to the partial usage of fermentation ethanol. An example of the reaction schematic to produce ethyl acetate from raw materials is shown below, in Figure 2:

![Figure 2: Overall reaction pathway to form ethyl acetate from raw materials.](image)

Ethanol is synthesized from hydration of ethylene derived from steam cracking of hydrocarbons. Production of acetic acid is a two step process, which first requires the creation of syn-gas from hydrocarbons through Steam Reforming/Water Gas Shift, followed by methanol production. Finally, methanol undergoes carbonylation to form acetic acid. Ethanol and acetic acid react through acid-catalyzed Fischer Esterification to form the desired ethyl acetate and water.

The Dow Chemical Company\(^8\) (formerly Union Carbide) and Celanese\(^9\) have published patents on the process design to manufacture ethyl acetate using the Fischer Esterification reaction pathway. Ethyl acetate is produced by reaction over a strong sulfuric acid catalyst in a reaction vessel. The resulting vapors are passed through the bottom of a distillation

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\(^8\)Papa and Bryant [1993]

\(^9\)Horan, Murphy, Stephens, Warner, and Windhorst [2004]
column. A second distillation is performed to accomplish the desired separation for high purity ethyl acetate. A portion of the product is sent to the reaction vessel for usage as an azeotropic separation agent. For every mole of ester produced, a mole of water is also produced. Unfortunately, there is an excess of water in the system that exceeds the azeotrope between water and ethyl acetate and the desired separation cannot be achieved through distillation. Product is recycled into the distillation column to optimize the molar ratio between the ester and water in the system to allow for separation past the azeotrope. Adjusting this molar ratio in the distillation column is important for economic production of ethyl acetate.

12.2 Novel Chemistry

The novel reaction chemistry is a two-step reaction that utilizes ethanol as the initial feedstock as proposed by Gaspar et al.\textsuperscript{[10]} The first step, as shown below, involves a partial dehydrogenation of ethanol to acetaldehyde over a copper catalyst at elevated pressures and elevated temperatures below 250 °C.

\[
CH_3OH \rightarrow CH_3COH + H_2
\]

Acetaldehyde can be converted to ethanol through two possible mechanisms over a ZnO/Al\textsubscript{2}O\textsubscript{3} catalyst via: (1) dimerization of acetaldehyde (Tischenko Reaction) or (2) nucleophilic addition of ethanol to acetaldehyde.

\[
2CH_3COH \rightarrow CH_3COOCH_2CH_3 \quad (1)
\]

\[
CH_3COH + CH_3CH_2OH \rightarrow CH_3COOCH_2CH_3 + H_2 \quad (2)
\]

\textsuperscript{[10]}Gaspar, Esteves, Mendes, Barbosa, and Appel 2009
Acetaldehyde can undergo various side reactions during the dimerization process through the mechanism shown in Figure 3.

**Figure 3:** Byproduct Reactions in Novel Reaction Pathway. Acetaldehyde can undergo self-aldol addition, followed by dehydration, and then hydrogenation to form aldehyde and ketone byproducts.

Lab scale product selectivities and conversion data have been reported by Gaspar et al. [12], Gadewar [13], and Santacesaria et al. [14]. Equilibrium and kinetics of the two step process over CuO/ZnO/Al₂O₃ (40:40:20%, BASF K-310) have been reported by Carotenuto et al. [15] for (1) dehydrogenation of ethanol and (2) nucleophilic addition of ethanol to acetaldehyde.

The temperature dependence of the equilibrium constant is shown below:

\[
\ln(K_{eq}) = A + \frac{B}{T}
\]

(1) : \( A = 16.5, B = -9136.4 \)

(2) : \( A = -4.79, B = 4386.0 \)

In a one pot synthesis, it is reasonable to assume that the dimerization reaction is outcompeted by the nucleophilic addition reaction, as excess ethanol is present. Therefore, the kinetics and equilibrium were not reported for the Tischenko reaction. At 200°C, where the reactions are reported to occur, the equilibrium constants are \( K_{eq1} = 0.0599 \) and \( K_{eq2} = 88.476 \).
respectively. The nucleophilic addition of ethanol to acetaldehyde severely favors the products. Dehydrogenation of ethanol is reported to be the rate limiting step\(^\text{[16]}\) in the process and can be seen from the relative ratio of the equilibrium constants.

Separation of the final product (ethyl acetate) from the resultant byproducts (namely, but-2-one and n-butanal) is difficult due to similarities in boiling point and volatility. Selective reduction of the ketone and aldehyde byproducts can allow for easier separation due to elevated boiling points from hydrogen bonding of the produced alcohols. The reactions are shown below:

\[
\begin{align*}
HCOCH_2CH_2CH_3 + H_2 & \underset{\text{RaneyNi}}{\longrightarrow} CH_3CH_2CH_2CH_2OH \\
CH_3COCCH_2CH_3 + H_2 & \underset{\text{RaneyNi}}{\longrightarrow} CH_3CH_2CHOHCH_3
\end{align*}
\]

Oldenburg et al\(^\text{[17]}\) reports reaction conditions and kinetics of vapor phase hydrogenation of C4 ketones and aldehydes over Raney Nickel in a packed bed reactor using a simple power law expression. The rate constant was found to be 1st order in aldehyde/ketone partial pressure and \(\frac{1}{2}\) order in hydrogen partial pressure.

In addition, separation between the reactants and desired products also proves to be a challenge in this process. Figure 4 shows the residue curve\(^\text{[18]}\) at various pressures of the main reactants and products: hydrogen, acetaldehyde, ethanol, and ethyl acetate.

\(^{16}\) Carotenuto, Tesser, Di Serio, and Santacesaria\, 2013
\(^{17}\) Oldenburg and Rase\, 1957
\(^{18}\) Gadewar\, 2013
Figure 4: Residue curves between ethanol, acetaldehyde, hydrogen, and ethyl acetate. An azeotrope exists between ethyl acetate and ethanol at pressures below 13 atm and makes separation difficult. At 20 atm (bottom right), residue curves show no evidence of azeotropes and all curves traverse towards the heaviest component, ethyl acetate.

12.3 Process Overview

Based on the patents and researched information, two possible configurations were proposed for the modeling of the ethyl acetate plant. The first configuration, shown in Figure 5, begins with a single feed of ethanol entering a reactive distillation column. A dehydrogenation zone exists within the column where the main reactions of the process, and associated side reactions, take place. Hydrogen exits from the top of this column. The bottoms products
include ethyl acetate and the byproducts that are produced in the reactive zone. The bottom products are fed to a hydrogenation reactor that converts the byproducts to alcohols. The final step of the first configuration process consists of a separation process to isolate the ethyl acetate and achieve the 99.8% purity requirement. The second configuration, shown in Figure 6, differs from that of the first because the former includes the hydrogenation step inside the reactive distillation column. There are two feed streams entering the column, one of ethanol and one of hydrogen. The column then includes a hydrogenation zone below the dehydrogenation reactive zone. The bottoms products from this column are then sent directly to a separation process.

Figure 5: First proposed plant schematic based on initial patent information.
Figure 6: Second proposed plant schematic based on initial patent information

Taking into account both engineering and economic considerations, the first configuration was selected as the basis for this design project. This decision was made for several reasons. First, choosing the first proposed configuration avoids the complexity of embedding the hydrogenation reactor section into the reactive distillation column. This allows for a more simple model of the reactive distillation column itself. Additionally, guidance from industrial consultants points to the fact that combining the two reactions in this way would be more expensive than having two separate units. In addition to the cost of the reactive distillation column, this design choice also took into account the cost of the final separation process. Insight from industrial consultants also led to the belief that using the first proposed configuration would lead to a higher purity ethyl acetate stream entering the final separation process than that of the second configuration. In turn, this would lead to a lower cost for the final separation process because the separation would be achieved with a fewer number of stages. From an engineering standpoint, another important consideration came from the limited available patent information. The patents included data for a lab scale
model of the reactive distillation column. The data was provided for a reactive distillation column that included only a dehydrogenation reactive zone; i.e the column present in the first proposed configuration. Given that this lab scale information was the starting point for the modelling of the plant, this availability of lab-scale information greatly influenced the decision to choose the first configuration.

The chosen process can be viewed in three main unit operations: reactive distillation (C-101), hydrogenation (R-100), and separation processes (C-102). Several intermediate blocks are required to connect the three main unit operations. Figure 7 illustrates the overall process flow diagram, components of which are described in subsequent sections.
Figure 7: Overall Proposed Process Flow Diagram for Greenyug’s Ethyl Acetate Plant
12.4 Reactive Distillation (C-101)

In the chosen configuration, a single stream of ethanol is fed to the reactive distillation column. Lab-scale data is available in the patents for the basis of modelling this column. Reactive distillation drives the chemical reaction by continuously removing its products.

The feed was chosen to be 200 proof liquid ethanol. This feed is provided from the neighboring ADM corn processing plant; the feed ethanol is assumed to arrive at Greenyug’s plant through a direct pipeline. The liquid feed will be fed above the reactive zone of the column. The decision to use 200 proof ethanol was made to avoid introducing more water to the system than is already produced in the existent side reactions. The decision was also impacted by the proximity of Greenyug’s commercial plant to ADMs corn processing plant. This will likely give Greenyug direct access as well as a possible discount to the ethanol needed for the process.

A key design consideration is the existence of the azeotrope between ethyl acetate, ethanol, and water, as discussed in Section 12.2. Available patent data shows that the binary azeotrope between ethyl acetate and ethanol disappears at pressures above 13 bar. This information, in addition to other research, led to the decision of operating the reactive distillation column at 20 bar.

The feed tray is assumed to be the reactive zone of the column. The entirety of the stage is packed with catalyst with a packing efficiency of 0.60. The catalyst chosen was a physical mixture of CuO/Al2O3 and ZnO/Al2O3. A list of potential catalysts studied by Gadewar are shown in Table 1.
Table 1: Conversion and Selectivity for Catalysts in a Fixed Bed Reactor at 220°C, 1 atm
CuO/ZnO/Al₂O₃ provides the best conversion and selectivity

<table>
<thead>
<tr>
<th>Catalyst Sample</th>
<th>Conversion</th>
<th>Selectivity</th>
<th>Conversion</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO/ZnO/Al₂O₃</td>
<td>18.9</td>
<td>92.4</td>
<td>35.0</td>
<td>89.7</td>
</tr>
<tr>
<td>CuO/Cr₂O₃/BaO</td>
<td>43.5</td>
<td>89.4</td>
<td>36.0</td>
<td>74.6</td>
</tr>
<tr>
<td>CuO/SiO₂</td>
<td>19.6</td>
<td>96.2</td>
<td>22.5</td>
<td>80.9</td>
</tr>
<tr>
<td>CuO/Al₂O₃</td>
<td>50.2</td>
<td>47.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CuO/ZnO</td>
<td>19.7</td>
<td>65.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CuO/ZrO₂</td>
<td>41.5</td>
<td>63.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CuO/MgO/SiO₂</td>
<td>37.9</td>
<td>70.0</td>
<td>32.1</td>
<td>65.7</td>
</tr>
<tr>
<td>CuO/CAO/SiO₂</td>
<td>33.3</td>
<td>73.4</td>
<td>29.0</td>
<td>42.7</td>
</tr>
<tr>
<td>CuO/ZrO₂/SiO₂</td>
<td>39.1</td>
<td>58.7</td>
<td>54.0</td>
<td>61.6</td>
</tr>
</tbody>
</table>

In the reducing conditions of the reaction, where two moles of hydrogen are produced for every mole of product, CuO/ZnO/Al₂O₃ provides the best selectivity for the desired products. Conversion is also relatively high; however, this is less of an issue as reactive distillation is being employed. High conversions can be achieved as product is being continually removed from the reaction zone to shift the equilibrium forward. In addition, CuO/ZnO/Al₂O₃ is easily sourced, as it is the catalyst used for methanol synthesis.

Hydrogen and small amounts of acetaldehyde exit from the top of this reactive distillation column. The bottoms products include ethyl acetate, n-butanal, butan-2-one, and water.

12.5 Hydrogenation Reactor (R-100)

The boiling points at atmospheric pressure of ethyl acetate, n-butanal, and butan-2-one are 77°C, 79°C, and 74.8°C, respectively. These are much too similar to easily isolate ethyl acetate. Therefore, the bottoms products are fed to a hydrogenation reactor to convert the
byproducts to n-butanol and 2-butanol. These have boiling points at atmospheric pressure of 117°C and 100°C, respectively, allowing for a much easier separation of the byproducts from ethyl acetate.

This reactor also requires a hydrogen feed. As hydrogen is produced from the reactive distillation column, a fraction of the hydrogen can be used as a feed to this reactor. The reactor is a packed bed with Raney Nickel catalyst and is modelled using kinetics reported in literature, referred to in Section 12.2.

12.6 Distillation Column (C-102)

The patents pointed to the possibility that the final separation process would be liquid-liquid extraction (LLE). However, following industrial consultants’ guidance, a distillation column is used instead. This decision was reached based on the belief that the relative difference in boiling points would allow for a cleaner split than the relative difference in solubilities. Thus, having a distillation column would be a more effective method of final separation.

The feed to this column consists of ethyl acetate, n-butanol, 2-butanol, and some hydrogen. The difference in boiling points allow for a relatively easy separation; ethyl acetate and hydrogen go to the top of the column while the heavier alcohols fall to the bottom. By adding a vent to the column’s condenser, enough of the remaining hydrogen is released to allow for the final ethyl acetate product stream to reach the desired purity of 99.8%.

12.7 Intermediate Blocks

12.7.1 Stripper (C-100)

The output from the top of the reactive distillation column is a stream that consists mainly of hydrogen. As a hydrogen feed is needed later in the process, part of this stream is recycled. However, it was found that the stream was not quite pure enough to be a
successful feed to the hydrogenation reactor, as it contained a small yet significant amount of acetaldehyde. A stripper was added as an intermediate block. The pure ethanol feed to the process enters the stripper. Acetaldehyde is transferred from the hydrogen stream into the ethanol stream due to solubility differences. The hydrogen stream reaches a purity that is now acceptable for the hydrogenation reaction. A splitter is in place to send the desired amount of hydrogen back to the reactor and allows the rest of the hydrogen stream to be combusted to provide fuel value. The ethanol stream then enters the reactive distillation column. Acetaldehyde is the reaction intermediate, so it is more useful being present in the reactive distillation column than being vented.

12.7.2 Molecular Sieve (S-100)

Unfortunately, the side reactions that occur introduce water into the system. The water exits the reactive distillation column as part of the bottoms products stream. To resolve this issue, a molecular sieve is present in the process following the reactive distillation column. The bottoms products are fed in and the water is absorbed and removed from the stream. The resulting stream is then ready to be heated and sent to the hydrogenation reactor.

12.7.3 Flash Heat Exchanger (E-103)

Initially, the stream exiting the hydrogenation reactor was sent directly to the final distillation column. The amount of hydrogen present in the final column introduced a new problem. In order to obtain the desired purity of ethyl acetate, a significant amount of the product was also being lost through the vent of the column’s condenser. To minimize the amount of product lost, a heat exchanger was added to the process before the final distillation column. This works to cool the stream to flash off a majority of the hydrogen from the stream before it enters the column. Less hydrogen then needs to exit through the vent of the condenser, and thus less ethyl acetate, allowing for the desired purity of the product stream with minimal product loss.
13 Assembly of Database

To produce ethyl acetate using the Greenyug process\textsuperscript{21}, ethanol is required as the sole feedstock. Spot prices from Bloomberg as of 16 April 2019 are used, with an ethanol purchase price of $0.21/lb and ethyl acetate selling price of $0.42/lb. Utility costs for cooling water, 150psig steam, 450psig steam, and electricity are sourced from Seider et. al\textsuperscript{22}. To meet safety standards and improve heat integration, a flare system is employed and fuel value for the vented hydrogen co-product is accounted for. The monetary value of the combusted hydrogen is assumed to be equivalent to that of natural gas, taken from current market prices.

ASPEN Plus is utilized to design, simulate, and optimize the entire process. Initially, a non-random two-liquid model (NRTL) was chosen to account for azeotropes in the system. Residue curves produced in literature were compared to those created in ASPEN Plus to verify the thermodynamics of the model. Hydrogen was specified as a Henry Component and binary parameters were retrieved from associated databases.

The design process utilized RADFRAC blocks to model all columns and RPLUG to model packed bed reactors as plug flow reactors. HEATX blocks were used for heating and cooling of streams for heat integration. Initial parameters for distillation columns were estimated using either existing patent data or DSTWU. Kinetics for the relevant chemistry and reactions are described in Section 12.2 and are taken from reported expressions and values in literature.

Ethyl acetate is a Category 2 flammable liquid, and is toxic when ingested or inhaled. OSHA regulations limit exposure to concentrations below 400ppm 8-hour total weight average (TWA). Ethanol is a Category 3 flammable liquid and can cause severe eye and skin irritation. OSHA regulations limit exposure to concentrations below 1000ppm TWA. Both substances are stored in floating head storage tanks to account for volatility and flamma-
bility concerns. Hydrogen is categorized as a Category 1 gas and is highly flammable. See Section 27.4 for all MSDS specification sheets. Trace amounts of vented hydrogen that are not used for fuel value motivated the inclusion of a flare system to combust the stream prior to release.
Figure 8: Overall Proposed Process Flow Diagram for Greenyug’s Ethyl Acetate Plant
Table 2: Equipment Block List for Segment 001 of the Process Flow Diagram

<table>
<thead>
<tr>
<th>Block Number</th>
<th>Block Type</th>
<th>Block Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-100</td>
<td>Tank</td>
<td>Feed Storage Tank</td>
</tr>
<tr>
<td>P-100</td>
<td>Pump</td>
<td>Feed Pump</td>
</tr>
<tr>
<td>C-100</td>
<td>Column</td>
<td>Stripping Column</td>
</tr>
<tr>
<td>C-101</td>
<td>Column</td>
<td>Reactive Distillation Column</td>
</tr>
<tr>
<td>E-100</td>
<td>Heat Exchanger</td>
<td>Reactive Distillation Column Condenser</td>
</tr>
<tr>
<td>D-100</td>
<td>Reflux Drum</td>
<td>Reactive Distillation Column Reflux Drum</td>
</tr>
<tr>
<td>P-101</td>
<td>Pump</td>
<td>Reactive Distillation Column Reflux Pump</td>
</tr>
<tr>
<td>P-102</td>
<td>Pump</td>
<td>Reactive Distillation Column Reboiler Pump</td>
</tr>
<tr>
<td>E-101</td>
<td>Heat Exchanger</td>
<td>Reactive Distillation Column Reboiler</td>
</tr>
</tbody>
</table>

Figure 9: Segment 001 of the Process Flow Diagram
Table 3: Material Balance for Segment 001 of the Process Flow Diagram

<table>
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<tr>
<th>Stream Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<th>6</th>
<th>7</th>
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<tr>
<td>Temperature (° F)</td>
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<td>99.2</td>
<td>103.3</td>
<td>189.8</td>
<td>206.8</td>
<td>405.0</td>
</tr>
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<td>Pressure (bar)</td>
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<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
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<td>13729</td>
<td>710.5</td>
<td>16202</td>
<td>3184</td>
<td>13019</td>
</tr>
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<td>Component Mass Flow (lb/hr)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>-</td>
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<td>trace</td>
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<td>331.0</td>
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<td>119.5</td>
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<td>1796</td>
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<td>0.0</td>
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<td>-</td>
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<td>n-Butanal</td>
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<td>0.57</td>
<td>80.4</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<td>2-Butanol</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>Molar Flow (lbmol/hr)</td>
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<td>Volume Flow (cuft/hr)</td>
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<td>6160</td>
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Table 4: Equipment Block List for Segment 002 of the Process Flow Diagram

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<th>Block Type</th>
<th>Block Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-100</td>
<td>Molecular Sieve</td>
<td>13X Molecular Sieve</td>
</tr>
<tr>
<td>E-102</td>
<td>Heat Exchanger</td>
<td>Double Piped Heat Exchanger</td>
</tr>
<tr>
<td>R-100</td>
<td>Reactor</td>
<td>Hydrogenation Reactor</td>
</tr>
<tr>
<td>E-103</td>
<td>Heat Exchanger</td>
<td>Double Piped Heat Exchanger</td>
</tr>
</tbody>
</table>

Figure 10: Segment 002 of the Process Flow Diagram
**Table 5:** Material Balance for Segment 002 of the Process Flow Diagram

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>3</th>
<th>4</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (** F**)</td>
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<td>103.3</td>
<td>405.0</td>
<td>405.0</td>
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<td></td>
<td></td>
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<td></td>
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<td>-</td>
<td>trace</td>
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<td>trace</td>
<td>trace</td>
<td>trace</td>
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<tr>
<td>Ethanol</td>
<td>119.5</td>
<td>107.5</td>
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<td>0.48</td>
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<td>12818</td>
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<td>0.01</td>
<td>trace</td>
<td>0.01</td>
</tr>
<tr>
<td>Buta-2-one</td>
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<td>trace</td>
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<td>80.40</td>
<td>trace</td>
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<td>80.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>trace</td>
<td>trace</td>
<td>80.4</td>
<td>80.40</td>
<td>trace</td>
<td>80.4</td>
<td>80.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>2-Butanol</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>295.8</td>
<td>266.2</td>
<td>149.9</td>
<td>147.7</td>
<td>29.6</td>
<td>177.3</td>
<td>177.3</td>
<td>175.1</td>
<td>29.6</td>
<td>145.4</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>6160</td>
<td>5544</td>
<td>348.3</td>
<td>347.5</td>
<td>616.0</td>
<td>18886</td>
<td>24979</td>
<td>25043</td>
<td>3188</td>
<td>236.6</td>
</tr>
</tbody>
</table>
Table 6: Equipment Block List for Segment 003 of the Process Flow Diagram

<table>
<thead>
<tr>
<th>Block Number</th>
<th>Block Type</th>
<th>Block Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-102</td>
<td>Column</td>
<td>Distillation Column</td>
</tr>
<tr>
<td>E-104</td>
<td>Heat Exchanger</td>
<td>Distillation Column Condenser</td>
</tr>
<tr>
<td>D-101</td>
<td>Reflux Drum</td>
<td>Distillation Column Reflux Drum</td>
</tr>
<tr>
<td>P-103</td>
<td>Pump</td>
<td>Distillation Column Reflux Pump</td>
</tr>
<tr>
<td>P-104</td>
<td>Pump</td>
<td>Distillation Column Reboiler Pump</td>
</tr>
<tr>
<td>E-105</td>
<td>Heat Exchanger</td>
<td>Distillation Column Reboiler</td>
</tr>
<tr>
<td>T-101</td>
<td>Tank</td>
<td>Ethyl Acetate Storage Tank</td>
</tr>
<tr>
<td>T-102</td>
<td>Tank</td>
<td>Waste (Byproducts) Storage Tank</td>
</tr>
</tbody>
</table>

Figure 11: Segment 003 of the Process Flow Diagram
Table 7: Material Balance for Segment 003 of the Process Flow Diagram

<table>
<thead>
<tr>
<th>Stream Number</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>122.0</td>
<td>102.2</td>
<td>102.2</td>
<td>263.2</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>4.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>12753</td>
<td>1.63</td>
<td>12573</td>
<td>178.5</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.43</td>
<td>0.24</td>
<td>0.20</td>
<td>trace</td>
</tr>
<tr>
<td>Water</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>11.5</td>
<td>trace</td>
<td>11.5</td>
<td>trace</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>12577</td>
<td>1.39</td>
<td>12550</td>
<td>25.1</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.01</td>
<td>trace</td>
<td>0.01</td>
<td>trace</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>82.6</td>
<td>trace</td>
<td>0.02</td>
<td>82.6</td>
</tr>
<tr>
<td>5mm2-Butanol</td>
<td>82.1</td>
<td>trace</td>
<td>11.3</td>
<td>70.8</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>145.4</td>
<td>0.13</td>
<td>142.9</td>
<td>2.35</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>236.6</td>
<td>27.7</td>
<td>229.1</td>
<td>4.08</td>
</tr>
</tbody>
</table>
15  Process Descriptions

15.1  Segment 001 - Reactive Distillation

Segment 001 is outlined in Figure 9 and Tables 2 and 3. An ethanol storage tank (T-100) is employed to hold one day’s worth of feedstock inventory to prevent production halt due to possible site pipeline malfunctions. Stream 1 feeds ethanol from the storage tank into a pump (P-100) at a rate of 13,729 lb/hr at ambient conditions to pressurize the stream to 20 bar. A liquid, compressed ethanol stream (Stream 2) enters the top of a stripping column to remove acetaldehyde from Stream 6. The resultant stripping liquid (Stream 5) enters a 20 ideal stage reactive distillation column (C-101) on stage 8.

Stage 8 is packed with catalyst (CuO/ZnO/Al$_2$O$_3$, cylindrical pellets) with an estimated packing density of $0.60^{23}$ Both main reactions discussed in Section 12.2 occur in this reactive zone. A partial condenser, E-100, is used due to the presence of hydrogen in the stage 1 vapor stream. Stream 6, the vapor distillate stream from the the partial condenser (E-100), enters the stripping column mentioned previously. Stream 6 contains acetaldehyde that can be recovered in the stripping column using the feed ethanol (Stream 2). The resultant stripped gas (Stream 3) is a hydrogen product stream (with small amounts of ethanol) with a mass flow rate of 710.5 lb/hr.

The liquid distillate is sent to a reflux accumulator (D-100) and a reflux pump (P-101) at a molar reflux ratio of 1.6. The bottoms products (Stream 7) from the reactive distillation column is 98.5% purity ethyl acetate with 2:1:1 molar ratio of water:buta-2-one:n-butanal byproducts, with a total mass flow rate of 13,019 lb/hr. The reboiler (E-101) runs at 211°C and 20 bar.

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$^{23}$Donev, Cisse, Sachs, Variano, Stillinger, Connelly, Torquato, and Chaikin [2004]
15.1.1 Process Optimization

The initial design challenge in Segment 001 was the modeling and scaling up of the reactive distillation column. Lab scale data for a single ethanol feed reactive distillation column is given in patent data and summarized below\[24\].

A 200 proof feed of ethanol is fed into a 20 stage reactive distillation column with 8 stages in the rectifying section and 12 stages in the stripping section. The molar reflux ratio is 0.8 and the molar reboiler ratio is 4. A partial condenser operates at 20 bar. A vapor distillate product with a mass flow rate of 4g/hr is achieved. A bottoms products with a mass flow rate of 170g/hr is achieved with 98.5% purity of ethyl acetate. The column has a diameter of 10cm and a height of 3.5m.

Initial modeling was performed using ASPEN Plus to attempt to replicate the results from the lab scale data. The goal of the model was to generate a column that meets the criteria given the following priorities:

1. Has a bottoms flow rate and purity of ethyl acetate identical to that of the lab scale
2. Has 8 rectifying stages and 12 stripping stages
3. Operates at a condenser pressure of 20 bar
4. Has comparable dimensions
5. Has a molar reflux ratio of 0.8
6. Has a molar reboiler ratio of 4

Lower priority objects had their constraints relaxed until a satisfactory model was generated. To model the reactive section of the column, equilibrium data described in Section 12.2 was used\[25\]. An equilibrium relationship was used rather than a kinetic relationship due...
to the fact that tray spacing was unknown in the lab scale specifications. Kinetics would depend highly on the residence time of the reactants in the reactive zone of the column. It was assumed that the final column would have a sufficiently large tray spacing, and therefore residence time, to allow the reactions to reach equilibrium. In addition, the kinetic rate expression reported was not fit to a simple power law, but rather followed a more complicated functional form. While the equilibrium expression did not account for formation of byproducts, they must be included to successfully model the separation within the column.

A stoichiometric amount of byproducts was added to the reaction based on the purity given from the data. A 0th order dependence with respect to these byproducts was used for the calculation of the equilibrium constant. The byproducts all have similar volatilities to that of ethyl acetate, so accumulation within the column was not a concern and the stoichiometric coefficients could be determined with a mass balance.

A column was designed using RADFRAC that met the strict criteria of 1 through 4, with relaxed constraints on criteria 5 and 6. A RADFRAC was modeled as a 20 ideal stage column with a partial vapor condenser operating at 20 bar. The column intervals were specified using the given lab scale dimensions. A feed stream of ethanol enters the column on stage 8 as a liquid stream. Stage 8 was specified as the sole stage where reaction occurs. The stage was assumed to be packed with pelleted catalysts with a particle packing efficiency of 0.60. Once these design choices were finalized, there were two independent variables that corresponded to operating conditions that could be specified to determine the entirety of the system. The mass flow rate of the bottoms was forced to the desired value to satisfy criteria 1. The other free variable could be specified to be either the reflux ratio, boilup ratio, or reboiler duty. The reflux ratio is traditionally made the free variable due to it being
an operating condition that can easily be changed by an operator in a plant environment to reach the desired purity. The boilup ratio and reboiler duty can also be manipulated if convergence becomes an issue to achieve a similar effect. Using a design specification, the reflux ratio was varied to achieve a purity of 98.5% ethyl acetate in the bottoms stream. A final converged value of 1.2 was achieved for the reflux ratio, with a corresponding boilup ratio of 6.3.

However, despite generating a model that was similar to that of the reported data, using this column would lead to extreme operating conditions with respect to the condenser. The flow rate of the bottoms was specified to be within 10% of the stoichiometrically calculated value, which means the vapor distillate product would be highly concentrated in hydrogen. With the partial condenser running at 20 bar, an operating temperature of -256°F would be required, leading to the usage of cryogenic cooling. Therefore, criteria 1 must be relaxed with respect to the product flow rate to allow the vapor distillate to condense at a higher temperature that can be ideally achieved with either a cooling water or chilled water loop.

A sensitivity analysis was performed to determine the bottoms rate that would lead to a more ideal condenser temperature. The reflux ratio design specification was still in place to ensure the desired bottoms purity was met. Table 8 shows the condenser temperature as a function of the ratio between the bottoms and distillate mass flow rates.
Table 8: Dependence of Condenser Temperature on the Bottoms to Feed Molar Ratio. A molar ratio of 0.50 corresponds to an ideal stoichiometric amount of ethyl acetate produced without byproducts. A higher ratio corresponds to a higher purity hydrogen stream in the vapor distillate.

<table>
<thead>
<tr>
<th>Bottom to Feed Molar Ratio</th>
<th>Condenser Temperature(°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.404</td>
<td>102.3</td>
</tr>
<tr>
<td>0.406</td>
<td>85.6</td>
</tr>
<tr>
<td>0.409</td>
<td>60.1</td>
</tr>
<tr>
<td>0.411</td>
<td>52.1</td>
</tr>
<tr>
<td>0.414</td>
<td>45.9</td>
</tr>
<tr>
<td>0.416</td>
<td>40.1</td>
</tr>
<tr>
<td>0.417</td>
<td>1.5</td>
</tr>
<tr>
<td>0.419</td>
<td>-53.2</td>
</tr>
<tr>
<td>0.421</td>
<td>-103.9</td>
</tr>
<tr>
<td>0.424</td>
<td>-189.4</td>
</tr>
<tr>
<td>0.426</td>
<td>-256.1</td>
</tr>
<tr>
<td>0.490</td>
<td>-300.6</td>
</tr>
<tr>
<td>0.500</td>
<td>-356.9</td>
</tr>
</tbody>
</table>

As the molar ratio between bottom and feed flow rates increases, the mole fraction of hydrogen in the vapor distillate increases and the condenser temperature monotonically decreases as a result. The ideal molar ratio range is between 0.40 and 0.416, where a cooling and chilled water loop can be used to partially condenser the vapor distillate. The design specification of the molar reflux ratio converged to a value of 0.95.

However, the trade-off with increasing the condenser temperature is that the composition in the vapor distillate changes. The composition of the vapor distillate was mainly hydrogen and acetaldehyde with trace amounts of ethanol. At the chosen bottoms to feed molar ratio
of 0.415, the composition of the vapor distillate is 0.68 hydrogen and 0.32 acetaldehyde by mass fraction. To mitigate the lose of intermediates, a vapor liquid stripping column was introduced to recover some acetaldehyde. The ethanol fed originally to the reactive distillation column was re-routed and introduced into the stripping column as the stripping liquid. Then, the stripped liquid, now containing ethanol and acetaldehyde, is sent to the reactive distillation column as the feed source to complete the loop.

The stripping column was modeled using a RADFRAC block without a condenser or reboiler. The stripping liquid is fed above stage 1 and the vapor distillate from the reactive distillation column is fed on the bottom stage. The most important design choice of the stripping column that dictated the separation was the number of stages. To determine the number of stages, a case study sensitivity analysis was conducted to analyze the composition and flow rate of the product gas as a function of stages. However, it was found that the separation only required 2 ideal stages to achieve the maximum separation; any additional stages provided no separation advantage.

15.2 Segment 002 - Conversion of Byproducts

Segment 002 is outlined in Figure 10 and Tables 4 and 5. Stream 3 (710.5 lb/hr) contains a hydrogen and ethanol vapor stream and Stream 7 (13,019 lb/hr) contains the 98.5% purity ethyl acetate liquid stream with n-butanal, buta-2-one, and water impurities. There are two main goals in Segment 002:

1. Removal of water from the product stream

2. Reduction of reaction byproduct aldehydes and ketones into alcohols

The removal of water is achieved through the use of a molecular sieve. Stream 8 enters a 13X molecular sieve vessel (S-100) to remove water from the product stream. The spherical 13X molecular sieve has a static adsorption of 25 wt% and is assumed to have a 0.60 packing
efficiency in the vessel. A regeneration cycle of one day is assumed and an additional bed is accounted for. The regeneration of the bed requires heating the bed up to 572°F to allow for the desorption of adsorbed water molecules.

Stream 3, containing the hydrogen distillate, is split in a 9:1 mass ratio into Stream 4 and Stream 9. Stream 4 (639.5 lb/hr) is combusted for fuel value. Stream 9 is used as the hydrogen source for the reduction of the byproduct aldehydes and ketones in the bottoms products (Stream 7 and Stream 8). The split fraction was chosen to achieve a 20:1 molar ratio of hydrogen to aldehyde/ketone in the hydrogenation reactor. Stream 8 and Stream 9 are mixed at a pressure of 4 bar (from 20 bar) and enter a heat exchanger, E-102, to be heated to 302°F. A vapor, Stream 10, enters a packed bed reactor packed with Raney Nickel catalyst with a 0.60 packing efficiency. With a high hydrogen partial pressure due to the 20:1 hydrogen to ketone/aldehyde molar ratio, a 100% selective reduction to alcohols is achieved. The reaction conditions and catalyst combination are too mild to reduce ethyl acetate.

15.2.1 Process Optimization

The bottoms stream from the reactive distillation column, Stream 7, enters a molecular sieve that is modeled as a FSPLIT block in ASPEN. All water is removed from the stream for modeling purposes only. A regeneration cycle of one day is assumed for the operation. The distillate stream containing predominantly hydrogen is split in a 9:1 mass ratio and the smaller of the split streams is mixed with the dried bottoms stream. The 9:1 split was determined to allow for a 20:1 molar ratio of hydrogen to ketone/aldehyde in the hydrogenation reactor for kinetic purposes.

The subsequent mixed stream is dropped to a pressure of 4 bar and heated to a temperature of 302°F prior to entering the hydrogenation reactor. A heat exchanger is used to

\footnote{Donev, Cisse, Sachs, Variano, Stillinger, Connelly, Torquato, and Chaikin 2004}
heat the stream to the desired temperature. To determine the area of the heat exchanger, a sensitivity analysis was performed to calculate the steam requirement as a function of effective heat transfer area, shown below in Table 9. Low pressure (150 psig) steam is used to achieve a temperature of 302°F.

**Table 9: Required Utilities Versus Heat Exchanger Area**
As the heat transfer area decreases, the required utilities to achieve the desired temperature change increases. Heat transfer area requirements above 820 lb/hr of steam asymptotically approaches 44.50 ft\(^2\) and have diminishing returns in reduction of area which are not shown in the table.

<table>
<thead>
<tr>
<th>Heat Transfer Area (ft(^2))</th>
<th>Steam (150psig) Flow Rate (lb/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.2</td>
<td>704.0</td>
</tr>
<tr>
<td>52.7</td>
<td>712.8</td>
</tr>
<tr>
<td>49.8</td>
<td>721.6</td>
</tr>
<tr>
<td>48.1</td>
<td>730.4</td>
</tr>
<tr>
<td>47.1</td>
<td>739.2</td>
</tr>
<tr>
<td>46.4</td>
<td>748.0</td>
</tr>
<tr>
<td>45.9</td>
<td>756.8</td>
</tr>
<tr>
<td>45.5</td>
<td>765.6</td>
</tr>
<tr>
<td>45.2</td>
<td>774.4</td>
</tr>
<tr>
<td>45.0</td>
<td>783.2</td>
</tr>
<tr>
<td>44.8</td>
<td>792.0</td>
</tr>
<tr>
<td>44.7</td>
<td>800.8</td>
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<tr>
<td>44.6</td>
<td>809.6</td>
</tr>
<tr>
<td>44.6</td>
<td>818.4</td>
</tr>
</tbody>
</table>

As the heat transfer area of the heat exchanger increases, the amount of steam requirement decreases, as shown in Table 9. Steam flow rates higher than 818.4 lb/hr are not shown due to diminishing returns in heat exchanger area reduction; further increases in utilities were
found to asymptotically approach a constant value of heat exchanger area. The final area of 63 ft$^2$ minimized utility usage and was chosen solely on an economic basis, which is further explained in Section 20.1.2.

The heated hydrogen and bottoms stream enter a packed bed hydrogenation reactor modeled as a plug flow reactor using a RPLUG module. Kinetics for the reaction are reported by Oldenburg and Rase and are described in detail in Section 12.2. The plug flow reactor (PFR) was designed to meet the following criteria:

1. Adiabatic operation to remove design of cooling the reactor

2. 100% conversion and reduction of aldehyde and ketone byproducts to alcohols

The reactor was chosen to run adiabatically due to the amount of inerts in the stream that can act as a heat sink for the process. The adiabatic temperature rise was 12°F in the final optimized system. Full conversion of the byproducts was desired in this process to allow for easier separation in Segment 003. The aldehyde and ketone byproducts have almost identical boiling points compared to that of ethyl acetate, making separation difficult. However, the converted alcohols have larger boiling point disparities relative to the aldehyde and ketone byproducts, making separation less costly. Using the power law expressions given by Oldenburg and Rase, a residence time can be calculated given a 20:1 molar ratio of hydrogen to aldehyde/ketone (Section 27.1.2). A high hydrogen partial pressure was chosen to allow for faster conversions and lower residence times, thus reducing the size and price of the reactor. However, the residence time of a PFR is dependent on the reactor length. The length, however, depends on the volume, which is a function of vessel diameter. With two free variables, the system could not be fully determined. To mitigate this issue, an aspect ratio of $L/D = 5$ was chosen to mimic the reactor used by Oldenburg and Rase. Reactor dimensions of $D = 2.91$ ft and $L = 14.60$ ft were determined, using the aforementioned relationships. Using these preliminary dimensions, RPLUG was used as a model in ASPEN.

---

2. Oldenburg and Rase [1957]
A catalyst packing efficiency of 0.60 was assumed to account for pressure drop. The reactor dimensions were optimized by analyzing the final conversion and conversion profile as a function of position through the reactor. Final dimensions were found to be $D = 3.28\, ft$ and $L = 16.40\, ft$.

The effluent from the hydrogenation reactor contains excess hydrogen that must be removed from the process. A heat exchanger is employed to cool the stream to a given temperature to flash off a majority of the hydrogen from the stream. However, the flash temperature determines a few variables:

1. Vapor mass split fraction
2. Purity of the liquid streams
3. Utility requirement

The optimal flash temperature is one that (1) minimizes the loss of product in the vapor stream and (2) maximizes the purge of hydrogen from the liquid stream while minimizing utilities is desired. The determination of the flash temperature was conducted via a sensitivity analysis of split fraction and mass fraction of hydrogen in the liquid stream as a function of flash temperature, shown below in Table 10. A FLASH block was used rather than a heat exchanger to simplify the computations.

---

2 Donev, Cisse, Sachs, Variano, Stillinger, Connelly, Torquato, and Chaikin 2004
Table 10: Dependence of Split Fraction and Liquid Purity on Flash Temperature
As the flash temperature decreases, the vapor mass split fraction decreases and the mass fraction of hydrogen present in the liquid stream increases.

<table>
<thead>
<tr>
<th>Flash Temperature (F)</th>
<th>Vapor Mass Split Fraction</th>
<th>Mass Fraction of Hydrogen in Liquid Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.0</td>
<td>0.0124</td>
<td>3.14E-05</td>
</tr>
<tr>
<td>106.3</td>
<td>0.0167</td>
<td>3.27E-05</td>
</tr>
<tr>
<td>122.0</td>
<td>0.0227</td>
<td>3.38E-05</td>
</tr>
<tr>
<td>133.5</td>
<td>0.0288</td>
<td>3.44E-05</td>
</tr>
<tr>
<td>149.8</td>
<td>0.0406</td>
<td>3.48E-05</td>
</tr>
<tr>
<td>166.1</td>
<td>0.0581</td>
<td>3.44E-05</td>
</tr>
<tr>
<td>182.4</td>
<td>0.0851</td>
<td>3.30E-05</td>
</tr>
<tr>
<td>198.7</td>
<td>0.1290</td>
<td>3.02E-05</td>
</tr>
<tr>
<td>215.0</td>
<td>0.2088</td>
<td>2.56E-05</td>
</tr>
<tr>
<td>231.3</td>
<td>0.3876</td>
<td>1.87E-05</td>
</tr>
<tr>
<td>242.2</td>
<td>0.7016</td>
<td>1.26E-05</td>
</tr>
</tbody>
</table>

The sensitivity analysis was performed between the temperatures of 90°F to the bubble point of the effluent from the hydrogenation reactor. The lower bound was chosen due to it being the minimum temperature that can be achieved with a cooling water loop. As the flash temperature decreases, the vapor split fraction (and subsequent product lost in the vapor) decreases. The mass fraction of hydrogen in the liquid stream increases as the flash temperature decreases. Flash temperatures between 90°F and 150°F were able to reduce the split fraction to less than 5%. A final temperature was chosen to be 122°F due to diminishing returns in vapor split fraction as utilities increased.

After the flash temperature was chosen, a heat exchanger was employed and sized to accomplish the temperature drop. Similar to the design of the previous heat exchanger in
this section, a sensitivity analysis of the utility requirements versus the area was conducted, shown below in Table 11. An additional column specifying the exit stream of the cooling water was added to ensure the temperature did not exceed 120°F.

Table 11: Required Utilities and Exit Temperature for a Given Area
As the heat transfer area increases, the utility requirement decreases. The exit temperature of the cooling water was also accounted for to ensure the temperature did not exceed 120°F

<table>
<thead>
<tr>
<th>Heat Transfer Area (ft²)</th>
<th>Cooling Water Flow Rate (lb/hr)</th>
<th>Exit Cooling Water Temperature(°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>274.02</td>
<td>102294</td>
<td>120.0</td>
</tr>
<tr>
<td>270.68</td>
<td>113317</td>
<td>117.1</td>
</tr>
<tr>
<td>268.00</td>
<td>124341</td>
<td>114.7</td>
</tr>
<tr>
<td>265.80</td>
<td>135364</td>
<td>112.7</td>
</tr>
<tr>
<td>263.96</td>
<td>146387</td>
<td>111.0</td>
</tr>
<tr>
<td>262.41</td>
<td>157410</td>
<td>109.6</td>
</tr>
<tr>
<td>261.07</td>
<td>168433</td>
<td>108.3</td>
</tr>
<tr>
<td>259.91</td>
<td>179456</td>
<td>107.2</td>
</tr>
<tr>
<td>258.90</td>
<td>190479</td>
<td>106.2</td>
</tr>
<tr>
<td>258.00</td>
<td>201502</td>
<td>105.3</td>
</tr>
</tbody>
</table>

The upper and lower bound for the area and utility requirement, respectively, were determined by the maximum allowed exit temperature of the cooling water. The final area that minimized utilities was chosen on an economic basis; details are described in Section 20.1.2.

15.3 Segment 003 - Product Separation

Segment 003 is outlined in Figure 11 and Tables 6 and 7. Stream 14 enters a distillation column, C-102, with a mass flow rate of 12,753 lb/hr to complete the final product separation. The distillation column operates with a partial condenser (E-104) at 2 bar with a vapor
distillate (Stream 15) and a liquid distillate (Stream 16). A partial condenser running at 102°F is used due to the trace amounts of non-condensable hydrogen still present in Stream 14. The vapor distillate contains hydrogen and is vented out the top of the column. The liquid distillate containing 99.8% purity ethyl acetate is sent to a storage tank (T-101) to hold up to seven days of product for shipment purposes. The bottoms products, Stream 17, contains the converted alcohol byproducts, 2-butanol and n-butanol, from the hydrogenation reactor in Segment 002. Stream 17 enters a storage tank (T-102) to hold up to 30 days of waste for waste disposal purposes.

15.3.1 Process Optimization

The distillation column was designed to achieve 99.8% purity ethyl acetate in the distillate product. To get initial column specifications, calculations shown in Section 27.1.3 and the DSTWU shortcut method were employed to determine the number of stages and corresponding reflux ratio. The relative volatilities and separation specifications state ethyl acetate and 2-butanol to be the light and heavy keys, respectively. A partial condenser was employed with a conservative split fraction that would recover the greatest amount of product as well as allow the condenser to be cooled using a traditional cooling water loop (an in depth analysis on the split fraction was conducted, as described later in this section in Table 13). A sensitivity analysis was performed to determine the optimal conditions to design the column and is shown in Table 12.
Table 12: Estimated Number of Theoretical Stages and Reflux Ratio Required
The minimum number of stages needed to accomplish the desired separation is 19. As the number of stages increases, the reflux ratio monotonically decreases. There are diminishing returns in the reflux ratio as the number of stages increase.

<table>
<thead>
<tr>
<th>Theoretical Stages</th>
<th>Reflux Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>170.7</td>
</tr>
<tr>
<td>20</td>
<td>9.6</td>
</tr>
<tr>
<td>21</td>
<td>6.4</td>
</tr>
<tr>
<td>22</td>
<td>4.9</td>
</tr>
<tr>
<td>23</td>
<td>3.8</td>
</tr>
<tr>
<td>24</td>
<td>2.8</td>
</tr>
<tr>
<td>25</td>
<td>2.3</td>
</tr>
<tr>
<td>26</td>
<td>2.1</td>
</tr>
<tr>
<td>27</td>
<td>1.9</td>
</tr>
<tr>
<td>28</td>
<td>1.8</td>
</tr>
<tr>
<td>29</td>
<td>1.7</td>
</tr>
<tr>
<td>30</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The minimum number of theoretical stages needed to achieve the desired separation is 19. As the number of theoretical stages increases, the reflux ratio monotonically decreases with diminishing returns. The optimal number of stages is between 20 and 24 stages, where the required reflux ratio decreases significantly. A column with 20 ideal stages was used as the initial specification for a more detailed model using a RADFRAC block.

A RADFRAC block with 20 ideal stages was designed to meet the following criteria:

1. Has a liquid distillate purity of the desired 99.8% of ethyl acetate
2. Meets the 50kT/year ethyl acetate production specification
3. Has a partial condenser temperature that can be cooled using cooling water
4. Minimizes the lose of product in the vented vapor stream

To reach the desired ethyl acetate purity, a design specification was used that varied the molar reflux ratio to a 0.998 mass fraction of ethyl acetate. A similar technique was used in the reactive distillation column to achieve a purity result as well. The partial condenser temperature and product recovery are coupled in that the vapor liquid distillate split is dependent on the condenser temperature. A sensitivity analysis was performed that determined the relationship between mass split fraction and the condenser temperature, as shown in Table 13.

Table 13: Effect of Condenser Temperature on the Vapor Split Fraction and Product Purity
As the condenser temperature is lowered, more product is recovered. The minimum split fraction that can be achieved using cooling water is about 0.0001. The purity of ethyl acetate was found to not be sensitive to changes in the condenser temperature.

<table>
<thead>
<tr>
<th>Condenser Temperature(°F)</th>
<th>Vapor Mass Split Fraction</th>
<th>Ethyl Acetate Purity</th>
</tr>
</thead>
<tbody>
<tr>
<td>-423.3</td>
<td>1.00E-05</td>
<td>0.9983</td>
</tr>
<tr>
<td>-365.7</td>
<td>2.02E-05</td>
<td>0.9983</td>
</tr>
<tr>
<td>6.1</td>
<td>4.09E-05</td>
<td>0.9982</td>
</tr>
<tr>
<td>77.9</td>
<td>8.29E-05</td>
<td>0.9982</td>
</tr>
<tr>
<td>104.4</td>
<td>1.46E-04</td>
<td>0.9982</td>
</tr>
<tr>
<td>127.5</td>
<td>2.56E-04</td>
<td>0.9981</td>
</tr>
<tr>
<td>147.1</td>
<td>4.50E-04</td>
<td>0.9981</td>
</tr>
<tr>
<td>167.1</td>
<td>9.10E-04</td>
<td>0.9981</td>
</tr>
<tr>
<td>182.2</td>
<td>1.84E-03</td>
<td>0.9981</td>
</tr>
<tr>
<td>193.2</td>
<td>3.73E-03</td>
<td>0.9981</td>
</tr>
<tr>
<td>199.4</td>
<td>6.55E-03</td>
<td>0.9981</td>
</tr>
<tr>
<td>202.8</td>
<td>1.00E-02</td>
<td>0.9981</td>
</tr>
</tbody>
</table>
As the condenser temperature drops, the vapor split fraction decreases and more product is recovered in the liquid distillate stream. The ethyl acetate purity was found to be insensitive to changes in the condenser temperature. The range of split fractions corresponded to temperatures between 90 and 120°F was found to be compatible with a cooling water loop. The final vapor mass fraction was set to 1.3E-04 with a corresponding condenser temperature of 102°F. The corresponding design specified molar reflux ratio was found to converge at 10. The corresponding bottoms reboiler operates at 263°F and contains the byproducts of the reaction with the optimized distillate conditions.
16 Energy Balance

16.1 Energy Integration Method

The process produces several streams of almost pure hydrogen. However, the purity is not quite high enough to be able to sell this as a byproduct. The decision was made to burn these streams as a way to gain fuel value. To account for this, the amount of energy that would be released from the combustion of the hydrogen stream was calculated. An efficiency of 70% was assumed when this calculation was performed. From the calculated Btu/hr, a value of Btu/lb ethyl acetate was calculated. This was then included as a byproduct from the process to be sold. This is discussed further in the Section 23.

There are a total of 6 heat exchangers in this process, 4 of which are condensers and reboilers associated with columns. The temperature changes required are shown below in Table 14:

<table>
<thead>
<tr>
<th>Block</th>
<th>Description</th>
<th>Incoming Temperature (F)</th>
<th>Target Temperature (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-100</td>
<td>Condenser of reactive distillation column, C-100</td>
<td>206.8 (vapor)</td>
<td>206.8 (partial vapor-liquid)</td>
</tr>
<tr>
<td>E-101</td>
<td>Reboiler of reactive distillation column, C-100</td>
<td>411.8 (liquid)</td>
<td>411.8 (vapor)</td>
</tr>
<tr>
<td>E-102</td>
<td>Preheat feed for hydrogenation reactor, R-100</td>
<td>242.1</td>
<td>302.0</td>
</tr>
<tr>
<td>E-103</td>
<td>Flash products post-hydrogenation, R-100</td>
<td>313.7</td>
<td>122.0</td>
</tr>
<tr>
<td>E-104</td>
<td>Condenser of distillation column, C-101</td>
<td>210.8 (vapor)</td>
<td>101.4 (partial vapor-liquid)</td>
</tr>
<tr>
<td>E-105</td>
<td>Reboiler of distillation column, C-101</td>
<td>263.2 (liquid)</td>
<td>263.2 (vapor)</td>
</tr>
</tbody>
</table>

The only heat exchangers that can be networked are E-102 and E-103. However, the heating and cooling requirements for these units are negligible, being 1.5 orders of magnitude lower compared to those of the condensers and reboiler exchangers. As a cost saving measure,
it was decided to be uneconomical to add an integrated heat exchanger design.

16.2 Energy Requirements

The heat exchangers, column condensers, column reboilers, and molecular sieve all contribute significantly to the energy requirements for this process. In addition, the feed, reflux, and reboiler pumps contribute to the electricity needed. Table 15 below summarizes the heat duties, energy, and power requirements of each aforementioned block. These values were all obtained from the ASPEN model.

<table>
<thead>
<tr>
<th>Block ID</th>
<th>Requirement Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-100</td>
<td>Reactive Distillation Column Condenser Heat Duty (Btu/hr)</td>
<td>-9621280</td>
</tr>
<tr>
<td>E-101</td>
<td>Reactive Distillation Column Reboiler Heat Duty (Btu/hr)</td>
<td>16858600</td>
</tr>
<tr>
<td>E-102</td>
<td>Heat Exchanger 1 Heat Duty (Btu/hr)</td>
<td>708965</td>
</tr>
<tr>
<td>E-103</td>
<td>Heat Exchanger 2 Heat Duty (Btu/hr)</td>
<td>-3063260</td>
</tr>
<tr>
<td>E-104</td>
<td>Distillation Column Condenser Heat Duty (Btu/hr)</td>
<td>-28594700</td>
</tr>
<tr>
<td>E-105</td>
<td>Distillation Column Reboiler Heat Duty (Btu/hr)</td>
<td>28486200</td>
</tr>
<tr>
<td>S-100</td>
<td>Molecular Sieve Regeneration Energy Requirement (Btu/hr)</td>
<td>33177</td>
</tr>
<tr>
<td>P-100</td>
<td>Feed Pump Power Requirement (kW)</td>
<td>10.8</td>
</tr>
<tr>
<td>P-101</td>
<td>Reactive Distillation Reflux Pump Power Requirement (kW)</td>
<td>2.53</td>
</tr>
<tr>
<td>P-102</td>
<td>Reactive Distillation Reboiler Pump Power Requirement (kW)</td>
<td>1.89</td>
</tr>
<tr>
<td>P-103</td>
<td>Distillation Reflux Pump Power Requirement (kW)</td>
<td>1.25</td>
</tr>
<tr>
<td>P-104</td>
<td>Distillation Reboiler Pump Energy Power (kW)</td>
<td>0.0220</td>
</tr>
</tbody>
</table>
17 Utility Demands

The energy requirements listed in Table 15 above are all fulfilled by adding purchased cooling water, high pressure (450 psig) steam, low pressure (150 psig) steam, or electricity to the system. Using those values along with standard industry process for calculating amounts of water and steam, the necessary quantities of each utility were determined. Table 16 summarizes the utilities needed for each equipment block. Table 17 then summarizes the utility inputs as ratios per pound of ethyl acetate produced.

**Table 16: Utility Requirements per Hour for Each Process Unit**

<table>
<thead>
<tr>
<th>Utility</th>
<th>Equipment Item</th>
<th>Quantity (per hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Water (lb)</td>
<td>E-100</td>
<td>282696</td>
</tr>
<tr>
<td></td>
<td>E-103</td>
<td>90006</td>
</tr>
<tr>
<td></td>
<td>E-104</td>
<td>840180</td>
</tr>
<tr>
<td>Total (lb)</td>
<td></td>
<td><strong>1212882</strong></td>
</tr>
<tr>
<td>High Pressure Steam (450 psig) (lb)</td>
<td>E-101</td>
<td>22057</td>
</tr>
<tr>
<td></td>
<td>S-100</td>
<td>43.41</td>
</tr>
<tr>
<td>Total (lb)</td>
<td></td>
<td><strong>22101</strong></td>
</tr>
<tr>
<td>Low Pressure Steam (150 psig) (lb)</td>
<td>E-102</td>
<td>826</td>
</tr>
<tr>
<td></td>
<td>E-105</td>
<td>33217</td>
</tr>
<tr>
<td>Total (lb)</td>
<td></td>
<td><strong>34044</strong></td>
</tr>
<tr>
<td>Electricity (kW)</td>
<td>P-100</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>P-101</td>
<td>2.53</td>
</tr>
<tr>
<td></td>
<td>P-102</td>
<td>1.89</td>
</tr>
<tr>
<td></td>
<td>P-103</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>P-104</td>
<td>0.022</td>
</tr>
<tr>
<td>Total (kW)</td>
<td></td>
<td><strong>16.48</strong></td>
</tr>
</tbody>
</table>
Table 17: Total Utility Requirements per Pound of Ethyl Acetate Produced

<table>
<thead>
<tr>
<th>Utility</th>
<th>Unit</th>
<th>Ratio (per lb ethyl acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling Water</td>
<td>lb</td>
<td>96.64</td>
</tr>
<tr>
<td>High Pressure Steam (450 psig)</td>
<td>lb</td>
<td>1.76</td>
</tr>
<tr>
<td>Low Pressure Steam (150 psig)</td>
<td>lb</td>
<td>2.71</td>
</tr>
<tr>
<td>Electricity</td>
<td>kWh</td>
<td>0.0013</td>
</tr>
<tr>
<td>Process Water</td>
<td>lb</td>
<td>0</td>
</tr>
</tbody>
</table>

17.1 Cooling Water

Cooling water is used in this process in units E-100, E-103, and E-104. These are the reactive distillation column condenser, the heat exchanger prior to the final distillation column, and the distillation column condenser, respectively.

The heat capacity of the cooling water used was 1.001 Btu/(lb°F)\(^{30}\). The cooling water used was assumed to have a temperature change from 86°F to 120°F. These values were used to calculate the necessary flow rate of cooling water needed for the process. The 86°F starting temperature was chosen after taking into consideration the location of the plant and discussing the most likely temperature value of available cooling water with industry consultants. The total required cooling water for the process is 1,212,882 lb/hr.

17.2 High Pressure Steam

Following heuristics provided in Chapter 17 of Seider et. al, 2017, high pressure steam at 450 psig was used for the process. This steam is used in blocks E-101, the reactive distillation column reboiler, and S-100, the molecular sieve. A value of 764.305 Btu/lb was used as the latent heat of this high pressure steam to calculate the necessary mass flow rate of steam
needed. The utility requirement for high pressure steam is 22,101 lb/hr.

17.3 Low Pressure Steam

Similar to the rationale followed for high pressure steam, it was determined that low pressure steam at 150 psig would be used for the process. This steam is used in block E-102, the heat exchanger prior to the hydrogenation reactor, and E-105, the distillation column reboiler. The latent heat of the low pressure steam used in the calculations was 857.571 Btu/lb. The calculated total value for low pressure steam is 34,044 lb/hr.

17.4 Electricity

The final utility requirement comes from the electricity required to run each of the five pumps in the process. The total required electricity for the process is 16.48 kW.
18 Equipment List & Unit Description

This section describes the major process equipment units. For each unit described in this section, the associated specification sheets can be found in Section 19.

18.1 Pumps

*Feed Pump*

<table>
<thead>
<tr>
<th>Unit ID: P-100</th>
<th>Outlet Temperature: 97.5°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Centrifugal Pump</td>
<td>Pressure: 20 bar</td>
</tr>
<tr>
<td>Material: Stainless Steel 316</td>
<td>Work: 10.8382 kW</td>
</tr>
<tr>
<td>Specification Sheet: Page 77</td>
<td>Bare Module Cost: $30,815</td>
</tr>
</tbody>
</table>

The feed pump was designed with the aid of ASPEN, allowing a pressure rise of 19 bar and maintaining a flow rate of 279.5 ft³/hr. The inlet pressure is 1 bar and the head necessary to accommodate the pressure rise is 384 ft. This calculation was carried out on the basis of equations detailed in Section 27.1.1. Based on the head calculated, guidelines\(^3\) suggest that the feed pump be modelled as a standard centrifugal pump with Vertical Split Case (VSC) orientation with 1 stage, shaft rpm of 3600 and a maximum motor hp of 75. Stainless Steel 316 is used as the construction material for this pump, as this material is able to withstand corrosion. This is an important consideration as the end use of ethyl acetate is often a solvent, and therefore it is important that considerations be made to avoid material corrosion through the process.

18.2 Process Heat Exchangers

With the assistance of ASPEN Exchanger Design and rating (EDR) capabilities, both heat exchangers in this process were designed in accordance to TEMA\(^4\) (Tubular Exchanger Manufacturers Association) standards.

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\(^3\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017

\(^4\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
Heat Exchanger One: Flow to Hydrogenation Reactor

Unit ID: E-102  
Type: Double Pipe Heat Exchanger  
Material: Stainless Steel 316  
Heat Duty: 708,965 Btu/hr  
Pressure: 4 bar  
Specification Sheet: Page 78  
Inlet Hot Stream Temperature: 366.0°F  
Outlet Hot Stream Temperature: 244.8°F  
Inlet Cold Stream Temperature: 242.1°F  
Outlet Cold Stream Temperature: 302.0°F  
Area: 5.65 ft²  
Bare Module Cost: $11,138

Low pressure steam is used as the heat transfer media for this heat exchanger. E-102 was optimized on the basis of cost by specifying the inlet steam flow rates (See section 20.1.2). Using the specified inlet steam flow rate of 320 kg/hr, the heat exchanger surface area required is 5.65 ft², as determined from ASPEN outputs. For heat exchange surface areas of less than 200 ft², double pipe heat exchangers are selected over shell and tube heat exchangers\(^3\). Both the inner and outer pipe materials were chosen to be stainless steel. This design choice yields a material construction factor of 3. This heat exchanger has an average heat transfer coefficient of 149.7 Btu/hr – ft² –° F and a log-mean-temperature-difference (LMTD) of 77.9°F.

Heat Exchanger Two: Flow to Distillation Column

Unit ID: E-103  
Type: Double Pipe Heat Exchanger  
Material: Stainless Steel 316  
Heat Duty: -3,063,260 Btu/hr  
Pressure: 1 bar  
Specification Sheet: Page 79  
Inlet Hot Stream Temperature: 313.7°F  
Outlet Hot Stream Temperature: 122.0°F  
Inlet Cold Stream Temperature: 86.0°F  
Outlet Cold Stream Temperature: 120.0°F  
Area: 25.5 ft²  
Bare Module Cost: $14,176

Low pressure steam is used as the heat transfer media for this heat exchanger. E-103 was optimized on the basis of cost by specifying the inlet steam flow rates (see Section 20.1.2). Using the specified inlet steam flow rate of 46,400 kg/hr, the heat exchanger surface area required is 25.5 ft², as determined from ASPEN outputs. As discussed above, this surface area falls within the decision criteria to design this heat exchanger as a double pipe heat

\(^3\)Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
exchanger. Stainless Steel 316 was the material construction choice. This heat exchanger has an average heat transfer coefficient of $149.2 \text{ Btu/hr} - \text{ft}^2 - ^\circ\text{F}$ and a log-mean-temperature-difference (LMTD) of $74.7^\circ\text{F}$.

### 18.3 Reactors

**Reactive Distillation Column**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit ID: C-101</td>
<td></td>
</tr>
<tr>
<td>Type: Reactive Distillation Column</td>
<td></td>
</tr>
<tr>
<td>Material: Stainless Steel 316</td>
<td></td>
</tr>
<tr>
<td>Height: 73 ft</td>
<td></td>
</tr>
<tr>
<td>Diameter: 5.74 ft</td>
<td></td>
</tr>
<tr>
<td>Number of Theoretical Stages: 20</td>
<td></td>
</tr>
<tr>
<td>Number of Actual Trays: 31</td>
<td></td>
</tr>
<tr>
<td>Condenser Temperature: 206.8°F</td>
<td></td>
</tr>
<tr>
<td>Reboiler Temperature: 404.9°F</td>
<td></td>
</tr>
<tr>
<td>Bare Module Cost: $2,425,977</td>
<td></td>
</tr>
</tbody>
</table>

The reactive distillation column was simulated in ASPEN and used to optimize the separation of the newly created ethyl acetate and byproducts from the hydrogen byproduct. This process required 20 theoretical stages, a condenser pressure of 20 bar, a molar reflux ratio of 1.6 and a molar bottoms rate of 68.01 kmol/hr. Sieve trays were used and hydraulic data generated indicated a stripping section diameter of 5.74 ft and an enriching section diameter of 2.66 ft. Following guidance from industrial consultants, it was proposed that this column be costed as a singular section column, with the larger diameter of 5.74 ft. O’Connell correlations account for tray efficiencies, and were used to determine the total number of actual trays required for this unit. These calculations are outlined in Section 27.1.2. The number of actual trays required is 31, with one tray accounting for the reboiler. The feed tray location is the 12th ideal tray, which corresponds to the 20th real tray. The feed tray is assumed to be packed with catalyst, with a packing efficiency of 0.6. The assumed tray spacing was 2 ft and was used to calculate the total height of the column. The tray spacing was multiplied by the total number of actual trays, and an additional skirt length of 4 ft for the enriching section and 7 ft for the stripping section were added. These values follow the guidance provided in Chapter 16 of Seider et. al, 2017. The reactive distillation
column is constructed out of Stainless Steel 316 to ensure that the column can withstand higher temperatures.

Following guidance from industrial consultants, a residence time of 10 minutes was used to design the reflux accumulator. The L/D ratio was set at 2, and the reflux accumulator was modelled as a horizontal pressure vessel. Using the design equations described in Section 27.1.2, the reflux accumulator was designed to have a diameter of 6.1 ft and a length of 12.2 ft. The reflux accumulator is constructed of Stainless Steel 316.

The partial condenser is modelled as a fixed head, shell and tube heat exchanger and operates at 206.7°F. These conditions will be maintained using 282,696 lb/hr of cooling water in a 824 ft² area exchanger with a heat duty of −9.62 × 10⁶ Btu/hr. The LMTD for this exchanger is 119°F. The area for this exchanger was calculated on the basis of design equations detailed in Section 27.1.2, as described in Seider et al., 2017. The condenser is constructed of Stainless Steel 316 and has a tube length of 20 ft.

The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger with 20 ft tube length and operates at 404.9°F. A heat flux of 12,000 Btu/hr – ft² is assumed to avoid film boiling. The reboiler area was determined to be 1421 ft² and was calculated by using the equations outlined in Section 27.1.2. Again, for corrosion purposes, the reboiler was constructed out of Stainless Steel 316.

The reboiler and reflux pump for the reactive distillation column are each constructed entirely of stainless steel, to avoid concerns of high temperature and possible corrosion due to chemical products created. Both pumps were designed by considering the liquid flow through the pump, using output available from the ASPEN simulation. The reboiler pump was designed to have a head of 385 ft and the reflux pump was designed to have a head of 280 ft. Calculations for these pumps followed equivalent calculations for the feed pump, as described in Section 27.1.1.

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3Seider, Lewin, Seader, Widagdo, Gani, and Ng, 2017
### Hydrogenation Reactor

<table>
<thead>
<tr>
<th>Unit ID: R-100</th>
<th>Pressure: 4 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Packed Column</td>
<td>Length: 16.4 ft</td>
</tr>
<tr>
<td>Material: Stainless Steel 316</td>
<td>Diameter: 3.2 ft</td>
</tr>
<tr>
<td>Bare Module Cost: $300,602</td>
<td>Heat Duty: Adiabatic</td>
</tr>
<tr>
<td>Specification Sheet: Page 81</td>
<td></td>
</tr>
</tbody>
</table>

The hydrogenation reactor was modelled as a packed column. The catalyst packing chosen was Raney Nickel, with a packing efficiency of 0.60. The catalyst is assumed to be dumped packing for costing purposes. The catalyst is replaced every three months, in accordance to its reported lifetime.

The reactor is run adiabatically, with a adiabatic temperature increase of 12°F due to the large amounts of inerts in the stream acting as heat sinks. The residence time required for this reactor is short (20 seconds) due to running at excess hydrogen partial pressures. Information for the optimization of the reactor dimensions can be found in Section 15.2.1. The hydrogenation reactor is constructed out of Stainless Steel 316 to ensure that the reactor can withstand elevated temperatures.

### 18.4 Distillation Column

<table>
<thead>
<tr>
<th>Unit ID: C-102</th>
<th>Pressure: 2 bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Distillation Column</td>
<td>Height: 69 ft</td>
</tr>
<tr>
<td>Material: Stainless Steel 316</td>
<td>Diameter: 7.1 ft</td>
</tr>
<tr>
<td>Number of Theoretical Stages: 20</td>
<td>Condenser Temperature: 101.4°F</td>
</tr>
<tr>
<td>Number of Actual Trays: 29</td>
<td>Reboiler Temperature: 263.1°F</td>
</tr>
<tr>
<td>Specification Sheet: Page 82</td>
<td>Bare Module Cost: $893,539</td>
</tr>
</tbody>
</table>

As discussed previously, following guidance from industrial consultants, a distillation column was chosen as the optimal choice for the final separation of ethyl acetate from the alcohol byproducts. To estimate the base case for initial specifications in the ASPEN simulation, a series of design equations and algorithms were used. The distillation column operating conditions were initially chosen using Figure 9.9 Seider et.al, 2017. In initially

---

designing this column, the distillate stream was assumed to be 100% ethyl acetate, thereby assuming perfect separation for the initial design basis. The bubble point pressure of ethyl acetate at 120°F was calculated as 4.35 psia, using ASPEN’s chemical database. A total condenser was included in the design of this column, assuming no hydrogen was present. Following guidelines presented in *Seider et al., 2017*, the condenser outlet pressure was set to approximately 2 bar. Following guidance from the NIST Handbook, the condenser pressure drop was assumed to be between 0 and 2 psia and the tower pressure drop was assumed to be between 5 and 10 psia. Using these guidelines, it was expected that the bottoms pressure, \( P_B \), would be in the range of 5-12 psia higher than the condenser, and therefore the bottoms pressure was estimated to be around 2.2 bar. To determine the reboiler temperature, the bubble point temperature was established using ASPEN’s chemical database.

To estimate the number of theoretical stages and the reflux ratio for this distillation column, the Fenske-Underwood-Gilliand (FUG) shortcut method was used, which is a common chemical engineering method applicable to ordinary distillation.\(^{38}\) It is noted that this method is often used for ideal mixtures, free of azeotropes. This limitation was considered, yet was debunked after considering the magnitude of liquid-phase activity coefficients in this mixture and after noting that the mixture is free of azeotropes at the chosen operating conditions. In this column, 2-butanol is the heavy key and ethyl acetate is the light key. The number of minimum stages was estimated as 8.375 stages (or otherwise, 9 stages), using Fenske equations.\(^{39}\) The design equations used to estimate the minimum number of stages are outlined in Section 27.1.3. The minimum reflux ratio was then determined, by making the key assumption that the mixture in this column can be treated as pseudo binary. Using this assumption, the minimum reflux ratio was calculated as 2.065. The design equation used to calculate this ratio is outlined in Section 27.1.3. The overall column reflux ratio is typically 3.5 times the minimum reflux ratio. Therefore, the base case

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\(^{38}\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017

\(^{39}\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
estimation of the column reflux ratio was 7.23. This estimation was used to determine the
number of theoretical stages in the column, using the Gilliland correlation. The base case
number of theoretical stage was estimated to approximately be 11 stages. The graphical
correlation can be found in Section 27.1.3. The base case number of stripping and rectifying
stages was found to be 6.68 stages and 3.48 stages, respectively. These values were obtained
by following the Kirkbride equation, as outlined in Section 27.1.3.

As discussed in Section 15.3.1, the distillation column specifications were optimized
using DSTWU to ensure maximum separation. This optimization was done by using
the ASPEN program capabilities and sensitivity analyses. Using this optimization, the
calculated number of theoretical stages is 20 stages, with a condenser pressure of 2 bar and
a column reflux ratio of 10. Based on guidance from industrial consultants, sieve trays were
used with a 2 ft spacing. Hydraulic data generated in ASPEN indicated a stripping section
diameter of 7.1 ft and a rectifying section diameter of 7.0 ft. It is proposed that this column
be costed as a singular section, with the larger diameter of 7.1 ft.

O’Connell correlations account for tray efficiencies, and were used to determine the total
number of actual trays required for this unit. These calculations are outlined in Section
27.1.3. The number of actual trays required is 29, with one tray accounting for the reboiler.
The feed tray location is 15. Making use of the assumed tray spacing of 2 ft, the total
height was calculated by multiplying the total number of actual trays by the assumed tray
spacing, and then including the additional skirt length of 4 ft for the enriching section and
7 ft for the stripping section. To prevent against corrosion, the column is constructed out
of Stainless Steel 316.

For this column’s reflux accumulator, a residence time of 10 minutes was used once
again in designing the required specifications. The L/D ratio was set at 2, and the reflux
accumulator was modelled as a horizontal pressure vessel. Using the design equations
described in Section 27.1.3, the reflux accumulator was designed to have a diameter of 8.11
ft and a length of 16.2 ft. The reflux accumulator is constructed of Stainless Steel 316.

The partial condenser is modelled as a fixed head, shell and tube heat exchanger and operates at 101.3°F. These conditions will be maintained using 840,180 lb/hr flow rate of cooling water in a 2193 ft² area exchanger with a heat duty of \(-2.62 \times 10^7\) Btu/hr. The LMTD for this exchanger is 120°F. The area for this exchanger was calculated on the basis of design equations detailed in Section 27.1.3, as described in Seider et. al, 2017. The condenser is constructed of Stainless Steel 316, and has a tube length of 20 ft.

The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger with 20 ft tube length and operates at 263.1°F. A heat flux of 12,000 Btu/hr – ft² is assumed to avoid film boiling. The reboiler area was determined to be 2362 ft² and was calculated by using the equations outlined in Section 27.1.3. Again, the reboiler is constructed entirely of Stainless Steel 316.

The reboiler and reflux pump for the reactive distillation column are each constructed entirely of stainless steel, to avoid concerns of high temperature and possible corrosion due to chemical products created. Both pumps were designed by considering the liquid flow through the pump, using output available from the ASPEN simulation. The reboiler pump was designed to have a head of 331 ft and the reflux pump was designed to have a head of 262 ft. Calculations for these pumps followed equivalent calculations for the feed pump, as described in Section 27.1.1.
18.5 Stripper

Unit ID: C-100  Pressure: 20 bar
Type: Vertical Pressure Vessel  Height: 6.0 ft
Material: Stainless Steel 316  Diameter: 10.0 ft
Number of Theoretical Stages: 5  Temperature: 103.2°F
Specification Sheet: Page 83  Bare Module Cost: $601,796

The stripper was optimized to allow for maximum removal of intermediates from the hydrogen stream, leaving the reactive distillation column. The ASPEN simulation output and convergence outputs were used to determine the ideal specifications for this column. To account for efficiency limits, the column was oversized in its diameter and height specifications. An approximate 50% efficiency assumption was used, and the column was oversized using this specification. The stripper is modelled as a vertical pressure vessel and is constructed out of 316 Stainless Steel to account for potential corrosion effects. More information on the optimization of the column can be found in Section 15.1.1.

18.6 Molecular Sieve

Unit ID: S-100  Pressure: 20 bar
Type: Molecular Sieve  Heat Duty: 33177 Btu/hr
Material: Stainless Steel 316  Diameter: 2.06 ft
Bare Module Cost: $130,754 (each)  Length: 12.4 ft
Specification Sheet: Page 84

The molecular sieve is comprised of the sieve packing and holding vessel. The molecular sieve is assumed to have one day-bed, and one regenerating-bed. The total mass of the sieve packing material was found to be 3840 kg, as explained in Section 27.1.4. The molecular
sieve is assumed to have a void fraction of 0.40 and a packing density of 0.60. Professor Leonard Fabiano was consulted for the design of this molecular sieve vessel, and the aspect ratio (L/D) was set to 3. As outlined in Section 27.1.4, the molecular sieve vessel was sized with a diameter of 4.1 ft and a length of 12.4 ft. The molecular sieve vessel was modelled as a horizontal pressure vessel for cost correlation purposes. The molecular sieve vessel is constructed from Stainless Steel 316, to account for potential corrosive issues and elevated temperature operation during the regeneration process.

18.7 Storage Tanks

*Ethanol Feed Storage Tank*

- Unit ID: T-100
- Pressure: 1 bar
- Type: Storage Tank
- Temperature: 95°F
- Tank Type: Floating Roof
- Volume: 75240 ft³
- Specification Sheet: Page 85
- Bare Module Cost: $612,507

One day’s worth of ethanol feed is stored as an excess raw material. Ethanol has a boiling point of 173.1°F and because of this, the ethanol feed will be liquid at ambient temperatures and be a liquid in this storage tank. Using a volumetric flow of 279 ft³/hr, and a volumetric safety factor of 1, the ethanol feed storage tank was sized to have a volume of 75,240 ft³. This volumetric safety factor is imperative to ensure that the tank never operates at full capacity, for pressure and control considerations. A floating tank was chosen for this storage tank as the roof dynamically moves along with the height of the fluid in the tank. This design feature eliminates oxygen interacting with the ethanol in the storage tank. As discussed in Section 12.3, the ethanol is fed to this storage tank via a pipeline from a nearby ADM corn plant. Stainless Steel 316 is used for this storage tank construction material to ensure limited pipeline impurities that may occur from corrosion.

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4 Seider, Lewin, Seader, Widagdo, Gani, and Ng [2017]
**Ethyl Acetate Storage Tank**

Unit ID: T-101  
Pressure: 2 bar  
Type: Storage Tank  
Temperature: 101.3°F  
Tank Type: Floating Roof  
Volume: 432219 ft³  
Specification Sheet: Page 86  
Bare Module Cost: $1,486,117

One week’s worth of ethyl acetate product is stored on site. This assumption follows guidance from industrial consultants, as this storage tank is an intermediate storage before the ethyl acetate is delivered to customers. Ethanol has a boiling point of 170.8°F and because of this, the ethyl acetate will be liquid at ambient temperatures and be a liquid in this storage tank. Using a volumetric flow of 229 ft³/hr, and a volumetric safety factor of 1.5, the ethanol feed storage tank was sized to have a volume of 432,219 ft³. Following similar reasoning applied to the ethanol storage tank, the safety factor is imperative to ensure that the tank does not operate at full capacity. A floating tank is chosen for this storage tank, allowing for the elimination of oxygen from the ethyl acetate stored in the tank. The storage tank is constructed from Stainless Steel 316.

**Waste Storage Tank**

Unit ID: T-102  
Pressure: 2 bar  
Type: Storage Tank  
Temperature: 263.1°F  
Tank Type: Floating Roof  
Volume: 33114 ft³  
Specification Sheet: Page 87  
Bare Module Cost: $328,942

The primary waste products formed in this process are n-Butanol and 2-Butanol. As these byproducts comprise a relatively smaller volumetric flows produced from the separation in the final distillation column, it was decided that the byproducts would be sent to waste
disposal, rather than selling the byproducts. (The volumetric flow of the byproduct stream is 4.08 \text{ ft}^3/\text{hr}.) Following guidance from industrial consultants, these waste byproducts will be stored on site for one month, assuming a monthly waste collection from the chemical plant site. Using this volumetric flow and assumption, the volume of the storage tank was calculated to be 33,114 \text{ ft}^3. Note that this volume also assumes a volumetric safety factor of 1.5, as applied to the ethanol and ethyl acetate storage tanks. A floating tank is chosen for this tank to eliminate the interaction of oxygen with the alcohol byproducts. The storage tank is constructed from Stainless Steel 316.

18.8 Minor Equipment

As the hydrogen byproduct is burned for fuel value, a flare system is deemed necessary for safety and operation considerations. A series of control valves are also included in several equipment units for safety, especially in situations of emergency plant shutdown. These valves are all included in the bare modules for this process.
## 19 Specification Sheets

### SPECIFICATION SHEET
**FEED PUMP**

<table>
<thead>
<tr>
<th>Identification:</th>
<th>Item No: P-100</th>
<th>Date: 23 April 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Required:</td>
<td>1</td>
<td>By: KVN</td>
</tr>
</tbody>
</table>

**Function:** Pressurize initial ethanol feed

**Operation:** Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Feed</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F):</td>
<td>95.0</td>
<td>99.2</td>
</tr>
<tr>
<td>Pressure (bar):</td>
<td>1.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr):</td>
<td>13729</td>
<td>13729</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ethanol</td>
<td>13729</td>
<td>13729</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr):</td>
<td>298.0</td>
<td>298.0</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>279.5</td>
<td>279.5</td>
</tr>
</tbody>
</table>

**Design Data:**
- Material: Stainless Steel 316
- No. Stages: 1
- Shaft rpm: 3600
- Type: Centrifugal Pump
- Head: 384.0 ft
- Temperature: 97.5°F
- Pressure: 20 bar

**Utilities:** Electricity at 10.83 kW

**Comments & Drawings:** See Section 18.1
SPECIFICATION SHEET
HEAT EXCHANGER ONE: FLOW TO HYDROGENATION REACTOR

Identification:  
Item No: E-102  
No. Required: 1  
Date: 23 April 2019  
By: KVN

Function:  Heat effluent stream from molecular sieve

Operation:  Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cold In Vapor</th>
<th>Cold In Liquid</th>
<th>Cold Out</th>
<th>Hot In</th>
<th>Hot Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>242.1</td>
<td>242.1</td>
<td>302.0</td>
<td>366.0</td>
<td>244.8</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>10218</td>
<td>2831</td>
<td>13050</td>
<td>705.7</td>
<td>705.7</td>
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<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hydrogen</td>
<td>59.1</td>
<td>0.04</td>
<td>59.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
<td>705.7</td>
<td>705.7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>10.7</td>
<td>1.28</td>
<td>12.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>10022</td>
<td>2796</td>
<td>12818</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.01</td>
<td>trace</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>63.8</td>
<td>16.7</td>
<td>80.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>63.3</td>
<td>17.2</td>
<td>80.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>145.1</td>
<td>32.2</td>
<td>177.3</td>
<td>39.2</td>
<td>39.2</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>18886</td>
<td>18886</td>
<td>24979</td>
<td>2107</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Design Data:  
Surface Area: 5.65 ft²  
LMTD: 77.9°F  
Heat Duty: 708965 Btu/hr  
Transfer Coefficient: 149.7 Btu/hr-ft²-°F  
Type: Double Pipe Heat Exchanger  
Material: Stainless Steel 316

Utilities:  150 psig steam at 826 lb/hr

Comments & Drawings:  See Section 18.2
**SPECIFICATION SHEET**  
**HEAT EXCHANGER TWO: FLOW TO DISTILLATION COLUMN**

**Identification:**  
Item No: E-103  
No. Required: 1  
Date: 23 April 2019  
By: KVN

**Function:** Cool the hydrogenation reactor effluent

**Operation:** Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Cold In</th>
<th>Cold Out</th>
<th>Hot In</th>
<th>Hot Out</th>
<th>Hydrogen Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>86.0</td>
<td>120.0</td>
<td>313.7</td>
<td>122.0</td>
<td>122.0</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>1.0</td>
<td>1.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>102294</td>
<td>102294</td>
<td>13050</td>
<td>12753</td>
<td>296.8</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>-</td>
<td>-</td>
<td>54.6</td>
<td>0.43</td>
<td>54.1</td>
</tr>
<tr>
<td>Water</td>
<td>102294</td>
<td>102294</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>-</td>
<td>-</td>
<td>12.0</td>
<td>11.5</td>
<td>0.48</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>-</td>
<td>-</td>
<td>1288</td>
<td>12577</td>
<td>241.0</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>-</td>
<td>-</td>
<td>0.01</td>
<td>0.01</td>
<td>trace</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
<td>83.0</td>
<td>82.6</td>
<td>0.38</td>
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<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
<td>83.0</td>
<td>82.2</td>
<td>0.81</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>5678</td>
<td>5678</td>
<td>175.1</td>
<td>145.4</td>
<td>29.6</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>1660</td>
<td>1688</td>
<td>25043</td>
<td>236.6</td>
<td>3188</td>
</tr>
</tbody>
</table>

**Design Data:**  
Surface Area: 25.5 ft²  
LMTD: 74.7°F  
Heat Duty: 3063260 Btu/hr  
Transfer Coefficient: 149.2 Btu/hr·ft²·°F  
Type: Double Pipe Heat Exchanger  
Material: Stainless Steel 316

**Utilities:** Cooling water at 90006 lb/hr

**Comments & Drawings:** See Section 18.2
SPECIFICATION SHEET
REACTIVE DISTILLATION COLUMN

Identification: Item No: C-101  Date: 23 April 2019
No. Required: 1  By: KVN

Function: Allow and drive the ethyl acetate production reactions

Operation: Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Feed</th>
<th>Bottoms</th>
<th>Distillate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>189.8</td>
<td>405.0</td>
<td>206.8</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>16202</td>
<td>13019</td>
<td>3183</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>4.23</td>
<td>-</td>
<td>595.3</td>
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<tr>
<td>Water</td>
<td>330.9</td>
<td>40.2</td>
<td>330.9</td>
</tr>
<tr>
<td>Ethanol</td>
<td>13613</td>
<td>0.08</td>
<td>3.49</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>1796</td>
<td>12818</td>
<td>1796</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>454.8</td>
<td>0.01</td>
<td>454.8</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>2.29</td>
<td>80.4</td>
<td>2.29</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>0.57</td>
<td>80.4</td>
<td>0.57</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>346.7</td>
<td>149.9</td>
<td>344.5</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>356.1</td>
<td>348.3</td>
<td>8494</td>
</tr>
</tbody>
</table>

Design Data: Number of trays: 31  Material: Stainless Steel 316
Feed Tray: 20  Pressure: 20 bar
Tray Spacing: 2 ft
Molar reflux ratio: 1.6
Height: 73 ft
Diameter: 5.74 ft
Skirt Height: 11 ft

Utilities: Cooling water at 282696 lb/hr and 450 psig steam at 22057 lb/hr

Comments & Drawings: See Section 18.3
### SPECIFICATION SHEET
#### HYDROGENATION REACTOR

**Identification:**
- Item No: R-100
- No. Required: 1
- Date: 23 April 2019
- By: KVN

**Function:** Hydrogenate the aldehyde and ketone byproducts to form alcohols

**Operation:** Continuous

<table>
<thead>
<tr>
<th>Material</th>
<th>Feed</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>302.0</td>
<td>313.7</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>13050</td>
<td>13050</td>
</tr>
</tbody>
</table>

**Component Mass Flow (lb/hr):**
- Hydrogen: 59.1 lb/hr
- Water: trace lb/hr
- Ethanol: 12.0 lb/hr
- Ethyl Acetate: 12818 lb/hr
- Acetaldehyde: 0.01 lb/hr
- Buta-2-one: 80.5 lb/hr
- n-Butanal: 80.5 lb/hr
- n-Butanol: - lb/hr
- 2-Butanol: - lb/hr

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed Molar Flow (lbmol/hr)</th>
<th>Discharge Molar Flow (lbmol/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>59.1</td>
<td>54.6</td>
</tr>
<tr>
<td>Water</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>12818</td>
<td>12818</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>80.5</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>80.5</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>83.0</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>83.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed Volume Flow (cuft/hr)</th>
<th>Discharge Volume Flow (cuft/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>24979</td>
<td>25043</td>
</tr>
<tr>
<td>Ethanol</td>
<td>205.3</td>
<td>206.5</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>3171.9</td>
<td>3181.1</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>6.386</td>
<td>6.325</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>352.1</td>
<td>352.6</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>352.8</td>
<td>353.3</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>353.0</td>
<td>353.5</td>
</tr>
</tbody>
</table>

**Design Data:**
- Type: Packed Bed Reactor
- Catalyst: Raney Nickel
- Length: 16.4 ft
- Diameter: 3.2 ft
- Residence Time: 0.332 min
- Pressure: 4 bar
- Material: Stainless Steel 316

**Utilities:** None

**Comments & Drawings:** See Section 18.3
SPECIFICATION SHEET
DISTILLATION COLUMN

Identification:  
Item No: C-102  
No. Required: 1  
Date: 23 April 2019  
By: KVN

Function: Separate the ethyl acetate product stream from hydrogen and byproducts

Operation: Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Feed</th>
<th>Bottoms</th>
<th>Liquid Distillate</th>
<th>Vapor Distillate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>122.0</td>
<td>263.2</td>
<td>101.4</td>
<td>101.4</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>4.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>12753</td>
<td>178.5</td>
<td>12573</td>
<td>1.63</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.43</td>
<td>trace</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Water</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>11.5</td>
<td>trace</td>
<td>11.5</td>
<td>trace</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>12577</td>
<td>25.1</td>
<td>12550</td>
<td>1.39</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.01</td>
<td>trace</td>
<td>0.01</td>
<td>trace</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>82.6</td>
<td>82.6</td>
<td>0.02</td>
<td>trace</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>82.1</td>
<td>70.8</td>
<td>11.3</td>
<td>trace</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>82.6</td>
<td>82.6</td>
<td>0.02</td>
<td>trace</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>145.4</td>
<td>2.35</td>
<td>142.9</td>
<td>0.13</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
<td>236.6</td>
<td>4.08</td>
<td>229.1</td>
<td>27.7</td>
</tr>
</tbody>
</table>

Design Data:  
Number of trays: 29  
Material: Stainless Steel 316  
Feed Tray: 15  
Tray Spacing: 2 ft  
Molar reflux ratio: 10  
Height: 69 ft  
Diameter: 7.1 ft  
Skirt Height: 11 ft  
Pressure: 2 bar

Utilities:  
Cooling water at 840180 lb/hr and 150 psig steam at 33217 lb/hr

Comments & Drawings: See Section 18.4
SPECIFICATION SHEET
STRIPPER

Identification:  
Item No: C-100  
No. Required: 1  
Date: 23 April 2019  
By: KVN

Function: Remove valuable reaction intermediates from the C-101 distillate stream

Operation: Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Liquid Feed</th>
<th>Vapor Feed</th>
<th>Liquid Effluent</th>
<th>Vapor Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
<td>99.2</td>
<td>206.8</td>
<td>189.8</td>
<td>103.3</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>13729</td>
<td>3183</td>
<td>16202</td>
<td>710.5</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td>595.3</td>
<td>4.23</td>
<td>591.0</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
<td>330.9</td>
<td>331.0</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>13729</td>
<td>3.49</td>
<td>13613</td>
<td>119.5</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>-</td>
<td>1796</td>
<td>1796</td>
<td>trace</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>-</td>
<td>454.8</td>
<td>454.8</td>
<td>0.02</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
<td>2.29</td>
<td>2.29</td>
<td>trace</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
<td>0.57</td>
<td>0.57</td>
<td>trace</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>298.0</td>
<td>344.5</td>
<td>346.7</td>
<td>295.8</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
<td>280.5</td>
<td>8494</td>
<td>356.1</td>
<td>6160</td>
</tr>
</tbody>
</table>

Design Data:  
Theoretical trays: 5  
Height: 6.0 ft  
Diameter: 10.0 ft  
Material: Stainless Steel 316  
Pressure: 20 bar

Utilities: None

Comments & Drawings: See Section 18.5
SPECIFICATION SHEET
MOLECULAR SIEVE

Identification:  
Item No: S-100  Date: 23 April 2019  
No. Required: 1  By: KVN

Function:  Remove the water from the reactive distillation bottoms stream

Operation:  Continuous

<table>
<thead>
<tr>
<th>Materials</th>
<th>Feed</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F):</td>
<td>405.0</td>
<td>405.0</td>
</tr>
<tr>
<td>Pressure (bar):</td>
<td>20.0</td>
<td>20.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr):</td>
<td>13019</td>
<td>12979</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>trace</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>12818</td>
<td>12818</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>80.5</td>
<td>80.5</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>80.5</td>
<td>80.5</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr):</td>
<td>150.0</td>
<td>147.7</td>
</tr>
<tr>
<td>Volume Flow (cuft/hr)</td>
<td>348.3</td>
<td>347.5</td>
</tr>
</tbody>
</table>

Design Data:  
Sieve Packing: 13X  
Packing Mass: 3840 kg  
Void Fraction: 0.4  
Packing Density: 0.6  
Length: 12.4 ft  
Diameter: 2.06 ft  
Pressure: 20 bar  
Material: Stainless Steel 316

Utilities:  450 psig steam at 43.41 lb/hr

Comments & Drawings:  See Section 18.6
### SPECIFICATION SHEET

**ETHANOL FEED STORAGE TANK**

<table>
<thead>
<tr>
<th>Identification:</th>
<th>Item No: T-100</th>
<th>Date: 23 April 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Required:</td>
<td>1</td>
<td>By: KVN</td>
</tr>
</tbody>
</table>

**Function:** Store excess Ethanol for feed to production process

**Operation:** Continuous

**Materials**

<table>
<thead>
<tr>
<th>To Process</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Temperature(°F)</th>
<th>95.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (bar)</td>
<td>1.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>13729</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>-</td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
</tr>
<tr>
<td>Ethanol</td>
<td>13729</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>-</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>-</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>-</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>-</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>298.0</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
<td>4.70</td>
</tr>
</tbody>
</table>

**Design Data:**

<table>
<thead>
<tr>
<th>Amount Stored: 1 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Type: Floating Roof</td>
</tr>
<tr>
<td>Volume: 75240 ft³</td>
</tr>
<tr>
<td>Temperature: 95.0°F</td>
</tr>
<tr>
<td>Pressure: 1 bar</td>
</tr>
<tr>
<td>Material: Stainless Steel 316</td>
</tr>
</tbody>
</table>

**Utilities:** None

**Comments & Drawings:** See Section 18.7
## SPECIFICATION SHEET

**ETHYL ACETATE STORAGE TANK**

<table>
<thead>
<tr>
<th>Identification:</th>
<th>Item No: T-101</th>
<th>No. Required: 1</th>
<th>Date: 23 April 2019</th>
<th>By: KVN</th>
</tr>
</thead>
</table>

**Function:** Store ethyl acetate product from production

**Operation:** Continuous

<table>
<thead>
<tr>
<th>Materials From Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature(°F)</td>
</tr>
<tr>
<td>Pressure (bar)</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
</tr>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
</tr>
<tr>
<td>Acetaldehyde</td>
</tr>
<tr>
<td>Buta-2-one</td>
</tr>
<tr>
<td>n-Butanal</td>
</tr>
<tr>
<td>n-Butanol</td>
</tr>
<tr>
<td>2-Butanol</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
</tr>
</tbody>
</table>

**Design Data:**
- Amount Stored: 1 week
- Tank Type: Floating Roof
- Volume: 432219 ft³
- Temperature: 101.3°F
- Pressure: 2 bar
- Material: Stainless Steel 316

**Utilities:** None

**Comments & Drawings:** See Section 18.7
**SPECIFICATION SHEET**
**WASTE STORAGE TANK**

**Identification:**
- Item No: T-102
- No. Required: 1
- Date: 23 April 2019
- By: KVN

**Function:** Store waste from production until waste collection

**Operation:** Continuous

<table>
<thead>
<tr>
<th><strong>Materials</strong></th>
<th><strong>From Process</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°F)</td>
<td>263.2</td>
</tr>
<tr>
<td>Pressure (bar)</td>
<td>2.0</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>178.5</td>
</tr>
<tr>
<td>Component Mass Flow (lb/hr)</td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td>trace</td>
</tr>
<tr>
<td>Water</td>
<td>trace</td>
</tr>
<tr>
<td>Ethanol</td>
<td>trace</td>
</tr>
<tr>
<td>Ethyl Acetate</td>
<td>25.1</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>trace</td>
</tr>
<tr>
<td>Buta-2-one</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanal</td>
<td>-</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>82.6</td>
</tr>
<tr>
<td>2-Butanol</td>
<td>70.8</td>
</tr>
<tr>
<td>Molar Flow (lbmol/hr)</td>
<td>2.40</td>
</tr>
<tr>
<td>Volumetric Flow (cuft/hr)</td>
<td>4.10</td>
</tr>
</tbody>
</table>

**Design Data:**
- Amount Stored: 1 month
- Tank Type: Floating Roof
- Volume: 33114 ft³
- Temperature: 263.1°F
- Pressure: 1 bar
- Material: Stainless Steel 316

**Utilities:** None

**Comments & Drawings:** See Section 18.7
20 Equipment Costing Summary

To begin plant operation, a total capital investment (TCI) of $16.9 MM is required. The TCI is comprised of the total equipment bare module costs, the cost of site preparations, the cost of service facilities, the cost of contingencies and contractor fees, the cost of land and plant start-up, and the working capital costs.

The total permanent investment (TPI) is equal to $14.7 MM. Of the TPI, $10.1 MM is equal to the total bare module cost for all equipment units in this process. Table 18 describes the purchase and bare module cost of each unit in this process. Note that bare module costs are inclusive of costs of installation materials, installation labor, freight, insurance, taxes, construction overhead and contractor engineering expenses. All bare module factors listed in Table 18 (page 90) are found in Chapter 17 of Seider et al. 2017. Figure 12 includes a breakdown of the total bare module equipment costs for this plant.

![Figure 12: Breakdown of total bare module equipment costs for plant construction. The reactive distillation column, C-101, is classified as a reactor and represents 38.2% of the total bare module equipment cost. The distillation column, C-102, is the second most expensive unit, representing 25.5% of the total costs. The total bare module equipment cost is equal to $10.1 MM.](image)

---

Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
The reactors (reactive distillation column and hydrogenation reactor) constitute 41.3% of the total $10.1 MM required for all equipment. The reactive distillation column, specifically, is the most expensive equipment unit, costing approximately $3.9 MM, which is about 39% of the total bare module equipment costs. The distillation column constitutes 25.6% of the total equipment costs, approximated at a $2.6 MM bare module cost.

It is expected that the two distillation columns, the reactive distillation column (C-101) and distillation column (C-102), are the most expensive equipment units. Tray columns have a high bare module factor of 4.16, as installation costs and required installation materials are high for these units. These columns are also large in size, requiring approximately 30 trays for each of the two columns. The two columns are also constructed entirely of Stainless Steel 316, yielding a construction material factor of 2.16. All of these factors point towards the strong likelihood that the C-101 and C-102 are the most expensive equipment units.

Note that C-101 and R-100 make use of catalysts that are replaced at distinctive time periods, as discussed in Section 18.3. The first purchase of the catalyst for these two units, at the start-up point, is capitalized. Therefore, the first purchase of catalyst is considered an equipment cost and all subsequent purchases of replacement catalyst material are considered operating costs. Further note that the sieve packing material is capitalized and accounted for in a similar manner to the catalyst material; the sieve packing material is replaced on a yearly basis. The catalyst costs and sieve packing material are included in the TCI estimate of $16.9 MM and the total bare module equipment cost estimate of $10.1 MM.

The molecular sieve is the only equipment unit that has a swinging design, and therefore two units of the molecular sieve vessel and sieve packing were included in the equipment cost summary. Inclusion of spare units of the reactive distillation column, C-101, and the distillation column, C-102, were not deemed necessary for the first iteration of the design of this plant.

---

4 Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
Table 18: Summary Table for all Process Units including purchase costs, bare module factor, and bare module costs; not inclusive of first purchase of catalyst material for C-101 and R-100.

<table>
<thead>
<tr>
<th>Process Equipment ID</th>
<th>Equipment Type</th>
<th>Purchase Cost ($)</th>
<th>Bare Module Factor</th>
<th>Bare Module Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-100</td>
<td>Storage</td>
<td>153,127</td>
<td>4.00</td>
<td>612,507</td>
</tr>
<tr>
<td>P-100</td>
<td>Process Machinery</td>
<td>9,388</td>
<td>3.30</td>
<td>30,815</td>
</tr>
<tr>
<td>C-100</td>
<td>Fabricated Equipment</td>
<td>144,633</td>
<td>4.16</td>
<td>601,796</td>
</tr>
<tr>
<td>C-101</td>
<td>Fabricated Equipment</td>
<td>516,104</td>
<td>4.16</td>
<td>2,425,977</td>
</tr>
<tr>
<td>E-100</td>
<td>Fabricated Equipment</td>
<td>69,354</td>
<td>3.17</td>
<td>219,853</td>
</tr>
<tr>
<td>D-100</td>
<td>Fabricated Equipment</td>
<td>101,041</td>
<td>4.16</td>
<td>420,329</td>
</tr>
<tr>
<td>P-101</td>
<td>Process Machinery</td>
<td>9,375</td>
<td>3.30</td>
<td>30,938</td>
</tr>
<tr>
<td>E-101</td>
<td>Fabricated Equipment</td>
<td>207,986</td>
<td>3.17</td>
<td>659,317</td>
</tr>
<tr>
<td>P-102</td>
<td>Process Machinery</td>
<td>9,366</td>
<td>3.30</td>
<td>30,810</td>
</tr>
<tr>
<td>S-100A</td>
<td>Fabricated Equipment</td>
<td>31,431</td>
<td>4.16</td>
<td>130,754</td>
</tr>
<tr>
<td>S-100B</td>
<td>Spare</td>
<td>31,431</td>
<td>4.16</td>
<td>130,754</td>
</tr>
<tr>
<td>E-102</td>
<td>Fabricated Equipment</td>
<td>6,188</td>
<td>3.17</td>
<td>11,138</td>
</tr>
<tr>
<td>R-100</td>
<td>Fabricated Equipment</td>
<td>71,037</td>
<td>4.16</td>
<td>300,602</td>
</tr>
<tr>
<td>E-103</td>
<td>Fabricated Equipment</td>
<td>7,875</td>
<td>3.17</td>
<td>14,176</td>
</tr>
<tr>
<td>C-102</td>
<td>Fabricated Equipment</td>
<td>165,818</td>
<td>4.16</td>
<td>893,539</td>
</tr>
<tr>
<td>E-104</td>
<td>Fabricated Equipment</td>
<td>110,169</td>
<td>3.17</td>
<td>349,236</td>
</tr>
<tr>
<td>D-101</td>
<td>Fabricated Equipment</td>
<td>77,660</td>
<td>4.16</td>
<td>323,065</td>
</tr>
<tr>
<td>P-103</td>
<td>Process Machinery</td>
<td>9,532</td>
<td>3.30</td>
<td>31,456</td>
</tr>
<tr>
<td>E-105</td>
<td>Fabricated Equipment</td>
<td>256,601</td>
<td>3.17</td>
<td>813,424</td>
</tr>
<tr>
<td>P-104</td>
<td>Process Machinery</td>
<td>49,865</td>
<td>3.30</td>
<td>164,556</td>
</tr>
<tr>
<td>T-101</td>
<td>Storage</td>
<td>371,529</td>
<td>4.00</td>
<td>1,486,117</td>
</tr>
<tr>
<td>T-102</td>
<td>Storage</td>
<td>82,235</td>
<td>4.00</td>
<td>328,942</td>
</tr>
</tbody>
</table>
20.1 Unit Costing Considerations

20.1.1 Pumps

Cost estimates for all pumps in this process were determined by correlations available in *Seider et. al, 2017*. Purchase cost correlations for the pumps required the liquid flow rate, in gallons per minute, and the desired pump head, in feet. The liquid flow rate and the component values used to calculate the pump head was retrieved from ASPEN simulation results.

20.1.2 Process Heat Exchangers

Both heat exchangers were costed according to the required surface area and material construction. The correlation to cost both double pipe heat exchangers is outlined in Chapter 16 of *Seider et. al, 2017* 44. All input values for the cost correlation were determined from ASPEN output values. The heat exchangers were designed to minimize cost over an assumed 15 year useful life. Total equipment cost over 15 useful years was calculated as sum of the the upfront cost plus the utility costs over lifespan of the equipment. It was determined, for both heat exchangers (E-102 and E-103), that increased upfront equipment cost subsequently decreased utilities and minimized the cost of the equipment over 15 years. Therefore, the designs which minimized utility requirements led to the lowest overall cost. This is true for both E-102 and E-103. These cost optimizations are outlined in Table 19 and Table 20.

---

4 Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
Table 19: Total Equipment Cost Over a 15 Year Useful Lifespan of Heat Exchanger 1 (E-102)
Increasing the area of the heat exchanger decreases the utility requirement. Initial upfront savings for a smaller heat exchanger is not warranted over the lifetime of the equipment.

<table>
<thead>
<tr>
<th>Area ($ft^2$)</th>
<th>Steam (psig)</th>
<th>Total Equipment Cost Over 15 Year Useful Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.2</td>
<td>815.7</td>
<td>$714,611</td>
</tr>
<tr>
<td>46.4</td>
<td>804.7</td>
<td>$705,563</td>
</tr>
<tr>
<td>46.0</td>
<td>793.7</td>
<td>$696,464</td>
</tr>
<tr>
<td>46.1</td>
<td>782.6</td>
<td>$687,311</td>
</tr>
<tr>
<td>46.5</td>
<td>771.6</td>
<td>$678,105</td>
</tr>
<tr>
<td>47.3</td>
<td>760.6</td>
<td>$668,848</td>
</tr>
<tr>
<td>48.6</td>
<td>749.6</td>
<td>$659,548</td>
</tr>
<tr>
<td>50.2</td>
<td>738.5</td>
<td>$650,212</td>
</tr>
<tr>
<td>52.2</td>
<td>727.5</td>
<td>$640,849</td>
</tr>
<tr>
<td>54.6</td>
<td>716.5</td>
<td>$631,471</td>
</tr>
<tr>
<td>57.4</td>
<td>705.5</td>
<td>$622,086</td>
</tr>
</tbody>
</table>

Table 20: Total Equipment Cost Over a 15 Year Useful Lifespan of Heat Exchanger 2 (E-103)
Increasing the area of the heat exchanger decreases the utility requirement. Initial upfront savings for a smaller heat exchanger is not warranted over the lifetime of the equipment.

<table>
<thead>
<tr>
<th>Area ($ft^2$)</th>
<th>Cooling Water Flow Rate (lb/hr)</th>
<th>Total Equipment Cost Over 15 Year Useful Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>173.7</td>
<td>215600</td>
<td>$377,498</td>
</tr>
<tr>
<td>262.1</td>
<td>187000</td>
<td>$339,362</td>
</tr>
<tr>
<td>288.8</td>
<td>167200</td>
<td>$312,037</td>
</tr>
<tr>
<td>293.8</td>
<td>151800</td>
<td>$290,207</td>
</tr>
<tr>
<td>293.7</td>
<td>138600</td>
<td>$271,329</td>
</tr>
<tr>
<td>293.4</td>
<td>127600</td>
<td>$255,590</td>
</tr>
<tr>
<td>293.7</td>
<td>121000</td>
<td>$246,163</td>
</tr>
<tr>
<td>294.6</td>
<td>112200</td>
<td>$233,615</td>
</tr>
<tr>
<td>295.6</td>
<td>105600</td>
<td>$224,214</td>
</tr>
<tr>
<td>296.5</td>
<td>99000</td>
<td>$214,813</td>
</tr>
</tbody>
</table>
20.1.3 Reactors

Reactive Distillation Column

As discussed in Section 15.1.1, patent literature provided lab scale data that was used to model the reactive distillation column. In modelling the column in ASPEN, an initial estimate of the required stage number was determined. In using Murphee Tray efficiencies and O’Connell correlations (see Section 27.1.2), the actual number of trays required were found. This value was then used to calculate the total height of the column, as described in section 18.3. The cost correlations for the reflux accumulator, reboiler and condenser were outlined in Chapter 16 of Seider et. al, 2017, and the required input for these correlations were found from ASPEN simulation outputs\(^4\).

The reflux accumulator was modelled as a horizontal pressure vessel, with a residence time of 10 minutes. This residence time was suggested at the guidance of industrial consultants. The reflux accumulator was assumed to have an aspect ratio of 2, and detailed design calculations can be found in Section 27.1.2.

The partial condenser is modelled as a fixed head, shell and tube heat exchanger. The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger. These assumptions follow the guidance of industrial consultants, and assumptions presented in Chapter 12 of Seider et. al, 2017\(^5\).

Hydrogenation Reactor

The hydrogenation reactor was modelled as a packed bed, with a residence time of 20 seconds. It was noted that the diameter of the hydrogenation reactor is out of the costing correlation limits, as it is smaller than the minimum diameter for this correlation. This rose concerns on whether a packed column is the most appropriate costing model for the hydrogenation reactor. This concern, however, was debunked based on two observations.

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\(^4\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017

\(^5\) Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
First, the residence time is short and would therefore warrant the decision to use the packed column costing model. Second, the costing correlation’s extrapolation is linear when extrapolating to this smaller diameter. The linear extrapolation is a valid indication that the packed column costing model can be applicable to the hydrogenation reactor.

20.1.4 Distillation Column

The distillation column was initially designed using the equations and calculations outlined in Section 27.1.3. These specifications were a base case, and were used as an initial input into the ASPEN simulation model. As described in Section 15.3.1, a series of sensitivity analyses were conducted to optimize the column to ensure maximum separation. The O’Connell relationships are used to determine the Murphee tray efficiencies, to gather the actual number of trays required for the column. This actual number of required trays is used in the costing correlations available in Chapter 16 of Seider et al., 2017[47]. An example of these calculations can be found in Section 27.1.3. Using an assumed tray spacing of 2 ft, and an additional skirt length of 4 ft and 7 ft for the enriching and stripping sections, respectively. These values follow the guidance provided in Chapter 16 of Seider et al., 2017. Stainless Steel 316 is the chosen construction material to avoid issues of product contamination due to corrosion. The cost correlations for the reflux accumulator, reboiler and condenser were outlined in Chapter 16 of Seider et al., 2017., and the required input for these correlations were found from ASPEN simulation outputs.

The reflux accumulator was modelled as a horizontal pressure vessel, with a residence time of 10 minutes. This residence time was suggested at the guidance of industrial consultants. The reflux accumulator was assumed to have an aspect ratio of 2, and detailed design calculations can be found in Section 27.1.3.

The partial condenser is modelled as a fixed head, shell and tube heat exchanger. The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger. These assumptions

\[\text{Seider, Lewin, Seader, Widagdo, Gani, and Ng (2017)}\]
follow the guidance of industrial consultants and assumptions presented in Chapter 12 of *Seider et. al, 2017*.

### 20.1.5 Stripper

The stripper was designed with the use of the ASPEN simulation model and made use of convergence outputs in the simulation. The stripper was modelled as a vertical pressure vessel, constructed of Stainless Steel 316 material. The stripper column was oversized to account for efficiency considerations, and was therefore sized to account for a 50% efficiency through the stripper. It is noted that this is a conservative estimate of the stripper efficiency. The number of theoretical stages in this column is 5. Cost correlations for the stripper were obtained from Chapter 16 of *Seider et. al, 2017*.

### 20.1.6 Molecular Sieve

The molecular sieve vessel was modelled as a horizontal pressure vessel. The molecular sieve has one day-bed and one regenerating-bed. The molecular sieve vessel was designed with an aspect ratio (L/D) of 3, with a diameter of 2.06 ft and a length of 12.38 ft. The vessel is constructed of Stainless Steel 316, to account for potential corrosion limitations in the process. The cost correlations for the vessel were obtained from Chapter 16 of *Seider et. al, 2017*.

The molecular sieve has a spherical particle size and is assumed to pack with a packing efficiency of 0.60. The sieve packing material cost estimates were obtained by calculating the amount of water that must be removed and determining the appropriate mass of sieve required to perform this process. The chosen 13X molecular sieve can hold 25 wt% of water. The volume of the sieve vessel was determined via the density of the chosen bead, 0.68 kg/L, coupled with the estimated packing efficiency.

A spare molecular sieve will be purchased as the packing material is regenerated on a
daily basis. This swinging design of the molecular sieve accounts for the time required for the regeneration. In including this swinging design, we are ensuring that there will be no interruption in ethyl acetate production.

### 20.1.7 Storage Tanks

Storage tanks T-100, T-101, and T-102 were costed using costing correlations available from Chapter 16 of *Seider et. al, 2017*. All storage tanks make use of a volumetric safety factor of 1.5\textsuperscript{[5]} to ensure that the storage tanks never operate at full capacity. All three storage tanks in this process make use of a floating tank, which is considered as an additional safety consideration. Insulation costs for the byproduct storage tank, Tank-102, are considered unnecessary as this storage tank’s temperature does not need to be maintained at a high temperature as all the byproducts are considered to be waste products. The ethanol and ethyl acetate storage tanks (T-100 and T-101, respectively) are at ambient conditions, and therefore no insulation costs were considered for these two storage tanks.

\textsuperscript{[5]} Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
21 Fixed Capital Investment Summary

The TCI for this process is $16.9 MM, of which $14.7 MM is equal to the TPI. $10.1 MM is the total bare module cost for all equipment required in this process. As discussed in Section 20, note that the first purchase of the catalyst is capitalized and considered an equipment cost, included in the total bare module estimations with a bare module factor of 1.51. The TCI for this process is estimated using the following accounting formula:

$$C_{TCI} = C_{TDC} + C_{start} + C_{land} + C_{WC}$$

where $C_{TDC}$ is the total depreciable capital cost and $C_{WC}$ is the total working capital cost.

The total working capital costs is equal to approximately $2.2 MM. The working capital calculations follow standard accounting practices of assuming thirty days of cash reserves (excluding raw materials), thirty days of accounts receivable for product at the sales price and thirty days of accounts payable by the company for the feedstocks (in this case, ethanol) at the purchase price. As discussed in Section 12.3, this plant will be in close proximity to a corn plant, and therefore it is assumed that the raw material (ethanol) inventory will be for one day. For this process, the working capital comprises 13.1% of the TCI. Note that the cost of capital was approximated as 15% for working capital calculations, as the working capital estimate of $2.2 MM is the present value of the working capital requirements for this process. Table 21 includes a detailed breakdown of working capital calculations and estimations.
**Table 21:** Breakdown of calculation of $C_{WC}$

The total working capital is the present value of the working capital over the first three years of this project, calculated at a cost of capital of 15%.

<table>
<thead>
<tr>
<th></th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accounts Receivable ($)</td>
<td>1,724,587</td>
<td>862,293</td>
<td>862,293</td>
</tr>
<tr>
<td>Cash Reserves ($)</td>
<td>246,443</td>
<td>123,222</td>
<td>132,222</td>
</tr>
<tr>
<td>Accounts Payable ($)</td>
<td>(1,007,570)</td>
<td>(503,785)</td>
<td>(503,785)</td>
</tr>
<tr>
<td>Ethyl Acetate Inventory ($)</td>
<td>402,404</td>
<td>201,202</td>
<td>201,202</td>
</tr>
<tr>
<td>Raw Materials ($)</td>
<td>30,704</td>
<td>15,352</td>
<td>15,352</td>
</tr>
<tr>
<td><strong>Total ($)</strong></td>
<td><strong>1,396,567</strong></td>
<td><strong>698,284</strong></td>
<td><strong>298,284</strong></td>
</tr>
<tr>
<td>Present Value at 15%</td>
<td><strong>1,214,406</strong></td>
<td><strong>528,003</strong></td>
<td><strong>459,133</strong></td>
</tr>
<tr>
<td><strong>Total Working Capital ($)</strong></td>
<td><strong>2,201,542</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The total permanent investment (TPI) for this process is $14.7$ MM. Table 22 describes the cost components for the calculation of TPI.
**Table 22:** Breakdown of Total Permanent Investment (TPI) Estimation.
Cost correlations and assumptions applicable in this summary are outlined in Table 23.

<table>
<thead>
<tr>
<th>Bare Module Costs ($)</th>
<th>Total Bare Module Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabricated Equipment</td>
<td>7,293,960</td>
</tr>
<tr>
<td>Process Machinery</td>
<td>288,575</td>
</tr>
<tr>
<td>Spares</td>
<td>-</td>
</tr>
<tr>
<td>Storage</td>
<td>2,427,566</td>
</tr>
<tr>
<td>Other Equipment</td>
<td>-</td>
</tr>
<tr>
<td>Catalysts</td>
<td>96,596</td>
</tr>
<tr>
<td>Computer, Software, etc.</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><strong>10,106,697</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direct Permanent Investment ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Site Preparations</td>
</tr>
<tr>
<td>Cost of Service Facilities</td>
</tr>
<tr>
<td>Allocate Costs for Utility Plants and Related</td>
</tr>
<tr>
<td>Total Direct Permanent Investment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Depreciable Capital ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Contingencies &amp; Contractor Fees</td>
</tr>
<tr>
<td>Total Depreciable Capital</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Permanent Investment ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Land</td>
</tr>
<tr>
<td>Cost of Royalties</td>
</tr>
<tr>
<td>Cost of Plant Start-Up</td>
</tr>
<tr>
<td>Total Permanent Investment - Unadjusted</td>
</tr>
<tr>
<td>Site Factor</td>
</tr>
<tr>
<td>Total Permanent Investment</td>
</tr>
</tbody>
</table>
In this process costing model, the cost correlations and assumptions are outlined in Table 23. The cost of royalties for this plan are assumed to be zero.

Table 23: Outline of cost correlations and assumptions to calculate TPI

<table>
<thead>
<tr>
<th>TPI Cost Component</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of Site Preparations</td>
<td>5.00 % of Total Bare Module Costs</td>
</tr>
<tr>
<td>Cost of Service Facilities</td>
<td>5.00 % of Total Bare Module Costs</td>
</tr>
<tr>
<td>Cost of Contingencies and Contractor Fees</td>
<td>18.00% of Direct Permanent Investment</td>
</tr>
<tr>
<td>Cost of Land</td>
<td>2.00% of Total Depreciable Capital</td>
</tr>
<tr>
<td>Cost of Plant Start-Up</td>
<td>10.00% of Total Depreciable Capital</td>
</tr>
</tbody>
</table>

Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017

100
22 Operating Costs

22.1 Variable Operating Costs

22.1.1 Raw Materials

As discussed in Section 12.3, this plant will be located in close proximity to a corn plant, and therefore this economic analysis assumes that only a one day inventory of ethanol will be required. The ethanol feed arrives at this plant via a pipeline from this corn plant, as discussed in Section 12.3. Although it would be safe to assume that the ethanol could be purchased at a discount due to this plant’s proximity to the corn plant, a conservative approach to the economic analysis was adopted and the purchase price of ethanol instead reflects no such discount. The ethanol purchase price used in this analysis is the market spot price of ethanol as of market close on 16 April 2019. The catalyst used in C-101 is Copper Oxide/Zinc Oxide on Alumina, and this catalyst is replaced four times a year. The cost for this catalyst was determined by obtaining a quotation from a local vendor. The catalyst used in R-100 is Raney Nickel, which is also replaced four times a year. The cost for this catalyst was also determined by obtaining a quotation from a local vendor. The sieve packing material is replaced on a yearly basis, and the quotation was obtained from a local vendor. As discussed in Section 20, the first purchase of each catalyst/sieve packing material is capitalized, and subsequent purchases are treated as variable operating costs. Table 24 outlines the relevant raw material costs. Note that these raw material costs are quoted on a yearly basis, using the goal basis of 50kT of ethyl acetate production per year. The total raw material cost is calculated as $0.27 per lb of Ethyl Acetate produced, or $24.9MM per year.
Table 24: Breakdown of Raw Material Costs and Requirements

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Required Ratio (lb per lb of Ethyl Acetate)</th>
<th>Cost of Raw Material ($/lb of Ethyl Acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>1.109</td>
<td>0.20</td>
</tr>
<tr>
<td>CuO/ZnO on Aluminna Catalyst</td>
<td>$1.65 \times 10^{-6}$</td>
<td>90.90</td>
</tr>
<tr>
<td>Molecular Sieve Packing</td>
<td>$1.58 \times 10^{-5}$</td>
<td>1.00</td>
</tr>
<tr>
<td>Raney Nickel Catalyst</td>
<td>$3.36 \times 10^{-5}$</td>
<td>13.64</td>
</tr>
</tbody>
</table>

22.1.2 Utility Costs

The utility requirements and relevant costs for the utilities are outlined in Table 25. The total utility cost is calculated as $0.021 per lb of ethyl acetate produced, or $2.34MM per year. Note that this process did not require any process water, at least for the first iteration of this plant design.

Table 25: Utility Requirements on a Yearly Basis and Cost Ratios

<table>
<thead>
<tr>
<th>Utility</th>
<th>Required Ratio (per lb of Ethyl Acetate Produced)</th>
<th>Cost of Utility ($/ per unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Pressure Steam (450 psig)</td>
<td>1.76 lb</td>
<td>0.0050</td>
</tr>
<tr>
<td>Low Pressure Steam (150 psig)</td>
<td>2.71 lb</td>
<td>0.004</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>11.59 gal</td>
<td>0.00005</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.00131 kWh</td>
<td>0.07</td>
</tr>
</tbody>
</table>

22.1.3 Hydrogen Fuel Value

As discussed in Section 16.1, the hydrogen produced at this plant will be burnt to extract fuel value. The amount of energy released, assuming a 70% efficiency of combustion, was calculated as 1814 Btu/lb of ethyl acetate produced. Following guidance provided by industrial consultants, the hydrogen fuel value was determined by using the selling price of natural gas as a basis. The hydrogen fuel value is treated as a byproduct in this economic analysis. The
hydrogen fuel value was considered to be sold at $1.4 \times 10^{-5}/\text{Btu}$. The estimated fuel value of the hydrogen is therefore estimated to be $2.79$ MM, per year.

### 22.1.4 General Expenses

General expense data estimations and assumptions are outlined in Chapter 17 of *Seider et. al, 2017*. These assumptions and correlations are outlined in Table 26. General expenses, on a yearly basis, are estimated at $5.38$ MM.

#### Table 26: Breakdown of General Expense Calculations and Assumed Correlations

<table>
<thead>
<tr>
<th>General Expense</th>
<th>Relationship to Sales</th>
<th>Total Annual Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling/Transfer Expenses</td>
<td>3.00% of Sales</td>
<td>1,398,831</td>
</tr>
<tr>
<td>Direct Research</td>
<td>4.80% of Sales</td>
<td>2,238,130</td>
</tr>
<tr>
<td>Allocated Research</td>
<td>0.50% of Sales</td>
<td>233,139</td>
</tr>
<tr>
<td>Administrative Expense</td>
<td>2.0% of Sales</td>
<td>932,554</td>
</tr>
<tr>
<td>Management Incentive Compensation</td>
<td>1.25% of Sales</td>
<td>582,846</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11.55% of Sales</strong></td>
<td><strong>5,385,500</strong></td>
</tr>
</tbody>
</table>

### 22.1.5 Summary of Operating Variable Costs

Using the aforementioned assumptions and correlations, the total operating variable costs were estimated to be $29.8$ MM per year and are shown in Table 27.
Table 27: Summary of Total Operating Variable Costs on a Yearly Basis, assuming a target production of 50kT of Ethyl Acetate

General Expenses ($)

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling/Transfer Expenses</td>
<td>1,398,831</td>
</tr>
<tr>
<td>Direct Research</td>
<td>2,238,130</td>
</tr>
<tr>
<td>Allocated Research</td>
<td>233,139</td>
</tr>
<tr>
<td>Administrative Expense</td>
<td>932,554</td>
</tr>
<tr>
<td>Management Incentive Compensation</td>
<td>582,846</td>
</tr>
<tr>
<td><strong>Total General Expenses</strong></td>
<td><strong>5,385,501</strong></td>
</tr>
</tbody>
</table>

Raw Materials ($)  

<table>
<thead>
<tr>
<th>Description</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Materials</td>
<td>24,904,296</td>
</tr>
<tr>
<td>Byproducts</td>
<td>(2,799,426)</td>
</tr>
<tr>
<td><strong>Utilities</strong></td>
<td>2,337,415</td>
</tr>
<tr>
<td><strong>Total Variable Costs</strong></td>
<td><strong>29,827,785</strong></td>
</tr>
</tbody>
</table>

22.2 Fixed Operating Costs

22.2.1 Operations

To ensure successful and safe operation of the plant, five daily operator shifts were deemed necessary. Following guidance from industrial consultants, one operator was required for each main process unit, which yields three operators per shift for this process. A standard wage of $40/operator hour was used. The control laboratory costs were set to a conservative minimum as few quality controls are required, other than the quality control tests of the final ethyl acetate product. Table 28 outlines further assumptions necessary in determining the operations component of the fixed operating cost. This was estimated as $2.21 MM.

---

5 Seider, Lewin, Seader, Widagdo, Gani, and Ng 2017
Table 28: Breakdown of costing assumptions applied in calculation of operations component of fixed operating costs

<table>
<thead>
<tr>
<th>Fixed Operating Costs: Operations</th>
<th>Costing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operators per Shift</td>
<td>3 (assuming 5 shifts)</td>
</tr>
<tr>
<td>Direct Wages and Benefits</td>
<td>$40/operator hour</td>
</tr>
<tr>
<td>Direct Salaries and Benefits</td>
<td>15% of Direct Wages and Benefits</td>
</tr>
<tr>
<td>Operating Supplies and Services</td>
<td>6% of Direct Wages and Benefits</td>
</tr>
<tr>
<td>Technical Assistance to Manufacturing</td>
<td>$13,333 per year, per operator</td>
</tr>
<tr>
<td>Control Laboratory</td>
<td>$33,333 per year, per operator</td>
</tr>
</tbody>
</table>

22.2.2 Maintenance

Table 29 indicates the assumptions applied in determining the total site maintenance fixed costs for this plant. These assumptions follow guidelines listed in Chapter 17 of *Seider et. al, 2017*56. The total maintenance fixed operating costs are estimated to be $1.36 MM.

Table 29: Breakdown of costing assumptions applied in calculation of maintainence component of fixed operating costs

<table>
<thead>
<tr>
<th>Fixed Operating Costs: Maintenance</th>
<th>Costing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wages and Benefits</td>
<td>4.50% of Total Depreciable Capital</td>
</tr>
<tr>
<td>Salaries and Benefits</td>
<td>25% of Maintenance Wages and Benefits</td>
</tr>
<tr>
<td>Materials and Services</td>
<td>100% of Maintenance Wages and Benefits</td>
</tr>
<tr>
<td>Maintenance Overhead</td>
<td>5% of Maintenance Wages and Benefits</td>
</tr>
</tbody>
</table>

22.2.3 Overhead

Table 30 outlines the assumptions applied in determining the overhead fixed operating costs for this plant. These guidelines follow those listed in Chapter 17 of *Seider et. al, 2017*57.
The total operating overhead costs are estimated to be $495M. Following standard accounting practices, property taxes and insurance is assumed to be 2.00% of total depreciable capital. The total property taxes and insurance costs are estimated to be $262M. Note for this process, licensing and rental fees are assumed to be zero or negligible.

**Table 30:** Breakdown of costing assumptions applied in calculation of overhead component of fixed operating costs

<table>
<thead>
<tr>
<th>Fixed Operating Costs: Overhead</th>
<th>Costing Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Plant Overhead</td>
<td>7.1% of Maintenance and Operations Wages and Benefits</td>
</tr>
<tr>
<td>Mechanical Department Services</td>
<td>2.4% of Maintenance and Operations Wages and Benefits</td>
</tr>
<tr>
<td>Employee Relations Department</td>
<td>5.9% of Maintenance and Operations Wages and Benefits</td>
</tr>
<tr>
<td>Business Services</td>
<td>7.4% of Maintenance and Operations Wages and Benefits</td>
</tr>
</tbody>
</table>

### 22.2.4 Summary of Fixed Operating Costs

Using the aforementioned assumptions and correlations, the total operating fixed costs were estimated to be $4.3 MM, per year, as shown in Table 31.
Table 31: Fixed Operating Costs on a Yearly Basis

**Operations (\$)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Wages and Benefits</td>
<td>1,248,000</td>
</tr>
<tr>
<td>Direct Salary and Benefits</td>
<td>187,200</td>
</tr>
<tr>
<td>Operating Supplies and Services</td>
<td>74,880</td>
</tr>
<tr>
<td>Technical Assistance to Manufacturing</td>
<td>199,995</td>
</tr>
<tr>
<td>Control Laboratory</td>
<td>499,995</td>
</tr>
<tr>
<td><strong>Total Operations</strong></td>
<td><strong>2,210,070</strong></td>
</tr>
</tbody>
</table>

**Maintenance (\$)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wages and Benefits</td>
<td>590,332</td>
</tr>
<tr>
<td>Salaries and Benefits</td>
<td>147,583</td>
</tr>
<tr>
<td>Materials and Services</td>
<td>590,332</td>
</tr>
<tr>
<td>Maintenance Overhead</td>
<td>29,517</td>
</tr>
<tr>
<td><strong>Total Total Maintenance</strong></td>
<td><strong>1,357,764</strong></td>
</tr>
</tbody>
</table>

**Operating Overhead (\$)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Plant Overhead</td>
<td>154,291</td>
</tr>
<tr>
<td>Mechanical Department Services</td>
<td>52,155</td>
</tr>
<tr>
<td>Employee Relations Department</td>
<td>128,214</td>
</tr>
<tr>
<td>Business Services</td>
<td>160,811</td>
</tr>
<tr>
<td><strong>Total Operating Overhead</strong></td>
<td><strong>495,470</strong></td>
</tr>
</tbody>
</table>

**Property Taxes and Insurance (\$)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property Taxes and Insurance</td>
<td>262,370</td>
</tr>
<tr>
<td><strong>Total Taxes and Insurance</strong></td>
<td><strong>262,370</strong></td>
</tr>
</tbody>
</table>

**Other Annual Expenses (\$)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rental Fees</td>
<td>-</td>
</tr>
<tr>
<td>Licensing Fees</td>
<td>-</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Other Annual Expenses</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

**Total Fixed Costs**  

<table>
<thead>
<tr>
<th>Item</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Fixed Costs</strong></td>
<td><strong>4,325,674</strong></td>
</tr>
</tbody>
</table>
The novel process that Greenyug proposes to produce ethyl acetate from ethanol proves to be a profitable venture in the specialty chemicals industry, with a IRR of 38.73% and ROI of 43.2% for this project.

23.1 Cash Flow Model

Several key assumptions in costing correlations have been noted in previous sections. One important assumption in this cash flow model is that the plant will be operated for 330 days/year, which is equivalent to an operating factor of 0.904. Following standard industry practice, this plant is assumed to take one year to design and one year to construct. The TPI of $17.7MM is assumed to be paid up-front in the first year of construction. This cash flow model makes use of a start-up profile, a sensible and conservative assumption to include as chemical plants often need a period of time to achieve their full/desired operating capacity. This period of time is often used to ensure safety of the plant and scale production at an incremental level annually. This time is also taken for training purposes and to continuously improve the first iteration of the design. For this cash flow model, the plant achieves 50% of production capacity in the first year, and achieves 90% of design capacity within two years. For safety reasons, the maximum operating capacity is set at 90% of design capacity.

As this project inherently looks to determine the technical and economic feasibility of the Greenyug process, a conservative approach was taken in developing this cash flow model. Therefore, aligning with this approach, the net present value (NPV) projections consider a fifteen year time horizon. This is a typical assumption made in project cash flow models.

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58 Lager [2012]
59 Seider, Lewin, Seader, Widagdo, Gani, and Ng [2017]
A five year MACRS depreciation schedule was applied for this cash flow model. It is advantageous for a company to rapidly depreciate its capital investment early in the life of its process. Choosing a shorter (five year) MACRS depreciation schedule reduces tax liability and accelerates the rate of return.\textsuperscript{60}

This cash flow model assumes a weighted average capital cost (WACC) of 15\% and cash flows are discounted at this rate in the model. As mentioned previously, it is assumed that the selling price of ethyl acetate is $0.42/lb, with no green premium. The selling price of ethyl acetate is assumed to be constant through the fifteen years of the project, assuming no inflation. The argument and analysis of the green premium is elaborated upon later in this section. The choice to include no green premium as the base case is, once again, aligns with the conservative approach to the analysis. This analysis assumes that 100\% of the production is sold.

The detailed summary of the cash flow model can be found in Section 27.2. Table 32, however, outlines the undiscounted and discounted cash flows at a WACC of 15\%, on a yearly basis. As seen in Table 32, the cumulative NPV at the end of 15 years, at a WACC of 15\% is $23.08MM.
### Table 32: Summary of Cash Flows Over Fifteen-Year Lifespan of Project

<table>
<thead>
<tr>
<th>Year</th>
<th>Cash Flow ($)</th>
<th>Cumulative NPV at 15% ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2019</td>
<td>(16,089,300)</td>
<td>(13,990,700)</td>
</tr>
<tr>
<td>2020</td>
<td>2,395,600</td>
<td>(12,179,300)</td>
</tr>
<tr>
<td>2021</td>
<td>5,668,200</td>
<td>(8,452,300)</td>
</tr>
<tr>
<td>2022</td>
<td>8,890,900</td>
<td>(3,368,900)</td>
</tr>
<tr>
<td>2023</td>
<td>8,659,200</td>
<td>936,200</td>
</tr>
<tr>
<td>2024</td>
<td>8,659,200</td>
<td>4,679,800</td>
</tr>
<tr>
<td>2025</td>
<td>8,485,400</td>
<td>7,869,800</td>
</tr>
<tr>
<td>2026</td>
<td>8,311,600</td>
<td>10,586,800</td>
</tr>
<tr>
<td>2027</td>
<td>8,311,600</td>
<td>12,949,500</td>
</tr>
<tr>
<td>2028</td>
<td>8,311,600</td>
<td>15,004,000</td>
</tr>
<tr>
<td>2029</td>
<td>8,311,600</td>
<td>16,790,500</td>
</tr>
<tr>
<td>2030</td>
<td>8,311,600</td>
<td>18,344,000</td>
</tr>
<tr>
<td>2031</td>
<td>8,311,600</td>
<td>19,694,900</td>
</tr>
<tr>
<td>2032</td>
<td>8,311,600</td>
<td>20,869,500</td>
</tr>
<tr>
<td>2033</td>
<td>8,311,600</td>
<td>21,891,000</td>
</tr>
<tr>
<td>2034</td>
<td>11,104,700</td>
<td>23,077,700</td>
</tr>
</tbody>
</table>

As seen below in Figure 13, cumulative discounted cash flows remain negative until year three of production. The process yields constant yearly revenues of $41.9MM. An explanation for the negative cumulative discounted cash flows lies in the fact that for the first two years of this project, there are no ethyl acetate sales. The capital costs are also paid up-front in year one of construction. The graphical representation of the cumulative discounted cash flows illustrates that the break-even point lies between 2022 and 2023.
Figure 13: Cumulative discounted free cash flow ($MM) for project over fifteen-year lifespan assuming Ethyl Acetate selling price of $0.42/lb and Ethanol purchase of $0.20/lb. The process shows a break even point between years three and four of production. The production sees full operating capacity within two years of production.

23.2 Profitability Measures

23.2.1 Internal Rate of Return

Over the plant’s first fifteen years of useful life, this model projects an internal rate of return (IRR) of 38.7%. This is greater than the WACC of 15%, signalling the potential of a profitable venture. The IRR is generally a strong measure of profitability, as it takes into account the timing of the project and its timeline, giving weight to the time value of money.\(^6\)

As discussed in Section 23.3, the WACC can be variable for each company and a sensitivity analysis is conducted on the WACC to illustrate how a variation in WACC can affect the company’s profitability. The advantage with using IRR as a measure of profitability, is that the WACC and IRR are independent of each other. As Greenyug is a start-up company

\(^6\) Lanctot 2019
and new to the industry, it is quite likely that the estimation of the WACC at 15% may be misleading and affect profitability measures. However, this is not the case for the IRR measure, which remains at 38.7%, regardless of the variation in WACC.

A major assumption of IRR is that it assumes all cash flows are re-invested at the same rate as the IRR. Given that the IRR for this project is 38.7%, it is unlikely that it is realistic and possible. This, therefore, overestimates the annual equivalent rate of return. The formula inherently assumes that the company has other projects with equally attractive prospects. As Greenyug is a new start-up, it is unlikely that this is the case. Often, to sidestep this issue, a modified IRR formula is used with reinvestment at the cost of capital. This goes beyond the initial scope of analysis for the first iteration of this process design.

23.2.2 Return on Investment

The return on investment (ROI) is a measure of the efficiency of an investment. A positive ROI is roughly indicative of a profitable venture. The ROI is a simple formula that accounts for the change in the current value of investment and the cost of investment, and compares this change against the cost of investment. The ROI is calculated at the third production year as this is the year that the process achieves full operating capacity. Table 33, shown below, outlines the ROI calculations conducted for this analysis. Note that often the ROI and the IRR are used in conjunction with each other to determine the profitability of a project. In this case, both the IRR and ROI are positive, indicating a profitable venture.
Table 33: Breakdown and Summary of ROI Calculation

ROI Analysis (Third Production Year)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Sales ($)</td>
<td>41,964,942</td>
</tr>
<tr>
<td>Annual Costs ($)</td>
<td>(31,170,681)</td>
</tr>
<tr>
<td>Depreciation ($)</td>
<td>(980,004)</td>
</tr>
<tr>
<td>Income Tax ($)</td>
<td>(2,257,279)</td>
</tr>
<tr>
<td>Net Earnings ($)</td>
<td>7,556,978</td>
</tr>
<tr>
<td>Total Capital Investment ($)</td>
<td>17,485,846</td>
</tr>
<tr>
<td>ROI (%)</td>
<td>43.22</td>
</tr>
</tbody>
</table>

23.2.3 Working Capital Ratio

The working capital ratio is the ratio between current assets and current liabilities. The ratio is a measure of liquidity, illustrating a company’s ability to pay off its obligations. According to general accounting guidelines, a working capital ratio of less than 1.0 indicates possible future liquidity problems, whereas a working capital ratio at around 2.0 is indicative of good short-term liquidity. For this process, the working capital ratio is about 2.38, indicating that the process will allow the company to have a strong short-term liquidity to pay off its debt. This is yet another measure indicating a strong profitability narrative for this venture.

23.3 Sensitivity Analyses

Previous sections present the base case profitability analysis for this project, making use of several assumptions in the cash flow model, as outlined in Section 23.1. The following sensitivity analyses analyze the robustness of this project’s profitability in response to variations in several key project factors. Note that although the base case makes use of a
conservative and rigorous approach to determining the aforementioned profitability factors, this process is considered to only be in its first iteration of design. It is likely that as the process is continuously operated, further improvements are made which may increase capital or operating costs.

23.3.1 Sensitivity Analysis: IRR

A series of sensitivity analyses were carried out to further understand the effect of certain forces on the IRR for this project. As discussed in Section 22.1, the variable costs for this process are estimated to be $29.8MM. Table 34, shown below, illustrates the variation of variable costs and product price ± 50% from the base case. As expected, the IRR decreases as variable costs increase and the IRR increases as the product price increases. The IRR is relatively more sensitive to product price, falling to a negative range if the product price reduces by only 20%, whereas the IRR falls to a negative range only when the variable cost increases by 50%. As ethyl acetate is a specialty chemical, it is likely to be exposed to market risks and forces that govern the price in the free market. This is an important managerial consideration and is something the management team should be aware of, as it is a likely risk exposure and the IRR is significantly sensitive to the product price. Although the variable cost is also inclusive of a commodity chemical exposed to significant market risk (ethanol), this cost also includes the costs of utilities and general expenses which are less likely to change quite as drastically. Even so, the variable costs would have to increase by 50% for the company to see a negative IRR.
### Table 34: Sensitivity of IRR to Variations in Product Price and Variable Cost

<table>
<thead>
<tr>
<th>Product Price</th>
<th>$0.21</th>
<th>$0.25</th>
<th>$0.30</th>
<th>$0.34</th>
<th>$0.38</th>
<th>$0.42</th>
<th>$0.47</th>
<th>$0.51</th>
<th>$0.55</th>
<th>$0.59</th>
<th>$0.63</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$14,913,893</td>
<td>$17,896,071</td>
<td>$20,879,228</td>
<td>$23,862,376</td>
<td>$26,845,523</td>
<td>$29,827,670</td>
<td>$32,810,817</td>
<td>$35,793,964</td>
<td>$38,777,111</td>
<td>$41,760,258</td>
<td>$44,743,405</td>
</tr>
<tr>
<td>$14,913,893</td>
<td>11.94%</td>
<td>-7.07%</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$17,896,071</td>
<td>29.26%</td>
<td>18.64%</td>
<td>5.23%</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$20,879,228</td>
<td>43.22%</td>
<td>34.17%</td>
<td>24.39%</td>
<td>13.06%</td>
<td>-3.21%</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$23,862,376</td>
<td>55.75%</td>
<td>47.43%</td>
<td>38.75%</td>
<td>29.34%</td>
<td>19.35%</td>
<td>6.89%</td>
<td>-17.04%</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$26,845,523</td>
<td>67.39%</td>
<td>59.32%</td>
<td>51.43%</td>
<td>43.07%</td>
<td>34.28%</td>
<td>24.83%</td>
<td>14.05%</td>
<td>-0.44%</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$29,827,670</td>
<td>78.39%</td>
<td>70.84%</td>
<td>63.15%</td>
<td>55.27%</td>
<td>47.16%</td>
<td>38.73%</td>
<td>29.79%</td>
<td>20.00%</td>
<td>8.31%</td>
<td>-10.50%</td>
<td>Negative IRR</td>
</tr>
<tr>
<td>$32,810,817</td>
<td>88.87%</td>
<td>81.58%</td>
<td>74.17%</td>
<td>66.64%</td>
<td>58.96%</td>
<td>51.07%</td>
<td>42.92%</td>
<td>34.39%</td>
<td>25.25%</td>
<td>14.96%</td>
<td>1.74%</td>
</tr>
<tr>
<td>$35,793,964</td>
<td>98.93%</td>
<td>91.84%</td>
<td>84.47%</td>
<td>77.40%</td>
<td>70.02%</td>
<td>62.51%</td>
<td>54.82%</td>
<td>46.91%</td>
<td>38.70%</td>
<td>30.04%</td>
<td>20.60%</td>
</tr>
<tr>
<td>$38,777,111</td>
<td>108.62%</td>
<td>101.70%</td>
<td>94.72%</td>
<td>87.67%</td>
<td>80.53%</td>
<td>73.29%</td>
<td>65.93%</td>
<td>58.42%</td>
<td>50.73%</td>
<td>42.79%</td>
<td>34.49%</td>
</tr>
<tr>
<td>$41,760,258</td>
<td>117.98%</td>
<td>111.22%</td>
<td>104.40%</td>
<td>97.53%</td>
<td>90.59%</td>
<td>83.57%</td>
<td>76.46%</td>
<td>69.24%</td>
<td>61.90%</td>
<td>54.39%</td>
<td>46.68%</td>
</tr>
<tr>
<td>$44,743,405</td>
<td>127.06%</td>
<td>120.42%</td>
<td>113.75%</td>
<td>107.03%</td>
<td>100.26%</td>
<td>93.42%</td>
<td>86.52%</td>
<td>79.53%</td>
<td>72.45%</td>
<td>65.25%</td>
<td>57.92%</td>
</tr>
</tbody>
</table>

### Table 35: Sensitivity of IRR to Variations in Green Premium and TPI

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00%</td>
<td>60.19%</td>
<td>54.81%</td>
<td>50.07%</td>
<td>45.85%</td>
<td>42.10%</td>
<td>38.75%</td>
<td>35.69%</td>
<td>32.93%</td>
<td>30.43%</td>
<td>28.13%</td>
<td>26.03%</td>
</tr>
<tr>
<td>2.50%</td>
<td>64.77%</td>
<td>59.03%</td>
<td>53.98%</td>
<td>49.50%</td>
<td>45.50%</td>
<td>41.92%</td>
<td>38.70%</td>
<td>35.78%</td>
<td>33.13%</td>
<td>30.70%</td>
<td>28.48%</td>
</tr>
<tr>
<td>5.00%</td>
<td>69.25%</td>
<td>63.17%</td>
<td>57.81%</td>
<td>53.06%</td>
<td>48.83%</td>
<td>45.04%</td>
<td>41.63%</td>
<td>38.55%</td>
<td>35.75%</td>
<td>33.20%</td>
<td>30.86%</td>
</tr>
<tr>
<td>7.50%</td>
<td>73.64%</td>
<td>67.21%</td>
<td>61.35%</td>
<td>56.54%</td>
<td>52.08%</td>
<td>48.09%</td>
<td>44.50%</td>
<td>41.25%</td>
<td>38.31%</td>
<td>35.62%</td>
<td>33.17%</td>
</tr>
<tr>
<td>10.00%</td>
<td>77.90%</td>
<td>71.19%</td>
<td>65.23%</td>
<td>59.96%</td>
<td>55.27%</td>
<td>51.07%</td>
<td>47.30%</td>
<td>43.90%</td>
<td>40.81%</td>
<td>37.99%</td>
<td>35.42%</td>
</tr>
<tr>
<td>12.50%</td>
<td>82.10%</td>
<td>75.09%</td>
<td>68.85%</td>
<td>63.32%</td>
<td>58.40%</td>
<td>54.00%</td>
<td>50.05%</td>
<td>46.49%</td>
<td>43.26%</td>
<td>40.32%</td>
<td>37.63%</td>
</tr>
<tr>
<td>15.00%</td>
<td>86.35%</td>
<td>78.93%</td>
<td>72.40%</td>
<td>66.62%</td>
<td>61.48%</td>
<td>56.88%</td>
<td>52.76%</td>
<td>49.03%</td>
<td>45.66%</td>
<td>42.59%</td>
<td>39.79%</td>
</tr>
<tr>
<td>17.50%</td>
<td>90.46%</td>
<td>82.71%</td>
<td>75.90%</td>
<td>69.87%</td>
<td>64.51%</td>
<td>59.72%</td>
<td>55.41%</td>
<td>51.53%</td>
<td>48.02%</td>
<td>44.83%</td>
<td>41.91%</td>
</tr>
<tr>
<td>20.00%</td>
<td>94.49%</td>
<td>86.44%</td>
<td>79.34%</td>
<td>73.07%</td>
<td>67.49%</td>
<td>62.51%</td>
<td>58.03%</td>
<td>54.00%</td>
<td>50.34%</td>
<td>47.02%</td>
<td>44.00%</td>
</tr>
<tr>
<td>22.50%</td>
<td>98.47%</td>
<td>90.11%</td>
<td>82.74%</td>
<td>76.23%</td>
<td>70.43%</td>
<td>65.26%</td>
<td>60.61%</td>
<td>56.42%</td>
<td>52.63%</td>
<td>49.19%</td>
<td>46.05%</td>
</tr>
<tr>
<td>25.00%</td>
<td>102.40%</td>
<td>93.73%</td>
<td>86.09%</td>
<td>79.34%</td>
<td>73.33%</td>
<td>67.97%</td>
<td>63.16%</td>
<td>58.82%</td>
<td>54.89%</td>
<td>51.32%</td>
<td>48.07%</td>
</tr>
</tbody>
</table>
The green premium is an important factor to consider for any sustainably produced chemical. For the base case economic analysis, a green premium was not applied to the ethyl acetate product in order to maintain a rigorous and conservative approach. As expected and seen in Table 35, shown above, the greater the green premium, the greater the IRR. Table 35 also illustrates the effect of variation in TPI on the IRR. In this sensitivity analysis, the TPI was varied by ±50% from the base value of $14.8MM. It is expected that as TPI increases, the IRR decreases; however, even if the TPI increases by 50%, the IRR remains positive (albeit, is half the value). This illustrates that the IRR is relatively insensitive to variations in TPI.

As mentioned in Section 23.1, the base case cash flow model assumes that 100% of all ethyl acetate produced is sold to customers. For a start-up company like Greenyug, this may be unlikely, especially in the preliminary years of production as they are a new player in the market competing against large chemical companies. The reason for suspicion in a figure of 100% of production sold lies not in whether there remains to be enough demand, but rather lies in the fact that Greenyug is a new player and would have groundwork to do (just as any start-up) in establishing themselves in the industry. For this reason, a sensitivity analysis was conducted to determine the effect on the IRR in response to a variation in the percentage of production sold. As seen in Table 36, shown below, the IRR remains in the positive range if the percentage of production sold falls as low as 75%. However, this quickly changes if the product price falls by even 10%. As discussed above, the IRR is highly sensitive to the product price. However, this sensitivity is further accelerated when considering the percentage of production sold. This analysis therefore advocates for the important of a green premium for ethyl acetate, especially in the beginning years of the project when the percentage of production sold may not be 100%. As seen in Table 34, even a small increase in product price (and therefore an application of a modest green premium) will comfortably allow the project to see a positive IRR even as the percentage of production sold remains low in the preliminary years.
Table 36: Sensitivity of IRR to Variations in Product Price and % of Production Sold

<table>
<thead>
<tr>
<th>Product Price</th>
<th>% of Production Sold</th>
<th>75.00%</th>
<th>80.00%</th>
<th>85.00%</th>
<th>90.00%</th>
<th>95.00%</th>
<th>100.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.21</td>
<td>Negative IRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.25</td>
<td>Negative IRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.30</td>
<td>Negative IRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.34</td>
<td>Negative IRR</td>
<td>-2.61%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0.38</td>
<td>Negative IRR</td>
<td>-12.75%</td>
<td>2.18%</td>
<td>11.23%</td>
<td>18.47%</td>
<td>24.83%</td>
<td></td>
</tr>
<tr>
<td>$0.42</td>
<td>1.01%</td>
<td>11.26%</td>
<td>19.27%</td>
<td>26.27%</td>
<td>32.68%</td>
<td>38.73%</td>
<td></td>
</tr>
<tr>
<td>$0.47</td>
<td>16.67%</td>
<td>24.65%</td>
<td>31.83%</td>
<td>38.54%</td>
<td>44.93%</td>
<td>51.07%</td>
<td></td>
</tr>
<tr>
<td>$0.51</td>
<td>28.12%</td>
<td>35.67%</td>
<td>42.77%</td>
<td>49.56%</td>
<td>56.12%</td>
<td>62.51%</td>
<td></td>
</tr>
<tr>
<td>$0.55</td>
<td>38.00%</td>
<td>45.55%</td>
<td>52.79%</td>
<td>59.80%</td>
<td>66.62%</td>
<td>73.29%</td>
<td></td>
</tr>
<tr>
<td>$0.59</td>
<td>47.01%</td>
<td>54.73%</td>
<td>62.19%</td>
<td>69.47%</td>
<td>76.58%</td>
<td>83.57%</td>
<td></td>
</tr>
<tr>
<td>$0.63</td>
<td>55.42%</td>
<td>63.37%</td>
<td>71.11%</td>
<td>78.68%</td>
<td>86.11%</td>
<td>93.42%</td>
<td></td>
</tr>
</tbody>
</table>
The following tornado chart illustrates the degree to which IRR is sensitive to the variations in product price, percentage of production sold, variable costs, TPI and fixed costs. The tornado chart illustrates the variations in IRR while holding all other independent variables constant. As seen in Figure 14, the IRR is most sensitive to the product price and least sensitive to fixed costs. Figure 14 also lends itself to the discussion that a green premium would be advantageous in offsetting any market shocks to the product price as this factor is significant to the profitability of the project.

![Tornado chart illustrating the variation in IRR to a change in the product price, % of production sold, variable costs, TPI and fixed costs. The base case IRR is equal to 38.73%. This chart shows a variation of the independent variable by ± 20% from their base case, where applicable.](image)

**Figure 14**: Tornado chart illustrating the variation in IRR to a change in the product price, % of production sold, variable costs, TPI and fixed costs. The base case IRR is equal to 38.73%. This chart shows a variation of the independent variable by ± 20% from their base case, where applicable.

### 23.3.2 Sensitivity Analysis: NPV

A series of sensitivity analyses were carried out to further understand the effect of certain forces on the NPV for this project. The WACC used for the base case economic analysis was
15%. Although this follows general capital budgeting models, often the WACC is above or below this estimation and can affect the profitability and NPV of the project. The WACC is the average rate of return a company expects to compensate all its investors. This discount rate typically increases the "riskier" the project, and it is likely that a smaller start-up company such as Greenyug may face higher discount rates. As the IRR is indifferent to the WACC, a series of sensitivity analyses were carried out on the basis of the cumulative NPV over the fifteen year useful life of the project.

Table 37, as shown below, illustrates the variation of WACC and the product price. As expected, the NPV falls as the WACC increases. Table 37 outlines that the NPV falls within a negative range if the WACC increases by 30%. The NPV is even more sensitive to the product price, as the NPV falls within the negative range if the product price falls by 20%. 

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Table 37: Sensitivity of NPV to Variations in Product Price and WACC

<table>
<thead>
<tr>
<th>WACC</th>
<th>12.00%</th>
<th>13.50%</th>
<th>15.00%</th>
<th>16.50%</th>
<th>18.00%</th>
<th>19.50%</th>
<th>21.00%</th>
<th>22.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.21</td>
<td>$ (34,182,606)</td>
<td>$ (42,465,668)</td>
<td>$ (49,133,652)</td>
<td>$ (54,494,858)</td>
<td>$ (58,794,887)</td>
<td>$ (62,230,189)</td>
<td>$ (64,958,526)</td>
<td>$ (67,107,085)</td>
</tr>
<tr>
<td>$0.25</td>
<td>$ (16,623,467)</td>
<td>$ (26,571,918)</td>
<td>$ (34,691,382)</td>
<td>$ (41,323,223)</td>
<td>$ (46,740,312)</td>
<td>$ (51,161,692)</td>
<td>$ (54,763,918)</td>
<td>$ (57,689,879)</td>
</tr>
<tr>
<td>$0.30</td>
<td>$ 935,673</td>
<td>$ (10,678,168)</td>
<td>$ (20,249,112)</td>
<td>$ (28,151,587)</td>
<td>$ (34,685,738)</td>
<td>$ (40,093,196)</td>
<td>$ (44,569,311)</td>
<td>$ (48,272,673)</td>
</tr>
<tr>
<td>$0.34</td>
<td>$ 18,494,812</td>
<td>$ 5,215,582</td>
<td>$ (5,806,841)</td>
<td>$ (14,979,952)</td>
<td>$ (22,631,164)</td>
<td>$ (29,024,699)</td>
<td>$ (34,374,703)</td>
<td>$ (38,855,467)</td>
</tr>
<tr>
<td>$0.38</td>
<td>$ 36,053,952</td>
<td>$ 21,109,332</td>
<td>$ 8,635,429</td>
<td>$ (1,808,316)</td>
<td>$ (10,576,589)</td>
<td>$ (17,956,203)</td>
<td>$ (24,180,096)</td>
<td>$ (29,438,261)</td>
</tr>
<tr>
<td>$0.42</td>
<td>$ 53,613,091</td>
<td>$ 37,003,082</td>
<td>$ 23,077,699</td>
<td>$ 11,363,319</td>
<td>$ 1,477,985</td>
<td>$ (6,887,706)</td>
<td>$ (13,985,488)</td>
<td>$ (20,021,055)</td>
</tr>
<tr>
<td>$0.47</td>
<td>$ 71,172,231</td>
<td>$ 52,896,832</td>
<td>$ 37,519,969</td>
<td>$ 24,534,954</td>
<td>$ 13,532,560</td>
<td>$ 4,180,790</td>
<td>$ (3,790,881)</td>
<td>$ (10,603,849)</td>
</tr>
<tr>
<td>$0.51</td>
<td>$ 88,731,370</td>
<td>$ 68,790,582</td>
<td>$ 51,962,240</td>
<td>$ 37,706,590</td>
<td>$ 25,587,134</td>
<td>$ 15,249,287</td>
<td>$ 6,403,727</td>
<td>$ (1,186,643)</td>
</tr>
<tr>
<td>$0.55</td>
<td>$ 106,290,510</td>
<td>$ 84,684,332</td>
<td>$ 66,404,510</td>
<td>$ 50,878,225</td>
<td>$ 37,641,709</td>
<td>$ 26,317,783</td>
<td>$ 16,598,334</td>
<td>$ 8,230,563</td>
</tr>
<tr>
<td>$0.59</td>
<td>$ 123,849,649</td>
<td>$ 100,578,082</td>
<td>$ 80,846,780</td>
<td>$ 64,049,861</td>
<td>$ 49,696,283</td>
<td>$ 37,386,280</td>
<td>$ 26,792,942</td>
<td>$ 17,647,769</td>
</tr>
<tr>
<td>$0.63</td>
<td>$ 141,408,789</td>
<td>$ 116,471,832</td>
<td>$ 95,289,051</td>
<td>$ 77,221,496</td>
<td>$ 61,750,857</td>
<td>$ 48,454,776</td>
<td>$ 36,987,549</td>
<td>$ 27,064,975</td>
</tr>
</tbody>
</table>
To account for the sensitivity of NPV to the product price, a green premium can be applied to the ethyl acetate product, as explained previously. This green premium allows for more flexibility in keeping the NPV positive for this project, even if the company faces a higher WACC. As seen below in Table 38, if a modest green premium of 7.5% is added to the ethyl acetate selling price, the WACC can increase to an even greater extent (as far as 40%) before seeing a negative NPV. This sensitivity analysis furthers the case to include and consider the green premium, especially given the fact that a higher WACC is highly probable for a smaller company.

As described in previous sections, it is unlikely that a small company will be able to sell 100% of their total production, at least in the preliminary years of production. This could be true of a start-up such as Greenyug, who yet needs to establish themselves in the industry. As seen below in Table 39, the NPV for this project is sensitive to this metric, and reducing the % of production sold to even 80% at a WACC of 15%, will yield a negative NPV. This is again an important managerial consideration to be aware of, especially in the beginning years of production.
Table 38: Sensitivity of NPV to Variations in Green Premium and WACC

<table>
<thead>
<tr>
<th>WACC</th>
<th>12.00%</th>
<th>13.50%</th>
<th>15.00%</th>
<th>16.50%</th>
<th>18.00%</th>
<th>19.50%</th>
<th>21.00%</th>
<th>22.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00%</td>
<td>$53,613,091</td>
<td>$37,003,082</td>
<td><strong>$23,077,699</strong></td>
<td>$11,363,319</td>
<td>$1,477,985</td>
<td>$(6,887,706)</td>
<td>$(13,985,488)</td>
<td>$(20,021,055)</td>
</tr>
<tr>
<td>2.50%</td>
<td>$58,002,876</td>
<td>$40,976,520</td>
<td>$26,688,267</td>
<td>$14,656,228</td>
<td>$4,491,629</td>
<td>$(4,120,582)</td>
<td>$(11,436,836)</td>
<td>$(17,666,753)</td>
</tr>
<tr>
<td>5.00%</td>
<td>$62,392,661</td>
<td>$44,949,957</td>
<td>$30,298,834</td>
<td>$17,949,137</td>
<td>$7,505,272</td>
<td>$(1,353,458)</td>
<td>$(8,888,185)</td>
<td>$(15,312,452)</td>
</tr>
<tr>
<td>7.50%</td>
<td>$66,782,446</td>
<td>$48,923,395</td>
<td>$33,909,402</td>
<td>$21,242,046</td>
<td>$10,518,916</td>
<td>$1,413,666</td>
<td>$(6,339,533)</td>
<td>$(12,958,150)</td>
</tr>
<tr>
<td>10.00%</td>
<td>$71,172,231</td>
<td>$52,896,832</td>
<td>$37,519,969</td>
<td>$24,534,954</td>
<td>$13,532,560</td>
<td>$4,180,790</td>
<td>$(3,790,881)</td>
<td>$(10,603,849)</td>
</tr>
<tr>
<td>12.50%</td>
<td>$75,562,015</td>
<td>$56,870,270</td>
<td>$41,130,537</td>
<td>$27,827,863</td>
<td>$16,546,203</td>
<td>$6,947,914</td>
<td>$(1,242,229)</td>
<td>$(8,249,547)</td>
</tr>
<tr>
<td>15.00%</td>
<td>$79,951,800</td>
<td>$60,843,707</td>
<td>$44,741,105</td>
<td>$31,120,772</td>
<td>$19,559,847</td>
<td>$9,715,039</td>
<td>$(1,306,423)</td>
<td>$(5,895,246)</td>
</tr>
<tr>
<td>17.50%</td>
<td>$84,341,585</td>
<td>$64,817,145</td>
<td>$48,351,672</td>
<td>$34,413,681</td>
<td>$22,573,490</td>
<td>$12,482,163</td>
<td>$3,855,075</td>
<td>$(3,540,944)</td>
</tr>
<tr>
<td>20.00%</td>
<td>$88,731,370</td>
<td>$68,790,582</td>
<td>$51,962,240</td>
<td>$37,706,590</td>
<td>$25,587,134</td>
<td>$15,249,287</td>
<td>$6,403,727</td>
<td>$(1,186,643)</td>
</tr>
<tr>
<td>22.50%</td>
<td>$93,121,155</td>
<td>$72,764,020</td>
<td>$55,572,807</td>
<td>$40,999,499</td>
<td>$28,600,778</td>
<td>$18,016,411</td>
<td>$8,952,379</td>
<td>$1,167,659</td>
</tr>
</tbody>
</table>

Table 39: Sensitivity of NPV to Variations in % of Productino Sold and WACC

<table>
<thead>
<tr>
<th>WACC</th>
<th>12.00%</th>
<th>13.50%</th>
<th>15.00%</th>
<th>16.50%</th>
<th>18.00%</th>
<th>19.50%</th>
<th>21.00%</th>
<th>22.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.00%</td>
<td>$14,209,363</td>
<td>$1,308,958</td>
<td>$(9,381,520)</td>
<td>$(18,262,584)</td>
<td>$(25,655,845)</td>
<td>$(31,820,683)</td>
<td>$(36,967,187)</td>
<td>$(41,266,234)</td>
</tr>
<tr>
<td>80.00%</td>
<td>$22,090,109</td>
<td>$8,447,783</td>
<td>$(2,889,676)</td>
<td>$(12,337,403)</td>
<td>$(20,229,079)</td>
<td>$(26,834,088)</td>
<td>$(32,370,847)</td>
<td>$(37,017,198)</td>
</tr>
<tr>
<td>85.00%</td>
<td>$29,970,854</td>
<td>$15,586,607</td>
<td>$3,602,168</td>
<td>$(6,412,223)</td>
<td>$(14,802,313)</td>
<td>$(21,847,492)</td>
<td>$(27,774,507)</td>
<td>$(32,768,162)</td>
</tr>
<tr>
<td>90.00%</td>
<td>$37,851,600</td>
<td>$22,725,432</td>
<td>$10,094,011</td>
<td>$(4,87,042)</td>
<td>$(9,375,547)</td>
<td>$(16,860,897)</td>
<td>$(23,178,168)</td>
<td>$(28,519,127)</td>
</tr>
<tr>
<td>95.00%</td>
<td>$45,732,346</td>
<td>$29,864,257</td>
<td>$16,585,855</td>
<td>$5,438,138</td>
<td>$(3,948,781)</td>
<td>$(11,874,302)</td>
<td>$(18,581,828)</td>
<td>$(24,270,091)</td>
</tr>
<tr>
<td>100.00%</td>
<td>$53,613,091</td>
<td>$37,003,082</td>
<td>$23,077,699</td>
<td>$11,363,319</td>
<td>$1,477,985</td>
<td>$(6,887,706)</td>
<td>$(13,985,488)</td>
<td>$(20,021,055)</td>
</tr>
</tbody>
</table>
The following tornado chart illustrates the degree to which NPV is sensitive to the variations in product price, % of production sold, variable costs, TPI and fixed costs. The tornado chart illustrates the variations in NPV while holding all other independent variables constant. As seen in Figure 15, the NPV is most sensitive to the product price and least sensitive to fixed costs. It is important to note that the NPV is also significantly sensitive to the WACC. This follows a similar pattern to the variables that show significant sensitivity to IRR. Figure 15 lends itself to the discussion that a green premium would be advantageous in offsetting any market shocks to the product price and discount rate availabilities, as the product price is significant to the profitability of the project.

**Figure 15:** Tornado chart illustrating the variation in NPV to a change in the product price, % of production sold, variable costs, TPI and fixed costs. The base case NPV is equal to $23.07 MM. This chart shows a variation of the independent variable by ± 20% from their base case, where applicable.
24 Other Important Considerations

24.1 Health and Safety Considerations

Both ethanol and ethyl acetate are classified as hazardous materials by OSHA; they can cause harm from prolonged exposure or contact. The appropriate personal protective equipment must be worn by the workers in the plant to offer protection from the potential dangers. In addition, both of these chemicals are highly flammable in both the liquid and vapor forms. Floating head storage tanks were designed for each material to mitigate the risks associated with their high flammabilities. Explosion proof equipment and columns designed to accommodate the necessary high temperatures were also accounted for in the design of the plant. The MSDS sheets for both of these key materials as well as other intermediates in the process are included in Section 27.4.

In addition to explosion proof and fireproof equipment, the minor equipment detailed in Section 18 provides extra safety precautions for the process by accounting for necessary control valves and a flare system.

24.2 Environmental and Location Considerations

The overall Greenyug process presents a key environmental consideration. The use of fermentation ethanol as the single feed for the process gives Greenyug a sustainable edge. Compared to the current industry standard, the process Greenyug is implementing is decidedly more green.

The location of the plant in Columbus, NE also brings up key considerations and advantages for Greenyug. As previously mentioned, the proximity to ADM’s corn processing plant gives Greenyug easy access to the needed fermentation ethanol. It is possible that Greenyug is getting a discounted price of ethanol for this reason. Additionally, though a single day ethanol feed storage tank was designed here for this process, it is likely that Greenyug is simply using a direct pipeline to supply the feed to the process.
A further consideration based on plant location was the temperature of available cooling water. Meetings with industry consultants led to a discussion of a study done on cooling water temperatures in Iowa. This led to the decision of accounting for an initial cooling water temperature of 86°F.

24.3 Start Up Considerations

Starting up a new plant entails land purchase, site preparation, contractor fees, service facilities, building inventory, and the loading of chemicals into the process equipment. All of these considerations contribute to the previously mentioned up front and start up costs. The $262,370 land cost and the $1,311,849 start up costs discussed in Section 21, are a significant consideration for Greenyug as compared to more established companies.

Plant start up is also associated with several business considerations. Important mentions for Greenyug are establishing the agreements with the neighboring corn plant and procuring funding. As previously discussed, it is also imperative to consider a start-up profile. As a start up, it is unlikely that Greenyug will be able to sell all of its product in the first few years of production. The company will have to acquire customers and gain prominence in the existing market. In addition to this, Greenyug looks to establish a new segment of the ethyl acetate market by introducing a unique value proposition.

24.4 Continuous Evaluation

For the purpose of this project, additional backup units for the reactive distillation column, hydrogenation reactor, and distillation column were not included in the costing analysis. The design presented is the first iteration of plant design. Throughout the operating year, the plant would be continuously evaluated for process development and subsequent capital and control mechanisms may be improved. Note that the profitability analysis conducted above is rigorous and conservative in its approach and as shown in Section 23.3, profitability measures are able to withstand some degree of TPI variation. However, should
the continuous evaluation of this process yield higher investment requirements, it will be necessary that these profitability measures be revisited.
25 Conclusion and Recommendations

An investigation into Greenyug’s proposed process for the sustainable conversion of ethanol to ethyl acetate was conducted. This novel process makes use of three main unit operations, where the innovative technology stems from the reactive distillation component of the process. This proposed process yields a ethyl acetate purity of 99.8%, thereby satisfying customer and market demands. n-Butanol and 2-butanol are byproducts in this process and are treated as waste products. The hydrogen produced during this process is burned for fuel value.

As explained in previous sections, the Greenyug process was reverse engineered from limited patent information. The design of this process includes several optimizations on the basis of efficiency, separation, and cost. Following several assumptions on catalyst, kinetic and equilibrium operations, the investigation concludes that the Greenyug process is a feasible from a technical perspective.

The project yields a NPV of $23.08MM, and an IRR of 38.73%. These metrics suggest that the process is profitable and therefore it is deemed likely that Greenyug would be able to compete with large players in the industry effectively. However, as discussed in Section 23.3, these profitability measures are significantly sensitive to the product price (See Figure 14 and 15).

The ethanol is procured at a market price of $0.21/lb. Although the proposed plant is located in close proximity to the ADM corn plant and a discount on the feedstock could be seen, the economic analysis does not assume any discount, so to be rigorous in its approach.

This current economic model follows the base case that the ethyl acetate product can be sold at $0.42/lb. Note that this is the current market price, and assumes no green premium. As discussed throughout this report, the proposed process is sustainable and can therefore warrant the potential addition of a green premium. Economic analyses suggest that the green premium may be advantageous from a competitive standpoint for Greenyug as the green premium applied to the product price would be able to offset any other variations in
cost metrics (TPI, variable cost, etc.). Further note that the economic base case follows a WACC of 15%, which is standard of project modelling; however, given that Greenyug is a startup company, it is likely that the company may face a WACC greater than 15%. The profitability measures are sensitive to the WACC, however using a conservative approach, NPV and IRR still remain attractive even at a higher WACC.

This is the first iteration of the design, and therefore operating costs and TPI may vary after iterative improvements. Future evaluation may further account for design optimizations in the process. The investigation concludes that with the current proposed design, following all assumptions aforementioned, the process is feasible both from a technical and economic perspective, with no green premium necessary.
26 Acknowledgments

Our team would like to graciously acknowledge both Dr. Daeyeon Lee and Professor Bruce Vrana for their continuous guidance, and support over the course of this project. Their advice, feedback, and availability to provide information made this project possible. In addition, we would like to recognize Professor Leonard Fabiano for his time spent working with us over the course of the semester. His ASPEN expertise was extremely helpful in successfully modeling the key aspects of our design process. We would also like to thank Professor Warren Seider for his support and time spent meeting with our group.

We would also like to express our gratitude to the design consultants that met with us each week and provided valuable insights. Their recommendations and advice not only made this project possible, but also taught us a tremendous amount about the chemical engineering industry.
References


Kimberly Ann Horan, Carl David Murphy, Russel Mark Stephens, R. Jay Warner, and


28 Appendix

28.1 Equipment Design Calculations

28.1.1 Feed Pump

The head for the feed pump (P-xxx) was calculated on the basis of the pressure change and density, \( \rho \), of the fluid flowing through the pump. The density of liquid flow through this pump, as reported by ASPEN, is 48.9 \( \text{lb/ft}^3 \) and the pressure rise required is 19 bar (\( \approx 130.5 \text{psi} \)).

\[
\text{Head} = \frac{\text{Pressure Rise}}{\text{Liquid Flow Density}} = \frac{130.5 \text{ lb/ft}^3 \times 144 \text{ in}^2/\text{ft}^2 \times 32.2 \text{ ft/s}^2}{48.9 \text{ lb/ft}^3 \times 32.2 \text{ lb/ft/s}^2} \approx 383.6 \text{ ft}
\]

28.1.2 Reactors

Reactive Distillation Column

The operating conditions for the reactive distillation column were initially provided by patent literature, describing a lab-scale model of this column. The number of stages required for the reaction and adequate separation of ethyl acetate and by products from the hydrogen byproduct were also determined, and appropriately specified, in the ASPEN simulation model. Tray profiles from the ASPEN simulation provided data on the viscosity of liquid on each stage. The O’Connell relationship was initially a graphical correlation, but over the years, industry have proposed the following empirical relationship, where \( E_{OC} \) represents the Murphee Tray Efficiency, \( \alpha \) represents the relative volatility between key components and \( \mu \) represents the viscosity in cP:

\[
E_{OC} = 0.492 \times (\alpha \times \mu)^{-0.245}
\]

In this case, acetaldehyde is the light key and ethyl acetate is the heavy key. The relative volatility is calculated by taking the ratio of the K values for these two components, at each tray. A sample calculation to determine the relative volatility, and hence relevant efficiency...
and real number of trays, is carried out below using data from tray 5 as an example:

\[ \alpha = \frac{K_{1.5}}{K_{2.5}} = \frac{2.4732}{0.7308} = 3.384 \]

\[ E_{OC} = 0.492 \times (\alpha \times \mu)^{-0.226} = 0.492 \times (\alpha \times \mu)^{-0.226} = 0.586 \]

Number of Real Trays Required = \( \frac{1}{E_{OC}} = 1.705 \)

Table 40: Individual Stage Tray Efficiencies: Reactive Distillation

<table>
<thead>
<tr>
<th>Theoretical Stage Number</th>
<th>Viscosity of Liquid (cP)</th>
<th>K1 Value (Acetaldehyde)</th>
<th>K2 Value (Ethyl Acetate)</th>
<th>Relative Viscosity (cP)</th>
<th>Stage Efficiency</th>
<th>Real Trays Required</th>
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<tbody>
<tr>
<td>1</td>
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<td>-</td>
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<tr>
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<td>2.460</td>
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<td>1.710</td>
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<tr>
<td>4</td>
<td>0.136</td>
<td>2.474</td>
<td>0.729</td>
<td>3.393</td>
<td>0.586</td>
<td>1.707</td>
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<tr>
<td>5</td>
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<td>0.731</td>
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<tr>
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<td>1.706</td>
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<tr>
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<td>0.136</td>
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</tr>
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<tr>
<td>11</td>
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<td>0.732</td>
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</tr>
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<tr>
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<td>3.597</td>
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<td>0.973</td>
<td>3.504</td>
<td>0.642</td>
<td>1.557</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Number of Real Trays = \( \sum_{i=20}^{n} \) Real Trays Required = 30.1

The number of actual trays is rounded up to a whole number, for practical sense. Therefore, the reactive distillation column requires 31 trays.

\[
\text{Total Number of Real Stages} = (31 \text{ trays} \times 2 \text{ ft spacing}) + 4 + 7 \text{ ft} = 73 \text{ ft}
\]

**Reflux Accumulator Design**

The reflux accumulator is modelled as a horizontal pressure vessel. To determine the length and diameter of the reflux accumulator, the volumetric flow into the drum is first calculated. The reflux ratio and distillate volumetric flow rate were determined from ASPEN simulation results.

\[
V_{\text{drum,in}} = (1 + R) \times (D_{\text{volumetric}}) = (1 + 1.6) \times (9136^3/\text{hr}) = 23754 \text{ ft}^3/\text{hr}
\]

For a residence time of 10 minutes, assuming the reflux accumulator is half full, the total volume of the accumulator is calculated.

\[
\text{Volume} = 23754 \text{ ft}^3/\text{hr} \times 2 \times \frac{10\text{ min}}{60\text{ min/hr}} = 7918 \text{ ft}^3
\]

\[
D = \frac{2V^{\frac{1}{3}}}{\pi} = \frac{2 \times 7918 \text{ ft}^3}{\pi} = 17.1 \text{ ft}
\]

Using the L/D ratio equal to 2, the length of the reflux accumulator was calculated to be 34.2 ft.

**Partial Condenser Design**

The partial condenser is modelled as a fixed head, shell and tube heat exchanger. To
determine the area of the condenser, the heat duty and the LMTD was used.

\[
A_c = \frac{-9.62 \times 10^6 \text{Btu/hr}}{100 \text{Btu/hr} - 119^\circ F} = 824 \text{ft}^2
\]

**Reboiler Design**

The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger. To determine the area of the reboiler, the heat flux and heat duty was used.

\[
A_R = \frac{Q_R}{\text{Flux}} = \frac{1.701 \times 10^7 \text{Btu/hr}}{12000 \text{Btu/hr} - \text{ft}^2} = 1420 \text{ft}^2
\]

Catalyst Costing and Design The catalyst, CuO/ZnO/Al₂O₃ was chosen on a basis of selectivity and conversion from lab scale data. It is assumed that the entire tray spacing of the feed tray contains cylindrical pellets with a packing efficiency of 0.6 and corresponding void fraction of 0.4. The total mass of catalyst required can be found if the volume of the tray spacing and density of the catalyst is known. The former can be found from ASPEN Plus modeling, while the latter can be found from the catalyst specification sheet.

\[
V_{cat} = (1 - \epsilon)V = (1 - \epsilon)\pi \frac{D^2}{4} H
\]

\[
= 0.307 m^3 = 10.8 cu ft
\]

\[
m_{cat} = V_{cat} \times \rho_{cat} = 400 kg = 882 lb
\]

**Hydrogenation Reactor**

The hydrogenation reactor is assumed to be a plug flow reactor. A differential mass balance can be performed to achieve the following design equation:

\[
\frac{V}{F} = \tau = \int_0^{x_{a,i}} \frac{dx_a}{-r_a}
\]

The reaction kinetics are reported in literature and discussed in the Relevant Chemistry
The limiting reactant in the process in the aldehyde and ketone, denoted as "a". The rate expression can be written in terms of partial pressures and fractional conversion, then subsequently inputted into the design equation.

\[ r_a = k[P_a][P_{H_2}]^{1/2} \]

\[ = k[P_a_0](1 - x_a)([P_{H_20}] - [P_{a0}]x_a) \]

\[ \tau = \int_0^{x_{af}} \frac{dx_a}{-k[P_{a0}](1 - x_a)([P_{H_20}] - [P_{a0}]x_a)} \]

The rate constant changes as a function of temperature. However, the temperature will be essentially linearly dependent on the fraction conversion and can be found by an energy balance assuming complete conversion. This assumption is true if the heat capacity of the system stays constant. Since there is a major amount of inerts in the system, the heat capacity can be assumed to be constant.

\[ k = k_0 \exp\left[\frac{-E_a}{RT}\right] \]

\[ T = T_i + x_a(T_F - T_i) \]

\[ \tau = \int_0^1 \frac{dx_a}{-k_0 \exp\left[\frac{-E_a}{R(T_i + x_a(T_F - T_i))}\right][P_{a0}](1 - x_a)([P_{H_20}] - [P_{a0}]x_a)} \]

\[ = 10 \text{s} \]

Initial sizing of the reactor column utilized the following residence time. To account for pressure drop throughout the reactor due to a catalyst packing, modeling in ASPEN Plus was utilized.

The catalyst is assumed to pack in the reactor vessel with a packing efficiency of 0.6 and void fraction of 0.4. The volume and mass of catalyst required can then be calculated from the volume of the reactor (previously calculated) and density of the catalyst (from
28.1.3 Distillation Column

**Algorithm Used for Choice of Operating Conditions**

Note that this distillation column was designed using the Fenske Underwood Gillian (FUG) shortcut method. A key assumption of this method is that the relative volatility of the light key to the heavy key remains constant through the column.

**Determining The Minimum Number of Stages**

Firstly, the relative volatility of the light key to the heavy key was calculated. The K values for n-butanol and ethyl acetate were determined from the ASPEN simulation output.

\[
\alpha = \frac{K_{LK}}{K_{HK}} = \frac{0.79}{0.33} = 2.39
\]

Next, the Fenske equation was used to determine the minimum number of stages. Specific values for the component distillate and bottoms product can be found in the block reports in Section 28.7.3. The following is the Fenske equation used:

\[
N_{min} = \frac{\log(\frac{d_{LK}}{b_{LK}})(\frac{b_{HK}}{d_{HK}}))}{\log(a_{LK,HK})} = 8.375 \text{ stages}
\]

where \(d\) is a component flow rate in the distillate and \(b\) is a component flow rate in the bottoms product.

---

Seider, Lewin, Seader, Widagdo, Gani, and Ng [2017]
Determining The Minimum Reflux Ratio

The minimum reflux ratio was determined by following the assumption that the mixture could be treated as a pseudo binary mixture. The following design equation was used:

\[
\frac{L_{\text{min}}}{F} = \frac{(D \times x_{D,LK}/F \times x_{D,LK}) - \alpha_{LK,HK}(D \times x_{D,HK}/F \times x_{D,HK})}{\alpha_{LK,HK} - 1} = 2.065
\]

Kirkbride Equation: Number of Stripping and Rectifying Stages

The Kirkbride equation was used to determine the number of stripping and rectifying stages. The equation provides us with the ratio of the rectifying to stripping stages. The total number of stages is equal to the number of rectifying stages plus the number of stripping stages.

\[
\frac{N_R}{N_S} = \left(\frac{x_{HK,F}}{x_{LK,F}}\right)\left(\frac{x_{LK,B}}{x_{HK,D}}\right)^2 \left(\frac{B}{D}\right)^{0.206} = 0.5203
\]

\[N_R = 3.48 \text{ stages}\]

\[N_S = 6.68 \text{ stages}\]

O’Connell Relationships: Determining Actual Number of Stages As outlined in Section 29.2.2, the O’Connell relationship provides information on the efficiency of each tray and thereby the total number of actual stages required. In this case, the 2-butanol is the heavy key and the ethyl acetate is the light key. Equivalent calculations to Section 29.2.2 were carried out for this column.
The number of real trays is the sum of the number of real trays required for each stage.
The number of actual trays is rounded up to a whole number, for practical sense. Therefore, the reactive distillation column requires 29 trays.

Total Number of Real Stages = \((29 \text{ trays} \times 2 \text{ ft spacing}) + 4 + 7 \text{ ft} = 69 \text{ ft}\)
Reflux Accumulator Design

The reflux accumulator is modelled as a horizontal pressure vessel. To determine the length and diameter of the reflux accumulator, the volumetric flow into the drum is first calculated. The reflux ratio and distillate volumetric flow rate were determined from ASPEN simulation results.

\[ V_{\text{drum, in}} = (1 + R) \times (D_{\text{volumetric}}) = (1 + 10) \times (229.2^3/\text{hr}) = 2522 \text{ ft}^3/\text{hr} \]

For a residence time of 10 minutes, assuming the reflux accumulator is half full, the total volume of the accumulator is calculated.

\[ \text{Volume} = 2522 \text{ ft}^3/\text{hr} \times 2 \times \frac{10\text{min}}{60\text{min/ hr}} = 840.7 \text{ ft}^3 \]

\[ D = \frac{2V^{\frac{1}{3}}}{\pi} = \frac{2 \times 840.7 \text{ ft}^3}{\pi} = 8.11 \text{ ft} \]

Using the L/D ratio equal to 2, the length of the reflux accumulator was calculated to be 16.22 ft.

Partial Condenser Design

The partial condenser is modelled as a fixed head, shell and tube heat exchanger. To determine the area of the condenser, the heat duty and the LMTD was used.

\[ A_c = \frac{-2.62 \times 10^7 \text{ Btu/ hr}}{100 \text{ Btu/hr} - ^o F \times 120^o F} = 2193 \text{ ft}^2 \]

Reboiler Design

The reboiler is modelled as a kettle vaporizer, shell and tube heat exchanger. To determine the area of the reboiler, the heat flux and heat duty was used.

\[ A_R = \frac{Q_R}{Flux} = \frac{2.83 \times 10^7 \text{ Btu/ hr}}{12000 \text{ Btu/hr} - ft^2} = 2362 \text{ ft}^2 \]
28.1.4 Molecular Sieve

The molecular sieve consists of the 13X sieve material and the vessel containing the sieve. The sieve material has a static adsorption of 25 wt%. The total amount of sieve material needed can be found from the total mass of water removal required, which can be obtained from ASPEN Plus modeling. The bed is assumed to be regenerated every day, so the mass removal is on a daily basis.

\[ m_{\text{sieve}} = \frac{m_{\text{water}}}{0.25} = \frac{1920\, kg}{0.25} = 4233\, lb \]

The volume of the vessel can be calculated if the particle density is known (from the specification sheets) and assuming a packing efficiency of the spherical particles to be 0.6.

\[ V_{\text{sieve}} = m_{\text{sieve}} \cdot \rho_{\text{sieve}} = 2.82m^3 = 100\, cuft \]
\[ V_{\text{vessel}} = \frac{V_{\text{sieve}}}{1 - \epsilon} = \frac{4.7m^3}{0.4} = 166\, cuft \]

Finally, the vessel can be sized. A general heuristic is to size a molecular sieve vessel with a ratio of \( L/D = 3 \). The following system of equations can be solved:

\[ V_{\text{vessel}} = \pi \frac{D^2}{4} L = 166\, cuft \]
\[ \frac{L}{D} = 3 \]

\[ L = 12.5\, ft \]
\[ D = 4.12\, ft \]
Table 42: Detailed Cash Flow Summary Over 15 Years Useful Lifetime

<table>
<thead>
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<th></th>
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<th></th>
<th></th>
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<td>2018</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>(698,300)</td>
<td>-</td>
<td>-</td>
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<td>(26,845,000)</td>
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<td>647,800</td>
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A process for the production of high purity ethyl acetate from ethanol is described. The process involves reacting ethanol over a suitable catalyst in a reactive distillation column. The reactive distillation setup allows overcoming the reaction equilibrium for increased conversion of ethanol. Hydrogen is removed as the distillate and ethyl acetate is obtained as a bottoms product from the reactive distillation column. A feed of hydrogen at the bottom of the column and a suitable hydrogenation catalyst placed at the bottom of the column allows for a significant reduction of impurities such as butan-2-one, butyraldehyde in the ethyl acetate product. Adding side reactors to the reactive distillation column allows additional catalyst holdup for improved reactant conversion.
Figure 1: Reactive residue curve maps at pressures of 1 atm and 5 atm.
Figure 2: Reactive residue curve maps at pressures of 10 atm and 20 atm.
Figure 3: Single feed reactive distillation column schematic.
Figure 4: Schematic for a reactive distillation system with subsequent product hydrogenation.
Figure 5: Double feed reactive distillation column schematic with an upper feed of ethanol and lower feed of hydrogen.
Figure 6: Double feed reactive distillation column schematic using dual catalyst beds with an upper feed of ethanol and lower feed of hydrogen.
Figure 7: Side reactor configuration (a) upward flow feed to side reactor (b) downward flow feed to side reactor.
Figure 8: Double Side reactor configuration (a) upward flow feed to multiple side reactors (b) downward flow feed to multiple side reactors.
ETHYL ACETATE PRODUCTION

RELATED APPLICATIONS

[0001] This application claims the benefit of Guadewar, U.S. Prov. Appl. 61/253,349, filed Oct. 20, 2009, which is incorporated herein by reference in its entirety, including drawings.

FIELD OF THE INVENTION

[0002] The present invention relates to preparation of ethyl acetate by reactive distillation.

BACKGROUND OF THE INVENTION

[0003] The following discussion is provided solely to assist the understanding of the reader, and does not constitute an admission that any of the information discussed or references cited constitute prior art to the present invention.

[0004] Ethyl acetate can be produced from acetaldehyde according to the Tischenko reaction:

\[ 2C_H_3CHO \rightarrow C_H_3COOC_H_2 + H_2 \]

[0005] When acetaldehyde is produced from ethanol, ethyl acetate can be produced from ethanol according to the following reaction:

\[ 2C_H_3CHO + 2H_2 \rightarrow 2C_H_3COOC_H_2 \]

[0006] Alternatively, ethanol can react with acetaldehyde according to the following reaction:

\[ C_H_3CHO + C_H_3CHO \rightarrow C_H_3COOC_H_2 + H_2 \]


[0008] U.S. Pat. No. 4,996,007 describes a process for the oxidation of primary alcohols to aldehydes, esters and acids. A primary alcohol is reacted with oxygen, with a catalyst selected from ruthenium, rhodium, platinum, palladium, rhenium and mixtures thereof, with the option of quaternary C1 to C20 alkyl ammonium co-catalyst, and dihydriodihydroxy-ynaphthalene, dihydroxyanthracene or a mixture thereof as an oxygen activator.

[0009] In U.S. Pat. No. 4,220,803 catalytic dehydrogenation of ethanol for the production of acetaldehyde and acetic acid using a supported copper oxide essentially free of barium is proposed.

[0010] U.S. Pat. No. 4,052,424 suggested a silver-cadmium alloy catalyst for use in production of alkyl alkanoate esters, by contacting a primary alkyl in the vapor phase with the catalyst at a temperature of between about 250°C and 600°C.

[0011] In U.S. Pat. No. 4,440,946 there is a described process for producing a carboxylate ester which comprises contacting a mixture of alcohol and aldehyde in the vapor phase with a co-precipitate composition comprising silver-cadmium-zine-mercurium which is substantially in the free metal form.

[0012] Use of the Tischenko reaction for the production of mixed esters from aldehydes is described in U.S. Pat. No. 3,714,236.

[0013] U.S. Pat. No. 5,334,751 describes production of ethyl acetate by reaction of ethanol and oxygen in the presence of a solid catalyst that contains crystalline TiP2O7 and has the formula Pd,M, TiP2O7, where M is Cd, Au, Zn, Ti, or an alkali metal or alkaline earth metal, a is 0.0005-0.2, b is 0.3a, c is 0.5-2.5, x has a value to satisfy the valencies, and Ti and P of the crystalline TiP2O7, represent part of the crystalline TiP2O7.


[0015] Production of esters from primary alcohols by dehydrogenation using bromous acid or a salt thereof in acid medium is described in JP-A-59/025334.

[0016] In SU-A-362814 there is described a process for production of ethyl acetate by dehydrogenation of ethanol at 180°C to 300°C, in the presence of a copper catalyst containing zinc as an activator with an ethanol feed rate of 250 to 700 liters per liter of catalyst per hour.

[0017] The dehydrogenation of ethanol to form ethyl acetate is described in GB-A-2878464. This proposes use of a dehydrogenating agent, such as a copper catalyst, a temperature of from 250°C to 500°C, and a pressure of more than 10 atmospheres (1.013×106 Pa).

[0018] Vapor phase contact of ethanol at a temperature above its critical temperature with a catalyst comprising copper and a diffusely reducible oxide, such as zinc oxide or manganese oxide, is proposed in GB-A-312345, use of a temperature of 375°C and a pressure of 4000 psi (27.58 Mpa) being suggested.

[0019] GB-A-470773 teaches a process for conversion of ethanol to ethyl acetate by dehydrogenating ethanol over a catalyst consisting of a reduced metal, for example, copper on infusorial earth with 10% uranium oxide as promoter, maintained at a temperature of 220°C to 260°C, removing by condensation some of the gas-vapor product rich in hydrogen resulting from the reaction, and returning the gaseous remainder rich in hydrogen to the catalyzing zone.

[0020] EP-A-0151886 describes a process for the preparation of C2+ esters of alkyl carboxylic acids from C2+ primary alcohols which comprises contacting a vaporous mixture containing a primary C2+ alkane and hydrogen in an alkane: hydrogen molar ratio of from 1:10 to about 1000:1 at a combined partial pressure of alkane and hydrogen of from about 0.1 bar (103 Pa) up to about 40 bar (4×105 Pa) and at a temperature in the range of from about 180°C, at about 300°C in a catalytic reaction zone with a catalyst consisting essentially of a reduced mixture of copper oxide and zinc oxide, and recovering a reaction product mixture containing a primary C2+ alkyl ester of an alkyl carboxylic acid which ester contains twice as many carbon atoms as the primary C2+ alkane.

[0021] In EP-A-0201105 there is described a method for converting primary alcohols, such as ethanol, to their corresponding alkanoate esters which involves the regulation of the molar feed ratio of hydrogen gas to alkane in the reaction zone of a copper-chromite containing catalyst.

[0022] One method of separating ethyl acetate from ethanol and water involves extractive distillation with an extractive agent comprising polyethylene glycol and dipropylene glycol, diethylene glycol, or triethylene glycol as described in U.S. Pat. No. 4,569,726 or with an extractive agent containing dimethyl sulfoxide as described in U.S. Pat. No. 4,379,028.

[0023] Separation of ethyl acetate from a composition comprising ethyl acetate, ethanol and water is described in JP-A-05/186392 by feeding the composition to a distillation column to obtain a quasi-azeotropic mixture comprising ethyl acetate, ethanol and water, condensing it, separating the condensate into an organic layer and an aqueous layer, returning
the organic layer to the column, and recovering ethyl acetate as a bottom product from the column.

EP-A-031021 describes how carbonylation of olefins to produce monocarboxylate esters causes formation of aldehydes and acetals as byproducts. Monocarboxylate esters produced in this way are subjected to a three step purification process involving treatment with a strongly acidic agent, followed by hydrogenation and distillation. The initial treatment with a strongly acidic agent is intended to convert acetaldehyde to vinyl ethers and aldehydes and acetals to aldehydes. The subsequent hydrogenation step then converts these compounds to byproducts which are more easily separated from the desired monocarboxylate ester.

EP-A-0101910 contains a similar disclosure regarding carbonylation of olefins to give monocarboxylate esters. It proposes treatment of the monocarboxylate ester with hydrogen at elevated temperature in the presence of an acidic ion exchange or zeolite doped with one or more metals of Group VIII of the Periodic Table, followed by hydrogenation. It is stated that acetalts present as byproducts are converted to vinyl ethers which are converted by hydrogenation to low boiling esters or the aldehydes and acetals are converted to high boilers by an aldol reaction. Unsaturated ketones are converted to saturated ketones.

U.S. Pat. No. 4,435,595 describes the use of reactive distillation to produce high-purity methyl acetate, by esterifying methanol and acetic acid. The process provides for the use of acetic acid and methanol which flow in counter-current through a single reactive distillation column in the presence of an acid catalyst. The acetic acid, in addition to being a reagent, also acts as an extracting agent for the non-reacted methanol and for the water which has been produced. Therefore, the methyl acetate is separated continuously from the acetic acid and removed from the top of the column.

SUMMARY OF THE INVENTION

Current commercial methods for producing ethyl acetate present limitations in such areas as system complexity, the need for expensive prior syntheses, difficult product separations, and/or overall cost. This invention addresses these limitations by providing a reactive distillation system in which ethanol is the sole or primary feed. In some embodiments, the ethanol feed is used in conjunction with a separate second feed of hydrogen.

Thus, the present invention provides a process (and corresponding system) for the production of ethyl acetate from ethanol which includes reacting ethanol over a suitable dehydrogenation catalyst in a reactive distillation column, thereby producing ethyl acetate and hydrogen. Preferably a single reactive distillation column is used. Hydrogen gas is removed (preferably continuously) from the top of the reactive distillation column as a top product. Ethyl acetate is removed (preferably continuously) from the bottom of the column as a liquid bottom product.

Optionally but advantageously, contaminating byproducts present following reaction of the ethanol over the dehydrogenation catalyst can be reacted over a suitable hydrogenation catalyst in the lower part of the column or in a separate hydrogenation reactor. The hydrogenation can convert difficult to separate byproducts which are easier to separate from the ethyl acetate. Consequently, the process can also include purifying the ethyl acetate by distilling off resulting hydrogenated byproducts.

Thus, as indicated above, a first aspect of the invention concerns a reactive distillation process producing high purity ethyl acetate from ethanol, where the process involves dehydrogenating ethanol over a dehydrogenation catalyst in a reactive distillation column. Ethyl acetate is removed during the distillation process as a liquid bottoms product and hydrogen is removed during the distillation process as a gaseous top product.

In certain embodiments, the process also includes hydrogernating contaminants or reaction byproducts in the liquid bottoms product or in the reacted fluid after is has passed over the dehydrogenation catalyst and separating the hydrogenated contaminants or byproducts from the ethyl acetate.

Some implementations of the process utilize a single feed of ethanol; the reactive distillation column contains a generally central dehydrogenation catalyst zone and the single feed of ethanol is delivered into the column above or near the top of the catalyst zone; the reactive distillation column contains a generally central dehydrogenation catalyst zone and the single feed of ethanol is delivered into the column below or near the bottom of the catalyst zone.

In particular embodiments, the process also includes passing reaction fluid, after it has passed over the dehydrogenation catalyst, through a hydrogenation reactor which includes a hydrogenation catalyst, e.g., such that n-butyraldehyde and/or butan-2-one, if present, are hydrogenated; the hydrogenation catalyst may, for example, include metals and/or oxides of nickel, palladium, platinum, ruthenium, molybdenum and/or mixtures thereof as catalyst material, e.g., on a support material such as carbon, alumina, silica, chromia, and/or titania; bottoms product is separated in a separation column which receives product from the hydrogenation reactor, separating, for example, n-butanol and 2-butanone from ethyl acetate.

Some implementations of the process utilize dual feeds of ethanol and hydrogen fed to the reactive distillation column, where the ethanol feed is above the hydrogen feed. In many cases the reactive distillation column includes a dehydrogenation catalyst zone and the ethanol feed is above or near the top of that dehydrogenation catalyst zone (or alternatively within the dehydrogenation catalyst zone, e.g., within the upper 1/4, 1/2, 3/4, or 1/4 of the dehydrogenation catalyst zone) and the hydrogen feed is below or near the bottom of the dehydrogenation catalyst zone. The reactive distillation column can advantageously also include a hydrogenation catalyst zone below the dehydrogenation catalyst zone; usually the hydrogen feed is below or near the bottom of that hydrogenation catalyst zone.

For many embodiments in which dual feeds of ethanol and hydrogen are used, the molar ratio of Ethanol:Hydrogen for the dual feeds is from 1:10 to 1000:1, e.g., from 1:10 to 1:1, 1:1 to 5:1, 1:1 to 10:1, 5:1 to 25:1, 5:1 to 50:1, 10:1 to 50:1, 10:1 to 100:1, 50:1 to 200:1, 50:1 to 400:1, 100:1 to 500:1, 100:1 to 1000:1, 200:1 to 1000:1, or 500:1 to 1000:1.

For any of the column configurations used in the present invention, in certain embodiments, the reactive distillation is performed at a pressure from 1 bar to 50 bar, e.g., 1 to 5, 5 to 10, 7 to 12, 15 to 15, 15 to 20, 15 to 30, 20 to 30, 20 to 50, 30 to 40, 30 to 50, or 40 to 50 bar; the reactive distillation is performed at a pressure where ethanol-ethyl acetate azeotrope is not present: the number of stages or the number of height equivalents of a theoretical plate (HETP) is from 2 to 100, e.g., from 2 to 10, 10 to 20, 10 to 50,
20 to 30, 20 to 70, 30 to 40, 30 to 50, 30 to 100, 50 to 70, 50 to 100, or 70 to 100; the high purity ethyl acetate contains at least 95, 96, 97, 98, or 99.5% ethyl acetate by weight.

[0037] In the present process, a number of different catalysts can be used for the dehydrogenation, e.g., where the dehydrogenation catalyst includes a catalyst material such as metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum and/or mixtures thereof, in most cases on a support such as carbon, alumina, silica, chromia, and/or titania. Some catalysts are useful for either the single feed or dual feed process specified in embodiments above.

[0038] A related aspect of the invention concerns a reactive distillation system, e.g., as indicated in the preceding aspect. Thus, the invention also provides a reactive distillation system for producing high purity ethyl acetate from ethanol. The system includes a reactive distillation column which includes a dehydrogenation catalyst (usually located generally centrally or at intermediate level in the column), an ethanol feed which feeds ethanol into the column such that it passes over the dehydrogenation catalyst, a top product gaseous hydrogen removal passage, and a bottom product liquid ethyl acetate removal passage.

[0039] In certain advantageous embodiments, the system also includes a hydrogenation catalyst positioned to contact liquid product following passage over the dehydrogenation catalyst, generally with a hydrogen feed located prior to or at the hydrogenation catalyst.

[0040] In some embodiments, the chemical feed to the reactive distillation column is a single ethanol feed; the reactive distillation column contains a generally central dehydrogenation catalyst zone and the single ethanol feed is delivered into the column above or near the top of that catalyst zone; the reactive distillation column contains a generally central dehydrogenation catalyst zone and the single ethanol feed is delivered into the column below or near the bottom of that catalyst zone.

[0041] In certain embodiments, the system also includes a hydrogenation catalyst which hydrogenates contaminants or reaction byproducts in the liquid bottoms product or in the reacted fluid after it has passed over the dehydrogenation catalyst and separating the hydrogenated contaminants or byproducts from the ethyl acetate. The hydrogenation catalyst may be in the same column as the dehydrogenation catalyst or in a separate hydrogenation reactor.

[0042] Some embodiments of the system incorporate a single feed of ethanol into the reactive distillation column; the reactive distillation column contains a dehydrogenation catalyst zone (often generally central) and the single feed of ethanol is delivered into the column above or near the top of the catalyst zone; the reactive distillation column contains a generally central dehydrogenation catalyst zone and the single feed of ethanol is delivered into the column below or near the bottom of the catalyst zone.

[0043] In further embodiments, the system also includes a hydrogenation catalyst, e.g., in a hydrogenation reactor, over which reaction fluid (together with hydrogen) is passed after it has passed over the dehydrogenation catalyst; the reaction fluid, hydrogen, and hydrogenation catalyst are configured such that n-butylaldehyde and/or butan-2-one, if present, are hydrogenated, highly preferably without significantly hydrogenating ethyl acetate in the reaction fluid: the hydrogenation catalyst includes metals and/or oxides of nickel, palladium, platinum, ruthenium, iron, molybdenum and/or mixtures thereof as catalyst material, e.g., on a support material such as carbon, alumina, silica, chromia, and/or titania; bottoms product is separated in a separation column which receives product from the hydrogenation reactor, separating, for example, n-butanol and 2-butanol from ethyl acetate.

[0044] Some of the present systems incorporate dual feeds of ethanol and hydrogen fed to the reactive distillation column, where the ethanol feed is above the hydrogen feed. Thus, in many cases the reactive distillation column includes a dehydrogenation catalyst zone and the ethanol feed is above or near the top of that dehydrogenation catalyst zone (or alternatively within the dehydrogenation catalyst zone, e.g., within the upper ¼, ½, ¾, or ¾ of the dehydrogenation catalyst zone) and the hydrogen feed is below or within the dehydrogenation catalyst zone; but below the ethanol feed, e.g., near the bottom of the dehydrogenation catalyst zone. The reactive distillation column can advantageously also include a hydrogenation catalyst zone below the dehydrogenation catalyst zone; usually the hydrogen feed is below or within that hydrogenation catalyst zone, e.g., near the bottom of the hydrogenation catalyst zone.

[0045] For many embodiments in which dual feeds of ethanol and hydrogen are used, the molar ratio of Ethanol:Hydrogen for the dual feeds is from 1:10 to 1000:1, e.g., from 1:10 to 1:1, 1:1 to 5:1, 1:1 to 10:1, 5:1 to 25:1, 5:1 to 50:1, 10:1 to 50:1, 10:1 to 100:1, 50:1 to 200:1, 50:1 to 400:1, 100:1 to 500:1, 100:1 to 1000:1, 200:1 to 1000:1, or 500:1 to 1000:1.

[0046] For any of the column configurations used in the present invention, in certain embodiments, the reactive distillation is performed at a pressure from 1 bar to 50 bar, e.g., 1 to 5, 5 to 10, 7 to 12, 13 to 15, 13 to 20, 15 to 20, 15 to 30, 20 to 30, 20 to 50, 30 to 40, 30 to 50, or 40 to 50 bar; the reactive distillation is performed at a pressure where ethanol:ethyl acetate is not present; the number of stages or the number of height equivalents of a theoretical plate (HETP) is from 2 to 100, e.g., from 2 to 10, 10 to 20, 10 to 50, 20 to 30, 30 to 40, 30 to 50, 30 to 100, 50 to 70, 50 to 100, or 70 to 100; the high purity ethyl acetate contains at least 95, 96, 97, 98, 99, or 99.5% ethyl acetate by weight.

[0047] In the present system, a number of different catalysts can be used for the dehydrogenation, e.g., where the dehydrogenation catalyst includes a catalyst material such as metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum and/or mixtures thereof, in most cases on a support such as carbon, alumina, silica, chromia, and/or titania. Some catalysts are useful for either the single feed or dual feed processes specified in embodiments above.

[0048] In some embodiments of the process, side reactors, usually external side reactors, can be used with the reactive distillation column, e.g., to increase the residence time for reaction. The feed to the side reactors is liquid for top-down flow and vapor for bottom-up flow. One or more side reactors can be used.

[0049] The term “reactive distillation column” is used conventionally to refer to a distillation column in which both reaction and separation is performed. In this case, the primary and desired reaction is the conversion of two ethanol molecules to one ethyl acetate molecule with release of two hydrogen molecules.

[0050] Reference to a “single feed” to a reactive distillation column means that the column has only one chemical feed
stream supplying intended reactant(s) to the column. Nonetheless, such a single feed distillation column may have recycling feed streams where a part of the reactant liquid is drawn from the column and fed back into the column at a different point or a partial distillate is fed back into the column at a different point, e.g., to achieve improved separation and/or complete reaction. A “single ethanol feed” thus refers to a single feed stream, in which ethanol is the sole or at least the primary constituent.

0051 In contrast, the term “dual feed” in the context of a distillation column refers to two separate chemical feed streams. For example, in some of the present embodiments, dual feeds are an ethanol feed and a separate hydrogen feed.

0052 Additional embodiments will be apparent from the Detailed Description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

0053 FIG. 1 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 1 and 5 atmospheres (atm).

0054 FIG. 2 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 10 and 20 atm.

0055 FIG. 3 shows a simplified schematic of a reactive distillation system for catalytic conversion of ethene to ethyl acetate using a single ethanol feed and a single catalyst.

0056 FIG. 4 shows a simplified schematic of a reactive distillation system for catalytic conversion of ethanol to ethyl acetate using a single ethanol feed and a single catalyst, but with a hydrogenation reactor for the bottoms product from the reactive distillation column.

0057 FIG. 5 shows a simplified schematic of a reactive distillation system for catalytic conversion of ethanol to ethyl acetate using dual feeds of ethanol (top) and hydrogen (bottom) with a single catalyst.

0058 FIG. 6 shows a simplified schematic of a reactive distillation system for catalytic conversion of ethene to ethyl acetate using dual feeds of ethene (top) and hydrogen (bottom) with an upper dehydrogenation catalyst and a lower hydrogenation catalyst.

0059 FIG. 7 shows a simplified schematics of side reactor reactive distillation columns using dual feeds of ethanol (top) and hydrogen (bottom) with a single catalyst (a) upward flow feed to side reactor (b) downward flow feed to side reactor.

0060 FIG. 8 shows a simplified schematics of side reactor reactive distillation columns using dual feeds of ethanol (top) and hydrogen (bottom) with an upper dehydrogenation catalyst and a lower hydrogenation catalyst (a) upward flow feed to side reactor (b) downward flow feed to side reactor.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

0061 The present invention concerns a reactive distillation process for producing high purity ethyl acetate from ethanol. This process is highly beneficial as it provides an improved commercial method of upgrading ethanol to ethyl acetate, a more valuable product. This improved commercial process is particularly desirable and advantageous where there is an over-capacity for ethanol. Further, this process obviates the need for a separate acetaldehyde or acetic acid plant to prepare precursors for the ethyl acetate production process. These advantages are provided in a process which can also be less expensive than those in the art for ethyl acetate production from ethanol.

0062 Additionally, the invention can provide a route to ethyl acetate by dehydrogenation of ethanol which is capable of yielding high purity ethyl acetate from ethanol feed streams containing significant amounts of impurities. One particular problem in production of ethyl acetate by dehydrogenation of ethanol is that the reaction product mixture is commonly a complex mixture including esters, alcohols, aldehydes and ketones. From a distillative separation point of view, the mixture is further complicated due to the presence of azeotropes. The reaction product mixtures commonly contain components with boiling points close to ethyl acetate (such as n-butyraldehyde and butan-2-one), including components which can form azeotropes with ethyl acetate, and/or other components of the mixture. This is a particular problem when high purity ethyl acetate is desired.

0063 In conventional chemical processing, chemical reaction and the purification of the desired products by distillation are usually carried out sequentially. In many cases, the performance of this classic chemical process structure can be significantly improved by integration of reaction and distillation in a single multifunctional process unit. This integration concept is called ‘reactive distillation’. As advantages of this integration, chemical equilibrium limitations can be overcome, higher selectivities can be achieved, the heat of reaction can be used in situ for distillation, auxiliary solvents can be avoided, and azeotropic or closely boiling mixtures can be more easily separated. Increased process efficiency and reduction in overall capital costs are the direct results of this approach.

0064 Thus, as indicated above, the present invention provides a novel process for production of ethyl acetate from ethanol at a relatively low cost, along with a plant or distillation system with significantly reduced complexity using reactive distillation. The invention further provides an improved process for the production of high purity ethyl acetate from ethanol, or from a feedstock comprising a major proportion of ethanol and a minor proportion of impurities such as isopropanol and iso-butanol. While not commonly present in ethanol feed streams, impurities which could poison the particular catalyst used should be avoided or removed. For example, sulfur or nitrogen heterocyclic compounds can frequently act as catalyst poisons and, if present, should be removed before introducing the ethanol feed stream to the reactive distillation column.

0065 Ethyl acetate can be produced from ethanol according to the following reactions:

\[ \text{C}_2\text{H}_5\text{OH} \rightarrow \text{CH}_3\text{COOH} + \text{H}_2 \]

\[ 2\text{CH}_3\text{CHO} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5 \]

0066 In the present process, ethanol reacts in a single continuous reactive distillation column which provides sufficient residence time to achieve high conversion of ethanol. Table 1 shows the effect of pressure on the boiling point of the pure components and azeotrope in the mixture. The azeotrope between ethanol and ethyl acetate disappears above a pressure of 13 atm.
TABLE 1

<table>
<thead>
<tr>
<th>Boiling Point, °C</th>
<th>P = 1 atm</th>
<th>P = 5 atm</th>
<th>P = 10 atm</th>
<th>P = 20 atm</th>
<th>P = 30 atm</th>
<th>P = 40 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>-161</td>
<td>-137.6</td>
<td>-123.7</td>
<td>-105.5</td>
<td>-94.3</td>
<td>-84.5</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>204</td>
<td>71.9</td>
<td>103.1</td>
<td>136.4</td>
<td>160.7</td>
<td>180</td>
</tr>
<tr>
<td>Ethanol</td>
<td>78.3</td>
<td>125.2</td>
<td>150.2</td>
<td>179</td>
<td>198</td>
<td>212.7</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>77</td>
<td>136</td>
<td>169.6</td>
<td>210.3</td>
<td>238.4</td>
<td>260.7</td>
</tr>
<tr>
<td>Acetate azoetrop</td>
<td>77.1</td>
<td>123.5</td>
<td>150.1</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

[0067] Residue curve maps can be used to indicate feasible product compositions for distillation columns. In the presence of reaction along with separation, reactive residue curve maps can be used to determine feasible products from a reactive distillation column. Reactive residue curve maps at a pressure of 1 atm and 5 atm respectively are shown in FIG. 1. The stable nodes in the diagram are ethanol and ethyl acetate, and, therefore, it is possible to design a reactive distillation column where either ethanol or ethyl acetate can be obtained as the bottoms product. Hydrogen is an unstable node in the diagram and can be obtained as the distillate. Acetaldehyde and the ethanol/ethyl acetate azeotrope are saddle points in the diagram.

[0068] Reactive residue curves at pressures of 10 atm and 20 atm respectively are shown in FIG. 2. The reactive residue curve map for any pressure above 20 atm is essentially identical to the reactive residue curve map at 20 atm. In view of the reactive residue maps discussed above, a set of reactive distillation systems effective to produce high purity ethyl acetate from ethanol have been designed. The reactive distillation column can have single or multiple feed locations.

Reactive Distillation Column Configurations

[0070] As indicated above, the reactive distillation column is configured for the dehydrogenation of ethanol with the formation of ethyl acetate. The reaction is accomplished by passing the ethanol feed stream over a dehydrogenation cata-

lyst under conditions where ethyl acetate is formed and hydrogen and ethyl acetate are withdrawn as top and bottoms products respectively. Such product drives draw the thermo-
dynamics of the process toward the desired products. As one example of a useful reactive distillation column, a reactive distillation column with a single feed of ethanol as shown schematically in FIG. 3 can produce hydrogen as a distillate and ethyl acetate as a bottoms product. Column 10 contains a generally central catalyst zone 12, and usually will include a top stage or non-reactive rectifying section 13 and a bottom state or non-reactive stripping section 15. Ethanol feed 14 is commonly fed to the middle part of the reactive distillation column. Distillate removed at the top of the column is passed through a partial condenser 16, and hydrogen is separated from lower boiling constituents in reflux tank 18. The condensed lower boiling constituents (i.e., reflux) can be cycled back to the column for further reaction and/or separation. Bottoms product can be passed through reboiler 20, where a portion of the bottoms product is evaporated and added back to the bottom of the column. The column reflux and reboil ratios are maintained such that essentially pure ethyl acetate is obtained as the bottoms product. Ethyl acetate and hydrogen are produced due to the reaction over the dehydrogenation catalyst. Acetaldehyde may also be produced during the reaction if the conversion of acetaldehyde to ethyl acetate is incomplete.

[0071] Examples of useful catalysts for the reaction can include metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum, and mixtures thereof. In many cases, the catal-

yst material will be supported, e.g., on carbon, alumina, silica, chromia or titania.

[0072] During operation, the reactants and products flow through the reactor/column reacting and flashing along the length of the reactor/column. The removal of hydrogen product, by flashing, preferentially to the other components along the reactive distillation column increases the extent of reaction. Also, hydrogen concentration increases from the middle part of the column towards the top of the column. At pressures of about 13 bar or lower, as ethyl acetate is formed from the reactants, azeotrope between ethyl acetate and ethanol occurs. The vapor product leaving the top of the reactive distillation column may contain ethanol and acetaldehyde in addition to hydrogen.

[0073] A partial condenser 16 allows hydrogen to be removed as a distillate, while acetaldehyde and ethanol is recycled back to the top of the reactive distillation column. As noted, the ethyl acetate and ethanol azeotrope disappears above a pressure of 13 atm, which improves the operation of the reactive distillation column. The column can be operated between a pressure of about 1 atm and about 50 atm. The temperature profile in the column is dictated by the mixture boiling point along the height of the column. High conversion of ethanol to products can be achieved by the counter-current flow of reactants and products in addition to overcoming the reaction equilibrium by removal of products.

[0074] Aldehydes and ketones such as n-butylaldehyde and butan-2-one may be produced in the reaction. These byproducts boil at temperatures close to the boiling point of ethyl acetate and may be difficult to separate from ethyl acetate. FIG. 4 shows a process schematic where the bottoms product from the reactive distillation column illustrated in FIG. 3 is sent to a hydrogenation reactor 24 containing a hydrogenation catalyst 26 with a hydrogen co-feed 28. A suitable catal-

yst may comprise metals and/or oxides of nickel, palladium, platinum, ruthenium, iron, molybdenum, supported on carbon, alumina, silica, chromia or titania. The n-butynylaldehyde and butan-2-one impurities are hydrogenated and can then be separated using a distillation column. The outlet of the hydrogenation reactor may be cooled in condenser 30 before entering the distillation column 32. Ethyl acetate 36 with a purity of greater than 99% by weight can be obtained as the bottoms product of the distillation column. Unconverted hydrogen and the hydrogenated byproducts are removed as a distillate 34, e.g., to be used as fuel. This distillation column is operated between a pressure of 1 atm and 50 atm.

[0075] In another embodiment of the invention, the reactive distillation column has two feeds. Ethanol is fed to the upper part of the column (upper feed). Hydrogen is fed to the lower part of the column (lower feed). A schematic for the double feed reactive distillation column is shown in FIG. 5. This system includes column 40 containing catalyst 42 in catalyst zone 44, and commonly will include a top stage or non-

reactive rectifying section 50 and a bottom state or non-
reactive stripping section 52. In the illustrated system, ethanol feed 46 is delivered at or near the top of the catalyst zone 44, and the hydrogen feed 48 is delivered at or near the bottom of catalyst zone 44. It should be recognized that columns can be designed with the ethanol feed location in other locations, e.g., within the catalyst zone but above the hydrogen feed, such as from the approximate middle of the catalyst zone to the top of the column. Similarly, columns with the hydrogen feed in other locations can also be designed, e.g., with the hydrogen feed from the approximate middle of the catalyst zone to the bottom of the column or even higher within the catalyst zone but below the ethanol feed. Highly preferably the ethanol and hydrogen feeds are separated sufficiently to allow byproduct hydrogenation to be substantially completed before hydrogen from the feed reaches substantial concentrations of ethanol being dehydrogenated. Ethanol reacts over the catalyst producing ethyl acetate and hydrogen. Examples of catalysts may include metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum, and mixtures thereof, supported, e.g., on carbon, alumina, silica, chromia or titania.

Due to boiling point differences, hydrogen moves towards the top of the column and ethyl acetate moves towards the bottom of the column. Acetaldehyde may be produced during the reaction and moves up in the column, and can be condensed in condenser 84 and recycled back to the reaction zone through reflux tank 86. Byproducts such as n-butyraldehyde and butan-2-one produced in the reaction boil close to ethyl acetate. The lower hydrogen feed is useful in hydrogenating the by-products over the lower catalyst (Catalyst B) to produce components that can be separated easily from ethyl acetate. Examples of hydrogenation catalysts (Catalyst B) may comprise metals and/or oxides of nickel, palladium, platinum, rhenium, iron, molybdenum, and/or mixtures thereof supported, e.g., on carbon, alumina, silica, chromia or titania. Hydrogen product from the reaction leaves at the top of the column. Subsequent purification of ethyl acetate may be needed to remove the hydrogenated byproducts from ethyl acetate, e.g., using a distillation column such as that as shown in FIG. 4 as distillation column 32. The column is operated between a pressure of about 1 atm and about 50 atm.

In the dual feed systems described above, the hydrogen feed should be at a sufficiently low level that it does not significantly adversely affect the dehydrogenation of ethanol in the zone above, while being effective to dehydrogenate the undesirable close boiling point byproducts. Feed rates of hydrogen can be adjusted empirically to optimize this balance. Commonly, the ratio of product mixture:hydrogen will be in a range of about 500:1 to 1:1 molar ratio, more commonly about 500:1 to 10:1 or 500:1 to 100:1.

Side reactors connected to a reactive distillation column increases the catalyst holdup for improved reactant conversion. In the side reactor concept the reactor feed is withdrawn from the distillation column and the reactor effluent is returned back to the same column. The adequate catalyst amount is more easily arranged in a side reactor system where traditional reactor types and catalyst structures can be used. Also, the reaction conditions within the side reactor such as temperature can be adjusted independently of those prevailing in the distillation column by appropriate heat exchange.

Schematics for a side reactor reactive distillation column with a single catalyst are shown in FIG. 7. A single side reactor is shown, however, multiple side reactors along the length of the reactive distillation column can be used. FIG. 7 (a) shows a configuration where the feed 93 to the side reactor is bottom up and vapor phase. The outlet from side reactor 94 is stream 95 which is sent back to the distillation column at any location in the column below the location of feed 93. FIG. 7 (b) shows a configuration where the feed 96 to the side reactor is top down and liquid phase. The outlet from side reactor 97 is stream 98 which is sent back to the distillation column at any location in the column below the location of feed 96. The side reactors 94 and 97 each contain catalyst for converting ethanol into ethyl acetate. Examples of catalysts may include metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum, and mixtures thereof, supported, e.g., on carbon, alumina, silica, chromia or titania.

As with previous schematic designs shown, the column will usually include a top stage or non-reactive rectifying section 71 and a bottom stage or non-reactive stripping section 79.

Due to boiling point differences, hydrogen moves towards the top of the column and ethyl acetate moves towards the bottom of the column. Acetaldehyde may be produced during the reaction and moves up in the column, and

Schematics for a side reactor reactive distillation with two feeds and using two distinct catalyst zones are shown in FIG. 8. A single side reactor is shown for each catalyst zone in the reactive distillation column, however, multiple side reactors along the length of the reactive distillation column can be used for each catalyst zone. FIG. 8 (a) shows a configuration where the top zone feed 99 to the side reactor 100 is bottom up and vapor phase. The bottom zone feed 102 to another side reactor 103 is also bottom up and
vapor phase. The outlet from side reactor 100 is stream 101 which is sent back to the distillation column at any location in the column above the location of feed 99. The outlet from side reactor 103 is stream 104 which is sent back to the distillation column at any location in the column above the location of feed 102. FIG. 8 (b) shows a configuration where the top zone feed 105 to the side reactor 106 is top down and liquid phase. The bottom zone feed 108 to another side reactor 109 is also top down and liquid phase. The outlet from side reactor 106 is stream 107 which is sent back to the distillation column at any location in the column below the location of feed 105. The outlet from side reactor 109 is stream 110 which is sent back to the distillation column at any location in the column below the location of feed 108. Examples of catalysts for side reactors 100 and 106 may include metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminum, chromium, nickel, iron, molybdenum, and mixtures thereof, supported, e.g., on carbon, alumina, silica, chromia or titania. Examples of hydrogenation catalysts for side reactors 103 and 109 may comprise metals and/or oxides of nickel, palladium, platinum, ruthenium, iron, molybdenum, and mixtures thereof supported, e.g., on carbon, alumina, silica, chromia or titania.

Production of Methyl Formate from Methanol

[0083] In addition to use of the systems and methods described herein for converting ethanol to ethyl acetate, these systems can also be used in processes with methanol as a feed instead of ethanol, with the production of methyl formate and H2 as products according to the following formula:

\[ \text{CH}_3\text{OH} + \text{H}_2 \rightarrow \text{HCOOCH}_3 + \text{H}_2 \]

[0084] Such a system and method can utilize selections from the catalysts indicated for use with the ethanol feed. Products can be withdrawn in similar manner as described for the ethanol to ethyl acetate process.

**EXAMPLES**

**Example 1**

Production of Ethyl Acetate from Ethanol

[0085] A 10 cm diameter distillation column is used, which has been rendered adiabatic by heating casings with temperatures controlled in such a way that the temperature gradient in the column is reproduced. Over a height of 3.5 m, the column is comprised of rectification zone with 8 stages each with a catalytic cell consisting of a cylindrical container with a flat bottom. The bottom of the container is equipped with a grid for retaining the catalyst and also can act as a gas and liquid distributor. The stripping zone is comprised of 12 stages, also with catalyst-containing cells. The rectification section is considered to be above the feed stage and the stripping section is considered to be below the feed stage. Each catalytic cell contains 5 wt % copper oxide on silica. 200 proof ethanol is fed to the 13th stage of the column, starting from the bottom.

[0086] The column is regulated by establishing a reflux ratio which is equal to 2.5 and controlling the base temperature to 211°C and the absolute pressure to 20 bar. The reflux stream is mostly ethanol with small amounts of acetaldehyde. Under stabilized conditions, a bottoms stream and a distillate stream are collected with respective throughputs of about 170 g/h and 4 g/h. The bottoms product gives ethyl acetate purity of 98.5% with small amounts of n-butyraldehyde and butan-2-one.

**Example 2**

Selective Hydrogenation of n-butyraldehyde and butan-2-one

[0087] Selective hydrogenation of n-butyraldehyde and butan-2-one in the presence of ethyl acetate was conducted over a hydrogenation catalyst. The reactor was filled with 20 g of 0.1 wt % Pd on silica catalyst. Before the selective hydrogenation reaction, the catalyst was reduced at a temperature of 250°C for 30 minutes. The catalyst reduction was conducted at atmospheric pressure by delivering hydrogen using a mass flow controller. At the end of this procedure the catalyst was fully reduced.

[0088] The bottoms product from the reactive distillation column whose composition is given in Table 2 was introduced to a heater at a rate of 30 g/h and mixed with hydrogen prior to admission to the selective hydrogenation reactor. The reaction product was cooled using a jacketed condenser and the liquid condensate was analyzed by gas chromatography. The results are summarized in Table 2, showing n-butyraldehyde and butan-2-one reduced to trace levels.

**TABLE 2**

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>93</td>
<td>92.9</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>n-propanol</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>n-butyraldehyde</td>
<td>1.5</td>
<td>trace</td>
</tr>
<tr>
<td>butan-2-one</td>
<td>0.5</td>
<td>trace</td>
</tr>
<tr>
<td>2-butanone</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>n-butanone</td>
<td>0</td>
<td>1.52</td>
</tr>
</tbody>
</table>

[0089] All patents and other references cited in the specification are indicative of the level of skill of those skilled in the art to which the invention pertains, and are incorporated by reference in their entireties, including any tables and figures, to the same extent as if each reference had been incorporated by reference in its entirety individually.

[0090] One skilled in the art would readily appreciate that the present invention is well adapted to obtain the ends and advantages mentioned, as well as those inherent therein. The methods, variances, and compositions described herein as presently representative of preferred embodiments are exemplary and are not intended as limitations on the scope of the invention. Changes therein and other uses will occur to those skilled in the art, which are encompassed within the spirit of the invention, are defined by the scope of the claims.

[0091] It will be readily apparent to one skilled in the art that varying substitutions and modifications may be made to the invention disclosed herein without departing from the scope and spirit of the invention. Thus, such additional embodiments are within the scope of the present invention and the following claims.

[0092] The invention illustratively described herein suitably may be practiced in the absence of any element or ele-
ments, limitation or limitations which is not specifically disclosed herein. Thus, for example, in each instance herein any of the terms “comprising,” “consisting essentially of” and “consisting of” may be replaced with either of the other two terms. The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention that in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention as defined by the appended claims.

[0093] In addition, where features or aspects of the invention are described in terms of Markush groups or other grouping of alternatives, those skilled in the art will recognize that the invention is also thereby described in terms of any individual member or subgroup of members of the Markush group or other group.

[0094] Also, unless indicated to the contrary, where various numerical values or value range endpoints are provided for embodiments, additional embodiments are described by taking any 2 different values as the endpoints of a range or by taking two different range endpoints from specified ranges as the endpoints of an additional range. Such ranges are also within the scope of the described invention. Further, specification of a numerical range including values greater than one includes specific description of each integer value within that range.

[0095] Thus, additional embodiments are within the scope of the invention and within the following claims.

1. A reactive distillation process producing high purity ethyl acetate from ethanol, comprising dehydrogenating ethanol over a catalyst in a reactive distillation column, wherein ethyl acetate is removed during said distillation process as a liquid bottoms product and hydrogen is removed during said distillation process as a gaseous top product.

2. The reactive distillation process of claim 1, further comprising hydrogenating contaminants in said liquid bottoms product and separating the hydrogenated contaminants from said ethyl acetate.

3. (canceled)

4. The reactive distillation process of claim 1, wherein said high purity ethyl acetate comprises at least 98% ethyl acetate.

5. The reactive distillation process of claim 1, wherein a single feed of ethanol is used.

6. The reactive distillation process of claim 5, wherein said reactive distillation column contains a generally central dehydrogenation catalyst zone and said single feed of ethanol is delivered into said column above or near the top of said catalyst zone.

7. The reactive distillation process of claim 5, wherein said reactive distillation column contains a generally central dehydrogenation catalyst zone and said single feed of ethanol is delivered into said column below or within said catalyst zone.

8. The reactive distillation process of claim 5, wherein said reactive distillation column contains a generally central dehydrogenation catalyst zone and said single feed of ethanol is delivered into said column at about the middle ½ of said catalyst zone.

9. The reactive distillation process of claim 6, wherein said dehydrogenation catalyst comprises a catalyst material selected from the group consisting of metals and/or oxides of copper, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, gold, thallium, manganese, aluminium, chromium, nickel, iron, molybdenum, and mixtures thereof.

10. The reactive distillation process of claim 9, wherein said catalyst material is on a support selected from the group consisting of carbon, alumina, silica, and titania.

11. The reactive distillation process of claim 5, further comprising a hydrogenation reactor comprising a hydrogenation catalyst, wherein n-butylaldehyde and butan-2-one, if present, are hydrogenated.

12. The reactive distillation process of claim 11, wherein said hydrogenation catalyst comprises a catalyst material selected from the group consisting of metals and/or oxides of nickel, palladium, platinum, ruthenium, iron, molybdenum, and mixtures thereof.

13. The reactive distillation process of claim 12, wherein said catalyst material is supported on a support material selected from the group consisting of carbon, alumina, silica, chromia and titania.

14. The reactive distillation process of claim 11, further comprising a separation column which receives product from said hydrogenation reactor, wherein n-butanol and 2-butanol are separated from ethyl acetate.

15. The reactive distillation process of claim 1, wherein dual feeds of ethanol and hydrogen are fed to said reactive distillation column, and wherein said ethanol feed is above said hydrogen feed.

16. The reactive distillation process of claim 15, wherein said reactive distillation column comprises a dehydrogenation catalyst zone and said ethanol feed is above or near the top of said dehydrogenation catalyst zone and said hydrogen feed is below or near the bottom of said dehydrogenation catalyst zone.

17. The reactive distillation process of claim 16, wherein said reactive distillation column further comprises a hydrogenation catalyst zone below said dehydrogenation catalyst zone, and said hydrogen feed is below, near the bottom of, or within said hydrogenation catalyst zone.

18. The reactive distillation process of claim 15, wherein the molar ratio of Ethanol:Hydrogen for the dual feed is from 1:10 to 1000:1.

19. The reactive distillation process of claim 1, wherein said reactive distillation is performed at a pressure from 1 bar to 50 bar.

20. The reactive distillation process of claim 1, wherein the number of stages or the number of height equivalents of a theoretical plate (HETP) is from 2 to 100.

21. A reactive distillation system for producing high purity ethyl acetate from ethanol, comprising a reactive distillation column comprising a dehydrogenation catalyst located generally centrally in said column; an ethanol feed which feeds ethanol into said column such that it passes over said dehydrogenation catalyst; a top product gaseous hydrogen removal passage; a bottoms product liquid ethyl acetate removal passage.

22. (canceled)

23. (canceled)
24. (canceled)
25. (canceled)
26. (canceled)
27. (canceled)
28. (canceled)
29. (canceled)
30. (canceled)
31. (canceled)
32. (canceled)
33. (canceled)
34. (canceled)
35. (canceled)
36. (canceled)
37. (canceled)
38. (canceled)
39. (canceled)
40. (canceled)
41. (canceled)
42. (canceled)
43. A reactive distillation process producing high purity methyl formate from methanol, comprising dehydrogenating methanol over a catalyst in a reactive distillation column, wherein methyl formate is removed during said distillation process as a liquid bottoms product and hydrogen is removed during said distillation process as a gaseous top product.

* * * * *
A reactive distillation method comprises introducing an feed stream comprising ethanol to a reactive distillation column, contacting the feed stream with a catalyst in the reactive distillation column during a distillation, where the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen, removing ethyl acetate during the distillation from the reactive distillation column as a bottoms stream, and removing hydrogen during the distillation from the reactive distillation column as an overhead stream.

Side reactor configuration (a) upward flow feed to side reactor (b) downward flow feed to side reactor.
Figure 1: Reactive residue curve maps at pressures of 1 atm and 5 atm.
Figure 2: Reactive residue curve maps at pressures of 10 atm and 20 atm.
Figure 3: Single feed reactive distillation column schematic.
Figure 4: Schematic for a reactive distillation system with subsequent product hydrogenation.
Figure 5: Double feed reactive distillation column schematic with an upper feed of ethanol and lower feed of hydrogen.
Figure 6: Double feed reactive distillation column schematic using dual catalyst beds with an upper feed of ethanol and lower feed of hydrogen.
Figure 7: Side reactor configuration (a) upward flow feed to side reactor (b) downward flow feed to side reactor.
Figure 8: Double Side reactor configuration (a) upward flow feed to multiple side reactors (b) downward flow feed to multiple side reactors.
Figure 10: Process configuration for product purification and ethanol recycle.
Figure 11: Indirect separation sequence for product purification and ethanol recycle.
ETHYL ACETATE PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] None.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

REFERENCE TO A MICROFICHE APPENDIX

[0003] Not applicable.

BACKGROUND

[0004] Ethyl acetate can be produced from several different reactions. The most common method for making ethyl acetate is the esterification of acetic acid and ethanol. This reaction requires two raw material supplies with the associated storage or production facilities. In locations without a sufficient supply of reliable, inexpensive acetic acid, this process may not be economically viable.

[0005] Ethyl acetate can also be produced from the oxidation of ethanol over supported precious metal catalysts. The high costs of precious metal catalyst can also make this option uneconomical. In addition, the oxidation of ethanol results in the presence of water in the product stream, which can result in a relatively expensive separation system to purify the product.

[0006] The Tishchenko reaction (dimerization of aldehydes into esters) is another alternative process for production of ethyl acetate. Dimerization of acetaldehyde results in ethyl acetate, however, aldol condensation also occurs, resulting in by-products such as 2-butanone and 2-propanol, both of which form azeotropes with ethyl acetate. In addition, the Tishchenko reaction requires a supply of acetaldehyde, which may not be readily available and can be difficult to store and handle due to its high toxicity.

SUMMARY

[0007] In an embodiment, a reactive distillation method comprises introducing an feed stream to a reactive distillation column, wherein the feed stream comprises ethanol, contacting the feed stream with a catalyst in the reactive distillation column during a distillation, wherein the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen, removing ethyl acetate during the distillation from the reactive distillation column as a bottoms stream, and removing hydrogen during the distillation from the reactive distillation column as an overhead stream. The method may also include contacting the bottoms stream with a hydrogenation catalyst and hydrogen to hydrogenate at least a portion of a contaminant in the bottoms stream, and separating the hydrogenated portion of the contaminant from the bottoms stream. The hydrogenation catalyst may comprise a Group VIII metal, a Group VI metal, or any combination thereof. The catalyst may comprise at least one catalytic component selected from the group consisting of: copper, copper oxide, barium, barium oxide, rhenium, rhenium oxide, rhodium, rhodium oxide, platinum, platinum oxide, palladium, palladium oxide, rhenium, rhenium oxide, silver, silver oxide, cadmium, cadmium oxide, zinc, zinc oxide, zirconium, zirconium oxide, gold, gold oxide, thallium, thallium oxide, magnesium, magnesium oxide, manganese, manganese oxide, aluminum, aluminum oxide, chromium, chromium oxide, nickel, nickel oxide, iron, iron oxide, molybdenum, molybdenum oxide, sodium, sodium oxide, sodium carbonate, strontium, strontium oxide, tin, tin oxide, and any mixture thereof. The catalyst may comprise a support, wherein the support comprises at least one support material selected from the group consisting of: carbon, silica, silica-alumina, alumina, zirconia, titania, ceria, vanadia, nitride, boron nitride, heteropolyacids, hydroxyapatite, zinc oxide, chromium, a zeolite, a carbon nanotube, carbon fullerene, and any combination thereof. The catalyst may comprise copper, and the catalyst may have a copper weight loading of between about 0.5% and about 80% of the catalyst.

[0008] The catalyst may comprise copper oxide and zinc oxide disposed on a support; copper oxide, zinc oxide, zirconium oxide, and aluminum; and/or copper oxide, zinc oxide, zirconium oxide, and chromium oxide. The catalyst may comprise an alkaline earth metal or alkaline earth metal oxide, copper or copper oxide, and a support. The catalyst may comprise sodium carbonate, and/or the catalyst may be at least partially reduced in the presence of hydrogen. A conversion of ethanol in the feed stream may be at least about 10%, and/or a selectivity of the conversion of ethanol to ethyl acetate may be at least about 60%. The method may also include removing a side stream from the reactive distillation column, and contacting the side stream with a second catalyst, wherein the side stream reacts in the presence of the second catalyst to produce ethyl acetate. A liquid portion of the feed stream may react in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen.

[0009] In an embodiment, a reactive distillation system comprises a reactive distillation column comprising: a dehydrogenation catalyst located generally centrally in the column, an ethanol feed in fluid communication with the reactive distillation column and configured to pass ethanol over the dehydrogenation catalyst, an overhead product hydrogen removal passage, and a bottoms product ethyl acetate removal passage. The reactive distillation system also comprises a product separation system comprising an inlet configured to receive the bottoms product from the reactive distillation column, an ethyl acetate product removal passage, and an ethanol removal passage; and a recycle line coupling the ethanol removal passage from the product separation system and an inlet to the reactive distillation column. The system may also include a hydrogenation catalyst positioned to contact a liquid product following passage over the dehydrogenation catalyst. The product separation system may also include at least one of a lights product removal passage or a heavy product removal passage. The reactive distillation column may comprise a batch reactor configured to contact a liquid ethanol feed with the dehydrogenation catalyst and remove hydrogen during the contacting of the liquid ethanol feed with the dehydrogenation catalyst.

[0010] In an embodiment, a reactive distillation method comprises introducing an feed stream to a reactive distillation column, wherein the feed stream comprises ethanol; contacting the feed stream with a catalyst in the reactive distillation column during a distillation, wherein the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen; separating bottoms stream during the distillation from the reactive distillation column.
column, wherein the bottoms stream comprises ethyl acetate and ethanol; separating a recycle stream from the bottoms stream, wherein the recycle stream comprises at least a portion of the ethyl acetate from the bottoms stream; and recycling the recycle stream to the reactive distillation column. The method may also include separating the bottoms stream into an overhead stream and the recycle stream at a first pressure, where the overhead stream comprises ethanol and ethyl acetate; and separating the overhead stream into an ethanol stream and an ethyl acetate product stream at a second pressure, where the second pressure is greater than the first pressure. The method may also include combining the ethanol stream with the bottoms stream in the separation of the bottoms stream into the overhead stream and the recycle stream. The method may also include separating at least one byproduct from the recycle stream after separation of the recycle stream from the bottoms stream and prior to recycling the recycle stream to the reactive distillation column. The method may also include separating the bottoms stream into a product stream and the recycle stream; and separating the product stream into a byproduct stream and an ethyl acetate product stream.

These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and the advantages thereof, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description.

FIG. 1 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 1 and 5 atmospheres (atm) for an embodiment.

FIG. 2 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 10 and 20 atm for an embodiment.

FIG. 3 shows a simplified schematic of a reactive distillation system according to an embodiment.

FIG. 4 shows a simplified schematic of a reactive distillation system according to another embodiment.

FIG. 5 shows a simplified schematic of a reactive distillation system according to still another embodiment.

FIG. 6 shows a simplified schematic of a reactive distillation system according to yet another embodiment.

FIGS. 7(a) and 7(b) shows a simplified schematic of a reactive distillation system according to an embodiment.

FIGS. 8(a) and 8(b) shows a simplified schematic of a reactive distillation system according to another embodiment.

FIG. 9 illustrates a schematic flow diagram of a reactive distillation system with a recycle according to an embodiment.

FIG. 10 illustrates a schematic flow diagram of a product separation system according to an embodiment.

FIG. 11 illustrates a schematic flow diagram of a product separation system according to another embodiment.

DETAILED DESCRIPTION

A reactive distillation system and process are disclosed herein for producing high purity ethyl acetate from ethanol. This process is beneficial as it provides an improved commercial method of upgrading ethanol to ethyl acetate, a more valuable product. This improved commercial process may be used where there is a supply and/or a surplus supply of ethanol. Further, this process reduces and/or eliminates the need for a separate acetaldehyde or acetic acid plant to provide the precursors for the ethyl acetate production process. The raw material may comprise only ethanol, which may present an advantage relative to other processes requiring multiple feedstocks. In addition, bio-derived ethanol may be used to allow the process to be operated from renewable ethanol sources. Further, the present system and method may utilize base-metal catalysts, which may be less expensive than the precious metal based catalysts of other ethyl acetate production routes. Such catalysts can comprise copper, and may be composed of copper oxide mixed with one or more additional metals and/or metal oxides. The present systems and methods may allow for a one-step ethyl acetate production process, which may be advantageous relative to other processes that require further steps to purify the ethyl acetate product, including a selective removal of 2-hexanone, which forms a low boiling azeotrope with ethyl acetate. Each of these advantages may be provided in a process that can also be less expensive than alternative processes by ethyl acetate production from ethanol.

In an embodiment, the present systems and methods can provide a route to ethyl acetate by dehydrogenation and dimerization of ethanol which is capable of yielding high purity ethyl acetate from ethanol feed streams containing significant amounts of impurities. One issue in the production of ethyl acetate by dehydrogenation of ethanol is that the reaction product mixture is commonly a complex mixture including esters, alcohols, aldehydes and ketones. From a distillation separation point of view, the mixture is further complicated due to the presence of azeotropes. The reaction product mixtures commonly contain components with boiling points close to ethyl acetate (such as n-butyraldehyde and/or butan-2-one), including components which can form azeotropes with ethyl acetate, and/or other components of the mixture. This may present a challenge when high purity ethyl acetate is desired.

In chemical processing, chemical reaction and the purification of the desired products by distillation may be carried out sequentially. The performance of this chemical process structure may be improved by the integration of reaction and distillation in a single multifunctional process unit. This integration concept is called “reactive distillation.” As advantages of this integration, chemical equilibrium limitations may be overcome, higher selectivities may be achieved, the heat of reaction can be used in situ for distillation, auxiliary solvents may be avoided, and/or azeotropic and/or closely boiling mixtures may be more easily separated. Increased process efficiency and reduction in overall capital costs may result from the use of this approach.

A reactive distillation system comprises at least one separator (e.g., a distillation tower) in which a reaction is occurring. In general, suitable separators may include any process equipment suitable for separating at least one inlet stream into a plurality of effluent streams having different compositions, states, temperatures, and/or pressures. For example, the separator may be a column having trays, packing, or some other type of complex internal structure. Examples of such columns include scrubbers, strippers, absorbers, adsorbers, and distillation columns having valve, sieve, or other types of trays. Such columns may employ weirs, downspouts, internal baffles, temperature control elements, and/or pressure control elements.
Such columns may also employ some combination of reflux condensers and/or reboilers, including intermediate stage condensers and reboilers. In an embodiment, the reactive distillation system described herein may comprise a distillation tower having at least one catalyst disposed therein.

[0028] As indicated above, the present systems and methods provide for the production of ethyl acetate from ethanol at a relatively low cost, along with a plant or distillation system with significantly reduced complexity using reactive distillation. The present disclosure further provides an improved process for the production of high purity ethyl acetate from ethanol, or from a feedstock comprising a major proportion of ethanol and a minor proportion of impurities such as isopropanol and iso-butanol. While not commonly present in ethanol feed streams, impurities that can poison the particular catalyst used should be limited, avoided and/or removed. For example, sulfur or nitrogen heterocyclic compounds can frequently act as catalyst poisons and, if present, should be removed before introducing the ethanol feed stream to the reactive distillation column. In an embodiment, the ethanol feed may comprise water. The presence of water in the ethanol feed does not severely reduce the performance of the catalysts, which can tolerate up to 5% water by weight in the ethanol. Ethanol conversion is reduced when using an ethanol source with significant water content, but the reaction selectivity increases. The use of an ethanol feed comprising a small amount of water may be advantageous by allowing for the use a potentially less expensive ethanol source in the form of the ethanol/water azeotrope (about 4.4% water by weight). The effects of water in the feed are demonstrated in the Examples described herein.

[0029] Ethyl acetate can be produced from ethanol according to the following reactions:

\[ \text{C}_2\text{H}_5\text{OH} \rightarrow \text{CH}_2\text{CHOH} \]  

(Eq. 1)

\[ \text{CH}_2\text{CHO}+\text{C}_2\text{H}_5\text{OH} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5+\text{H}_2 \]  

(Eq. 2)

[0030] In an embodiment, ethanol reacts in a single continuous reactive distillation column which provides sufficient residence time to achieve a relatively high conversion of ethanol. In an embodiment, the reactive distillation column may be configured to provide a conversion of ethanol of at least about 10% and a selectivity of at least about 60%, as described in more detail herein. Table 1 shows the effect of pressure on the boiling point of the pure components and azeotrope in the mixture. The azeotrope between ethanol and ethyl acetate is substantially avoided above a pressure of 13 atm.

![Table 1: Boiling point of reaction components.](data:image/png;base64,.ascii_img)

<table>
<thead>
<tr>
<th>Component</th>
<th>P = 1 atm</th>
<th>P = 5 atm</th>
<th>P = 10 atm</th>
<th>P = 20 atm</th>
<th>P = 30 atm</th>
<th>P = 40 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>-161</td>
<td>-137.6</td>
<td>-123.7</td>
<td>-106.5</td>
<td>-94.3</td>
<td>-84.5</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>20.4</td>
<td>71.9</td>
<td>101.1</td>
<td>136.4</td>
<td>160.7</td>
<td>180</td>
</tr>
<tr>
<td>Ethanol</td>
<td>78.3</td>
<td>125.2</td>
<td>150.2</td>
<td>179</td>
<td>198</td>
<td>212.7</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>77.4</td>
<td>136.6</td>
<td>160.6</td>
<td>210.3</td>
<td>236.4</td>
<td>250.7</td>
</tr>
<tr>
<td>Ethanol/Ethyl acetate azeotrope</td>
<td>71.7</td>
<td>123.5</td>
<td>150.1</td>
<td>No Azeotrope</td>
<td>No Azeotrope</td>
<td>No Azeotrope</td>
</tr>
</tbody>
</table>

[0031] Residue curve maps can be used to indicate feasible product compositions for distillation columns. In the presence of reaction along with separation, reactive residue curve maps can be used to determine feasible products from a reactive distillation column. Reactive residue curve maps at a pressure of 1 atm and 5 atm respectively are shown in FIG. 1. The stable nodes in the diagram are ethanol and ethyl acetate, and, therefore, it is possible to design a reactive distillation column where either ethanol or ethyl acetate can be obtained as the bottoms product. Hydrogen is an unstable node in the diagram and can be obtained as the distillate. Acetaldehyde and the ethanol/ethyl acetate azeotrope are saddle points in the diagram.

[0032] Reactive residue curve maps at pressures of 10 atm and 20 atm respectively are shown in FIG. 2. The reactive residue curve maps for any pressure above 20 atm substantially similar to the reactive residue curve map at 20 atm.

[0033] In view of the reactive residue maps discussed above, a set of reactive distillation systems effective to produce high purity ethyl acetate from ethanol have been designed. The reactive distillation column can have single or multiple feed locations.

Reactive Distillation Column Configurations

[0034] The present systems and methods provide a reactive distillation system in which ethanol may be the sole or primary component of the feed. In some embodiments, the ethanol feed is used in conjunction with a separate, second feed of hydrogen. Reference to a “single feed” to a reactive distillation column means that the column has only one chemical feed stream supplying intended reactant(s) to the column. Nonetheless, such a single feed distillation column may have multiple entry points for the reactant, or recycling feed streams where a part of the reactant liquid or a partial distillate is drawn from the column and fed back into the column at a different point, e.g., to achieve improved separation and/or more complete reaction. A “single ethanone feed” this refers to a single feed stream, in which ethanol is the sole or at least the primary constituent. In contrast, the term “dual feed” in the context of a distillation column refers to two separate chemical feed streams. For example, in some of the present embodiments, dual feeds are an ethanol feed and a separate hydrogen feed. The term “reactive distillation column” is used conventionally to refer a to distillation column in which both reaction and separation is performed. In this case, the primary and desired reaction is the conversion of two ethanol molecules to one ethyl acetate molecule with release of two hydrogen

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molecules. Thus, the present invention provides systems and methods for the production of ethyl acetate from ethanol which includes reacting ethanol over a suitable dehydrogenation and/or dimerization catalyst in a reactive distillation column, thereby producing ethyl acetate and hydrogen.

[0035] In an embodiment, a single reactive distillation column is used. Hydrogen gas is removed (e.g., continuously) from the top of the reactive distillation column as an overhead stream. Ethyl acetate is removed (e.g., continuously) from the bottom of the column as bottoms stream. Optionally, contaminating byproducts present following reaction of the ethanol over the dehydrogenation catalyst can be reacted over a suitable hydrogenation catalyst in the lower part of the column or in a separate hydrogenation reactor. The hydrogenation can convert difficult to separate byproducts into species which are easier to separate from the ethyl acetate. Consequently, the process can also include purifying the ethyl acetate by distilling out resulting hydrogenated byproducts.

[0036] In an embodiment, the reactive distillation column is configured for the dehydrogenation of ethanol with the formation of ethyl acetate. The reaction is accomplished by passing the ethanol feed stream over a dehydrogenation catalyst under conditions where ethyl acetate is formed and hydrogen and ethyl acetate are withdrawn as top and bottoms products respectively. Such products draw drive the thermodynamics of the process toward the desired products. In its simplest form, a reactive distillation system may comprise a reactor vessel operating with a liquid phase reaction in which hydrogen and/or other light gases are removed as the overhead product and a reaction product is removed as the bottoms product. Such a system may comprise a batch reactor in which hydrogen is removed during the reaction and the liquid product is removed after completion of the reaction to a desired degree of conversion.

[0037] In an embodiment of a reactive distillation column, a reactive distillation column with a single feed of ethanol as shown schematically in FIG. 3 can produce hydrogen as a distillate and ethyl acetate as a bottoms product. Column 10 contains a generally central catalyst zone 12, and usually will include a top stage or non-reactive rectifying section 13 and a bottom stage or non-reactive stripping section 15. Ethanol feed 14 is commonly led to the middle part of the reactive distillation column. Distillate removed at the top of the column is passed through a partial condenser 16, and hydrogen is separated from lower boiling constituents in reflux tank 18. The hydrogen may leave the system as an overhead product stream 19, which in an embodiment may comprise trace amounts of additional components including ethanol, ethyl acetate, and/or one or more reaction byproducts. The condensed lower boiling constituents (i.e., reflux), or at least some portion thereof, can be cycled back to the column for further reaction and/or separation. The bottoms product can be passed through reboiler 20, where a portion of the bottoms product is evaporated and added back to the bottom of the column. The remaining bottoms product may pass out of the system as product stream 22. Alternatively, only a portion of the bottoms product may be passed through reboiler 20, with the vapor portion passing back to the bottom of the column and the remainder of the bottoms product being combined with any bottoms product bypassing the reboiler 20 and passing out of the system as product stream 22 for further processing and/or use as a final product. The product stream 22 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction. The column reflux and reboil ratios are maintained such that essentially pure ethyl acetate is obtained as the bottoms product. In an embodiment, the bottoms product stream 22 may comprise greater than about 99%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

[0038] During operation, the reactants and products flow through the reactor/column reacting and flashing along the length of the reactor/column. In an embodiment, the reaction of the reactants and/or products may occur in the catalyst zone 12, and the reactions may occur in the vapor and/or liquid phase. Specific catalysts useful in the reactive distillation systems and methods disclosed herein are discussed in more detail below. Ethyl acetate and hydrogen are produced due to the reaction over the dehydrogenation and dimerization catalyst. Acetaldehyde may also be produced during the reaction if the conversion of acetaldehyde to ethyl acetate is incomplete. The removal of the overhead stream 19 comprising hydrogen, which may occur by flashing, increases the extent of reaction. In general, the hydrogen concentration increases from the middle part of the column towards the top of the column. At pressures of about 13 bar or lower, as ethyl acetate is formed from the reactants, an azetrope between ethyl acetate and ethanol occurs. This azetrope may result in the overhead product 19 that leaves the top of the reactive distillation column 10 containing ethanol/ethyl acetate and/or acetaldehyde in addition to hydrogen. A partial condenser 16 allows hydrogen to be removed as a distillate, while acetaldehyde and ethanol are recycled back to the top of the reactive distillation column. At a pressure above about 13 atm, the ethyl acetate and ethanol azetrope disappears, which improves the operation of the reactive distillation column.

[0039] The column 10 can be operated at any suitable pressure between about 1 atm and about 80 atm. In an embodiment, the column 10 may be operated at a pressure ranging from about 1 atm to about 5 atm, about 5 atm to about 10 atm, about 7 atm to about 12 atm, about 13 atm to about 15 atm, about 13 atm to about 20 atm, about 15 atm to about 20 atm, about 15 atm to about 30 atm, about 20 atm to about 30 atm, about 20 atm to about 50 atm, about 30 atm to about 40 atm, about 40 atm to about 50 atm, or about 50 atm to about 60 atm, about 60 atm to about 70 atm, about 60 atm to about 80 atm, or about 70 atm to about 80 atm. In an embodiment, the reactive distillation is performed at a pressure where ethanol/ethyl acetate azetrope is not present. The temperature profile in the column is dictated by the mixture boiling point along the height of the column. In an embodiment the temperature within the column may range from about 100 °C to about 350 °C, alternatively about 150 °C to about 250 °C. The column 10 may comprise any number of stages equivalent to a number of theoretical stages sufficient to effect the reaction and separation of ethyl acetate to a desired purity. In an embodiment, the number of stages or the number of height equivalents of a theoretical plate (HETP) may range from about 1 to about 100, including for example from about 1 to about 10, about 10 to about 20, about 10 to about 50, about 20 to about 30, about 20 to about 70, about 30 to about 40, about 30 to about 50, about 30 to about 100, about 50 to about 70, about 50 to about 100, or about 70 to about 100. As described in more detail below, a relatively high conversion of ethanol to products can be achieved by the counter-current flow of reactants and products in addition to overcoming the reaction.
equilibrium by removal of products through the concurrent distillation within the column 10. In an embodiment, the systems and methods may also include hydrogenation contaminants or reaction byproducts in the bottoms stream or in the reactant fluid after it has passed over the dehydrogenation catalyst and separating the hydrogenated contaminants or byproducts from the ethyl acetate. Aldehydes and/or ketones such as n-butyraldehyde and butan-2-one may be produced as byproducts in the reaction. These byproducts boil at temperatures close to the boiling point of ethyl acetate and may be difficult to separate from ethyl acetate. FIG. 4 shows a process schematic where the bottoms product 22 from the reactive distillation column 10 is sent to a hydrogenation reactor 24 comprising a hydrogenation catalyst 26 with a hydrogen co-feed 28. Suitable hydrogenation catalyst(s) may comprise various components and are described in more detail herein. At least a portion of the n-butyraldehyde and/or butan-2-one impurities can be hydrogenated and can then be separated using a separator 32. The separator 32 may comprise any of the types of separators described herein with respect to the reactive distillation system. Alternatively or in combination with the separators already described, the separator 32 may be a phase separator, which is a vessel that separates an inlet stream into a substantially vapor stream and a substantially liquid stream, such as a knock-out drum, flash drum, reboiler, condenser, or other heat exchanger. Such vessels also may have some internal baffles, temperature control elements, and/or pressure control elements, but generally lack any trays or other type of complex internal structure commonly found in columns. The separator also may be any other type of separator, such as a membrane separator. In a specific embodiment, the separator is a knockout drum. Finally, the separator may be any combination of the aforementioned separators arranged in series, in parallel, or combinations thereof. In an embodiment, separator 32 comprises a distillation column. The outlet of the hydrogenation reactor 24 may be passed through a heat exchanger 30 (e.g., a condenser) and cooled before entering the separator 32. The heat exchanger 30 may be any equipment suitable for heating or cooling one stream using another stream. Generally, the heat exchanger 30 is a relatively simple device that allows heat to be exchanged between two fluids without the fluids directly contacting each other. Examples of suitable heat exchangers 30 include, but are not limited to, shell and tube heat exchangers, double pipe heat exchangers, plate fin heat exchangers, bayonet heat exchangers, reboilers, condensers, evaporators, and air coolers. In the case of air coolers, one of the fluids comprises atmospheric air, which may be forced over tubes or coils using one or more fans.

The bottoms product stream 36 from the separator 32 may comprise ethyl acetate and may have a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight. Unconverted hydrogen and the hydrogenated byproducts may be removed as an overhead product 34, and may be used, for example, as fuel or a feed to one or more processes. In an embodiment, the separator 32 may be operated between a pressure of 1 atm and 80 atm.

In an embodiment, the bottoms product stream 36 may pass to another separator 38 to separate the bottoms product stream into an ethyl acetate stream and a byproduct stream comprising one or more heavier hydrogenation products produced in the hydrogenation reactor 26. This separation scheme may allow the resulting ethyl acetate stream to have a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

In another embodiment of the invention, the reactive distillation column has two feeds. Ethanol may be fed to the upper part of the column (upper feed), and hydrogen may be fed to the lower part of the column (lower feed). A schematic for the double feed reactive distillation column is schematically illustrated in FIG. 5. This system includes column 40 containing catalyst 42 in catalyst zone 44, and commonly may include a top stage or non-reactive rectifying section 50 and a bottom stage or non-reactive stripping section 52. In the illustrated system, ethanol feed 46 is delivered at or near the top of the catalyst zone 44, and the hydrogen feed 48 is delivered at or near the bottom of catalyst zone 44. It should be recognized columns can be designed with the ethanol feed 46 location in other locations, e.g., within the catalyst zone 44 but above the hydrogen feed 48, such as from the approximate middle of the catalyst zone 44 to the top of the column 40. Similarly, columns with the hydrogen feed 48 in other locations can also be designed, e.g., with the hydrogen feed 48 from the approximate middle of the catalyst zone 44 to the bottom of the column 40 or even higher within the catalyst zone 44 but below the ethanol feed 46. In an embodiment, the ethanol feed 46 and the hydrogen feed 48 are separated sufficiently to allow byproduct hydrogenation to be substantially completed before hydrogen from the feed reaches substantial concentrations of ethanol being dehydrogenated. Ethanol reacts over the catalyst producing ethyl acetate and hydrogen. Examples of suitable dehydrogenation and dimerization catalysts are described in more detail herein.

Due to boiling point differences, hydrogen moves towards the top of the column 40 and ethyl acetate moves towards the bottom of the column 40. Acetaldehyde may be produced during the reaction and may move up in the column 40. At least a portion of the acetaldehyde, if present, can be condensed in condenser 54 (e.g., a partial condenser, or a total condenser), passed through reboiler tank 56, and recycled back to column 40 as reflux. A product stream 59 comprising hydrogen is taken out as distillate from the reflux tank 56. A part of the bottom draw is taken out as the ethyl acetate product stream 58, while the remaining part is passed through reboiler 60 to be recycled to the column 40. In an embodiment, the bottom draw may be passed through a reboiler (e.g., similar to reboiler 60) and optionally passed to a separator where the vapor portion may pass to the column 40 while at least a portion of the remainder is taken out as the ethyl acetate product stream 58. The stream passing through the reboiler 60 provides the evaporation effect and vapor flow for operating the column 40. The product stream 58 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction. Byproducts such as n-butyraldehyde and butan-2-one produced in the reaction may have boiling points close to the boiling point of ethyl acetate. The lower hydrogen feed 48 is useful in hydrogenating the by-products to produce components that can be separated easily from ethyl acetate. The ratio of the hydrogen feed to the ethanol feed can beneficially be adjusted to minimize the amount of close boiling byproducts, while not excessively reducing ethyl acetate to ethanol. In an embodiment, the molar ratio of ethanol to hydrogen ranges from about 1:10 to about 1000:1, e.g., from about 1:10
to about 1:1, from about 1:1 to about 5:1, from about 1:1 to about 10:1, from about 5:1 to about 25:1, from about 5:1 to about 50:1, from about 10:1 to about 50:1, from about 10:1 to about 100:1, from about 50:1 to about 200:1, from about 50:1 to about 400:1, from about 100:1 to about 500:1, from about 100:1 to about 1000:1, or from about 500:1 to about 1000:1. Hydrogen product from the reaction leaves at the top of the column. In an embodiment, the column 40 may operate at any of the conditions (e.g., operating pressure, operating temperature, etc.) discussed herein with respect to column 10 in FIG. 3. In addition, the column 70 may have any number of stages, and in an embodiment have any number of stages as described with respect to column 10 in FIG. 3.

[0046] As schematically illustrated in FIG. 6, the reactive distillation column 70 has two feeds 80, 82 and uses two catalyst zones, identified as an upper zone 72 containing Catalyst A 74 and a lower catalyst zone 76 containing Catalyst B 78. Ethanol feed 80 is fed to the upper part of the column 70 (upper feed). Hydrogen feed 82 is fed to the lower part of the column 70 (lower feed). The molar ratio of ethanol to hydrogen may fall within any of the ranges described above with respect to FIG. 5 (e.g., from about 1:10 to about 1000:1, and all sub-ranges). Ethanol may react over the upper catalyst (Catalyst A 74) producing ethyl acetate and hydrogen. Examples of suitable upper catalysts are described in more detail herein with respect to the dehydrogenation and dimerization catalysts. As with previous schematic designs shown, the column 70 will usually include a top stage or non-reactive rectifying section 71 and a bottom stage or non-reactive stripping section 79.

[0047] Due to boiling point differences, hydrogen moves towards the top of the column 70 and ethyl acetate moves towards the bottom of the column 70. Acetaldheyde may be produced during the reaction and may move up in the column 70. At least a portion of the acetaldheyde, if present, can be condensed in condenser 84 and recycled back to the reaction zone through reflux tank 86. Byproducts such as n-butyaldehyde and butan-2-2zone produced in the reaction can have boiling points close to the boiling point of ethyl acetate. The lower hydrogen feed is useful in hydrogenating the by-products over the lower catalyst (Catalyst B) to produce components that can be separated easily from ethyl acetate. Examples of hydrogenation catalysts (Catalyst B) are described in more detail herein. A product stream 88 comprising hydrogen from the reaction leaves at the top of the column 70. A portion of the bottom draw is taken out as the ethyl acetate product stream 92, while the remaining portion is passed through reboiler 90 to be recycled to the column 70. In an embodiment, the bottom draw may be passed through a reboiler (e.g., similar to reboiler 90) and optionally passed to a separator where the vapor portion may pass to the column 70 while at least a portion of the remainder is taken out as the ethyl acetate product stream 92. The stream passing through the reboiler 90 provides the evaporation effect and vapor flow for operating the column 70. The product stream 92 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction. Subsequent purification of product stream 92 comprising ethyl acetate may be needed to remove the hydrodimerized byproducts from the ethyl acetate, e.g., using a separator such as that shown in FIG. 4 as separator 32, which in an embodiment may comprise a distillation column.

[0048] In an embodiment, the column 70 may operate at any of the conditions (e.g., operating pressure, operating temperature, etc.) discussed herein with respect to column 10 in FIG. 3. In addition, the column 70 may have any number of stages, and in an embodiment have any number of stages as described with respect to column 10 in FIG. 3.

[0049] In the dual feed systems described above with respect to FIGS. 5 and 6, the hydrogen feed should be at a sufficiently low level that it does not significantly adversely affect the dehydrogenation of ethanol in the zone above, while being effective to hydrogenate the undesirable close boiling point byproducts. Feed rates of hydrogen can be adjusted empirically to optimize this balance. Commonly, the ratio of ethanol:hydrogen will be in a range of about 500:1 to 1:1 molar ratio, more commonly about 500:1 to 10:1 or 500:1 to 100:1.

[0050] In an embodiment, side reactors can be connected to a reactive distillation column to increase the catalyst holdup for improved reactant conversion. In the side reactor embodiment, the side reactor feed is withdrawn from the distillation column and the reactor effluent is returned back to the same column. An adequate amount of catalyst may be arranged in a side reactor system where traditional reactor types and catalyst structures can be used. Also, the reaction conditions within the side reactor such as temperature can be adjusted independently of those prevailing in the distillation column by appropriate heat exchange.

[0051] Schematics for a side reactor reactive distillation column with a single catalyst are shown in FIG. 7. A single side reactor is shown, however, multiple side reactors along the length of the reactive distillation column can be used. FIG. 7(a) shows a configuration where the feed 93 to the side reactor 94 is bottom up and vapor phase. The outlet from side reactor 94 is stream 95 which is sent back to the distillation column 40 at any location in the column 40 above the location of feed 93. FIG. 7(b) shows a configuration where the feed 96 to the side reactor 97 is in top down and liquid phase. The outlet from side reactor 97 is stream 98 which is sent back to the distillation column 40 at any location in the column 40 below the location of feed 96. The side reactors 94 and 97 each contain catalyst for converting ethanol into ethyl acetate. Examples of suitable catalysts are described in more detail herein.

[0052] The use of a side reactor using a liquid feed may allow for the reaction to occur in the liquid phase. While not intending to be limited by theory, it is believed that the dehydrogenation dimerization of ethanol to ethyl acetate may occur over the dehydrogenation and dimerization catalysts described herein in the liquid phase. It has not been previously recognized that the dehydrogenation and dimerization conversion of ethanol to ethyl acetate would occur in the liquid phase. The use of a liquid phase reaction may allow for reactive distillation to be effectively used for converting ethanol into ethyl acetate and hydrogen.

[0053] While illustrated as a bottom up vapor phase design and a top down liquid phase design in FIGS. 7(a) and 7(b), the side reactors 94, 97 may also operate bottom up using a liquid phase draw from the column 40 and top down using a vapor phase draw from the column with the appropriate equipment such as pumps, compressors, valves, piping, etc. In an embodiment, the side reactors 94, 97 may be implemented as a single reactor vessel, or as a plurality of reactor vessels arranged in series and/or parallel. In an embodiment, a plurality of side reactors may be implemented as shown in FIGS. 7.
7(a) and 7(b) along the length of the column as needed. In addition, the catalyst in both the column 40 and the side reactor 94 may convert ethanol into ethyl acetate, though the specific catalysts (e.g., catalyst compositions, catalyst forms, and/or catalyst component loadings) in each of the column 40 and the side reactor 94, 97 may be the same or different. Suitable catalysts for converting ethanol into ethyl acetate may be selected based on the expected operating conditions, which may vary between the column 40 and the side reactor 94, 97.

[0054] Schematics for a side reactor reactive distillation with two feeds and using two distinct catalyst zones are shown in FIG. 8. A single side reactor is shown for each catalyst zone in the reactive distillation column 70; however, multiple side reactors along the length of the reactive distillation column 70 can be used for each catalyst zone. FIG. 8(a) shows a configuration where the top zone feed 99 to the side reactor 100 is bottom up and vapor phase. The bottom zone feed 102 to another side reactor 103 is also bottom up and vapor phase. The outlet from side reactor 100 is stream 101 which is sent back to the distillation column at any location in the column above the location of feed 99. The outlet from side reactor 103 is stream 104 which is sent back to the distillation column at any location in the column above the location of feed 102. FIG. 8(b) shows a configuration where the top zone feed 105 to the side reactor 106 is top down and liquid phase. The bottom zone feed 108 to another side reactor 109 is also top down and liquid phase. The outlet from side reactor 106 is stream 107 which is sent back to the distillation column at any location in the column below the location of feed 105. The outlet from side reactor 109 is stream 110 which is sent back to the distillation column at any location in the column below the location of feed 108. Examples of suitable catalysts for side reactors 100 and 106 may include methanol or any of the dehydrogenation and dimerization catalysts described in more detail herein. Examples of hydrogenation catalysts for side reactors 103 and 109 include any of the hydrogenation catalysts described in more detail herein.

[0055] While illustrated as a bottom up vapor phase design and a top down liquid phase design in FIGS. 8(a) and 8(b), the side reactors 100, 103, 106, 109 may also operate bottom up using a liquid phase draw from the column 70 and top down using a vapor phase draw from the column 70 with the appropriate equipment such as pumps, compressors, valves, piping, etc. In an embodiment, the side reactors 100, 103, 106, 109 may be implemented as a single reactor vessel, or as a plurality of reactor vessels arranged in series and/or parallel. In an embodiment, a plurality of side reactors may be implemented as shown in FIGS. 8(a) and 8(b) along the length of the column as needed. In addition, the respective catalysts in both the column 70 and the side reactors 100, 106 may convert ethanol into ethyl acetate, though the specific catalysts (e.g., catalyst compositions, catalyst forms, and/or catalyst component loadings) in each of the column 40 and the side reactors 100, 106 may be the same or different. Suitable catalysts for converting ethanol into ethyl acetate may be selected based on the expected operating conditions, which may vary between the column 40 and the side reactors 100, 106. Similarly, the respective catalysts in both the column 70 and the side reactors 103, 109 may comprise hydrogenation catalysts (e.g., catalyst compositions, catalyst forms, and/or catalyst component loadings) in each of the column 70 and the side reactors 103, 109 may be the same or different. Suitable hydrogenation catalysts may be selected based on the expected operating conditions, which may vary between the column 70 and the side reactors 100, 106.

[0056] As schematically illustrated in FIG. 9, an ethyl acetate production process may comprise a products separation section for use in separating the product stream and allowing at least a portion of any unreacted ethanol to be recycled to the inlet of the process. The products separation section may be configured to provide at least one product stream comprising ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight. At least one additional stream may be produced comprising the remaining components of the product stream from the reactive distillation column. In an embodiment, a plurality of streams are produced in the separation section comprising a stream predominantly comprising ethyl acetate, a stream comprising hydrogen, a stream comprising ethanol, and/or a heavies stream comprising one or more reaction products with boiling points above the boiling point of ethyl acetate. In an embodiment, the stream comprising ethyl acetate may be recycled to the reactive distillation column. In an embodiment, at least a portion of the stream comprising hydrogen may be recycled to the reactive distillation column to provide at least a portion of the hydrogen feed.

[0057] As schematically illustrated in FIG. 9, a system 200 for producing ethyl acetate may comprise a feed stream 202 comprising ethanol that may be combined with a recycle stream 220 comprising ethanol to form the inlet stream 204 to the reactive distillation system 206. The system 200 may be useful for embodiments in which there is an incomplete conversion of ethanols in the reactive distillation system 208. While illustrated as being combined prior to introduction to the reactive distillation system 206, the feed stream 202 and the recycle stream 220 may be fed individually to the reactive distillation system 206. In an embodiment, the reactive distillation system 206 may comprise any of the reactive distillation systems described with respect to FIG. 3-8 herein. The reactive distillation system may produce an overhead product stream 208 and a bottoms product stream 210. The overhead product stream 208 may comprise hydrogen and may generally correspond to any of the streams 19, 59, and/or 88 as illustrated in FIGS. 3-8. Similarly, the bottoms product stream 210 may comprise ethyl acetate and at least a portion of any unreacted ethanol and/or additional reaction products, and the bottoms product stream 210 may generally correspond to any of the streams 22, 23, 24, 25, 26, 27, and/or 92 as illustrated in FIGS. 3-8.

[0058] A products separation section 212 may receive the bottoms product stream 210 from the reactive distillation system 206, and, in some embodiments, the overhead product stream 208. The products separation section 212 may comprise any number or type of separation units, which may employ pressure- or temperature-swing distillation, pressure-swing adsorption, membrane-based separation, cryogenic distillation, and/or any other suitable separation technology, all of which may be used to generate a desired product distribution. The products separation section 212 may generally produce an ethyl acetate product stream 216. The ethyl acetate product stream 216 may comprise ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%,

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or greater than about 99.5% ethyl acetate by weight. In addition to the ethyl acetate product stream 216, one or more additional streams may be produced by the product's separation section 212. In an embodiment, a lights product stream 214 may be produced. The lights product stream 214 may comprise hydrogen and minor amounts of ethanol and/or other light components. In an embodiment, a heavies product stream 218 may comprise one or more reaction products (e.g., butanol, one or more aldehydes and/or ketones, etc.). In an embodiment, a recycle stream 220 may be produced. The recycle stream may comprise ethanol for use as a feed for the reactive distillation system 206. In some embodiments, the ethanol stream may not be recycled to the reactive distillation system, but rather may exit the system 200 as a separate product stream. Each of the potential product streams 214, 216, 218, and/or 220 may exit the system as separate product stream and/or exit the system 200 for use as fuel and/or as a feed to additional downstream processes. While illustrated as separate streams 214, 216, 218, and/or 220, one or more of these streams may exit the system 220 as a combined product stream.

In an embodiment illustrated in FIG. 10, a product separation system may comprise a plurality of separation units coupled to the reactive distillation system 113. In this embodiment, the reactive distillation system 113 may be the same or similar to the reactive distillation system 206 described above with respect to FIG. 9. A feed stream 111 comprising ethanol enters the reaction distillation system 113 along with a recycle stream 127. A product stream may be produced from the reactive distillation system 113 and cooled in heat exchanger 114. Stream 112 contains light boiling components such as H₂ and may pass out of the reactive distillation system 113. Heat exchanger 114 may comprise any of the heat exchanger types described herein. The product stream passing out of the heat exchanger 114 may pass to separator 117. The separator 117 may comprise any of the types of separators described herein, and in an embodiment, may comprise a phase separator of any of the types described herein. The separator 117 may produce a vapor stream 115 and a liquid stream 116. Vapor stream 115 predominantly comprises hydrogen, and the liquid stream 116 comprises higher boiling components. The separator 117 may operate at a pressure ranging from about 1 atm to about 80 atm.

The liquid stream 116 passes to separator 120. Separator 120 may comprise any of the types of separators described herein, and, in an embodiment, comprises a distillation column. The separator 120 may generally operate at a pressure of between about 1 atm to about 50 atm, and in an embodiment, may operate at a pressure of less or equal to about 5 atm. In an embodiment, separator 120 operates at a pressure below the pressure of separator 122 as described below. The temperature profile in the column may be dictated by the mixture boiling point along the height of the column. The separator 120 may separate the liquid stream 116 into an overhead stream and a bottoms stream 119. The overhead stream may pass through a heat exchanger and separator to produce a vapor overhead stream 121 and a liquid overhead stream 118. The vapor overhead stream 121 may comprise hydrogen and ethanol. The vapor overhead stream 121 can be used as fuel within the system, and/or the overhead stream 121 can be recycled within the system for use as a feed to the reactive distillation system 113. The liquid overhead stream 118 may predominantly comprise ethanol and ethyl acetate. The bottoms stream 119 may predominantly comprise ethano-

ol in addition to minor amounts of ethyl acetate, butanol, and/or additional reaction products.

Bottoms stream 119 may pass to separator 125. Separator 125 may comprise any of the separators described herein, and, in an embodiment, separator 125 comprises a distillation column. Separator 125 may separate the bottoms stream 119 into an overhead stream 127 comprising ethanol and a bottoms stream 126 comprising the higher boiling components including butanol. Overhead stream 127 may be recycled to the reactive distillation system 113 for use as a feed to the ethyl acetate production system. The bottoms stream 126 may exit the system for use as fuel, as a final product, and/or as a feed to one or more suitable downstream processes.

The liquid overhead stream 118 from separator 120 may pass to separator 122. Separator 122 may comprise any of the separators described herein, and, in an embodiment, comprises a distillation column. Separator 122 may operate at a higher pressure than separator 120. In an embodiment, separator 122 may operate a pressure of greater than about 160%, greater than about 200%, greater than about 250%, greater than about 300%, greater than about 400%, greater than about 500%, greater than about 600%, or greater than about 700% of the pressure of separator 120. In an embodiment, separator 122 may operate between about 8 atm and 80 atm, including between about 8 atm and about 20 atm, between about 15 atm and about 40 atm, between about 35 atm and about 60 atm, or between about 50 atm and about 80 atm. The increased operating pressure of separator 122 relative to separator 120 may provide for an improved separation of the components in the liquid overhead stream 118. Separator 122 may separate the liquid overhead stream 118 into an overhead stream 123 and a bottoms stream 124. Overhead stream 123 may comprise ethanol, ethyl acetate, and/or acetaldehyde in addition to other reaction products. Overhead stream 123 may pass back to separator 120 for further separation of the components. The bottoms stream 124 may comprise ethyl acetate as a product stream. In an embodiment, the bottoms stream 124 may comprise greater than about 90%, greater than about 95%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

The product separation system illustrated in FIG. 10 produces an ethyl acetate product stream 124, a first lights product stream 111, a second lights product stream 115, a third lights product stream 121, a heavies product stream 126, and a recycle stream 127 comprising ethanol. Some portion of the lights streams 111, 115, 121 may be recycled back to the reactive distillation system 113 for use as a hydrogen and/or ethanol feed. While illustrated as a separate feed to the reactive distillation system, the recycle stream 127 may be combined with the feed stream 111 comprising ethanol prior to the combined stream entering the reactive distillation system 113.

In an embodiment illustrated in FIG. 11, another product separation system may comprise a plurality of separation units coupled to a reactive distillation system 129. In this embodiment, the reactive distillation system 129 may be the same or similar to the reactive distillation system 206 described above with respect to FIG. 9. A feed stream 128 comprising ethanol enters the reaction distillation system 129 along with a recycle stream 141. Stream 140 contains light boiling components such as H₂ and may pass out of the reactive distillation system 129. A product stream may be
separated from the reactive distillation system 129 and cooled in heat exchanger 130. Heat exchanger 114 may comprise any of the heat exchanger types described herein. The product stream passing out of the heat exchanger 130 may pass to separator 133. The separator 133 may comprise any of the types of separators described herein, and in an embodiment, may comprise a phase separator of any of the types described herein. The separator 133 may separate the product stream into a vapor stream 131 and a liquid stream 132. Vapor stream 131 may predominantly comprise hydrogen, and the liquid stream 132 may comprise higher boiling components. The separator 133 may operate at a pressure ranging from about 1 atm to about 80 atm.

The liquid stream 132 passes to separator 134. Separator 134 may comprise any of the types of separators described herein, and, in an embodiment, comprises a distillation column. The separator 134 may generally operate at a pressure of between about 1 atm to about 80 atm, and the temperature profile in the column may be dictated by the mixture boiling point along the height of the column. The separator 134 may separate the liquid stream 132 into an overhead stream and a bottoms stream 119. The overhead stream may pass through a heat exchanger and separator to produce a vapor overhead stream 135 and a liquid overhead stream 141. The vapor overhead stream 135 may comprise hydrogen and ethanol. The vapor overhead stream 135 can be used as fuel within the system, and/or the overhead stream 135 can be recycled within the system for use as a feed to the reactive distillation system 129. The liquid overhead stream 141 may predominantly comprise ethanol, and may be recycled to the reactive distillation system 129 for use as a feed to the ethyl acetate production system. The bottoms stream 136 may comprises ethyl acetate, butanol, and/or additional reaction products.

The bottoms stream 136 from separator 134 may pass to separator 137. Separator 137 may comprise any of the separators described herein, and, in an embodiment, comprises a distillation column. In an embodiment, separator 134 may operate between about 1 atm and 80 atm, and may have a similar or different pressure than separator 134. Separator 137 may separate the bottoms stream 136 into an overhead stream 138 and a bottoms stream 139. Bottoms stream 139 may comprise butanol and higher boiling components in addition to other reaction products. The bottoms stream 139 may exit the system for use as fuel, as a final product, and/or as a feed to one or more suitable downstream processes. The overhead stream 138 may comprise ethyl acetate as a product stream. In an embodiment, the overhead stream 138 may comprise greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

The product separation system illustrated in FIG. 11 produces an ethyl acetate product stream 138, a first lights product stream 140, a second lights product stream 131, a third lights product stream 135, a heavies product stream 139, and a recycle stream 141 comprising ethanol. Some portion of the lights streams 131, 135 may be recycled back to the reactive distillation system 129 for use as a hydrogen and/or ethanol feed. While illustrated as a separate feed to the reactive distillation system, thehe may be combined with the feed stream 128 comprising ethanol prior to the combined stream entering the reactive distillation system 129. The embodiment illustrated in FIG. 11 may allow both separator 134 and 137 to operate at similar pressures, which can range from about 1 atm to about 80 atm, from about 5 atm to about 75 atm, from about 10 atm to about 70 atm, or from about 15 atm to about 60 atm.

Dehydrogenation and Dimerization Catalysts

Suitable dehydrogenation and dimerization catalysts are capable of converting at least a portion of the alcohol (e.g., ethanol) in a feed stream to a higher valued product such as ethyl acetate. Any catalyst capable of carrying out a dehydrogenation and dimerization reaction may be used alone or in combination with additional catalytic materials in the reactors. In an embodiment, suitable dehydrogenation and dimerization catalysts can generally comprise metals and/or oxides of copper, barium, ruthenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, zirconium, gold, thallium, magnesium, manganese, aluminum, chromium, nickel, iron, molybdenum, sodium, strontium, tin, and mixtures thereof. In many cases, the catalyst material will be provided on a support material. The catalyst can be treated with a carbonate (e.g., sodium carbonate), reduced with hydrogen, and/or other suitable treatments prior to use.

In certain embodiments, the dehydrogenation and dimerization catalysts may comprise a catalyst support. The catalyst support stabilizes and supports the catalyst. The type of catalyst support used depends on the chosen catalyst and the reaction conditions. Suitable supports may include, but are not limited to, carbon, silica, silica-alumina, alumina, zirconia, titania, ceria, vanadia, nitride, boron nitride, hetropolysilicic, hydroxyapatite, zinc oxide, chromia, zeolites, carbon nanotubes, carbon fullerenes, and any combination thereof.

The dehydrogenation and dimerization catalyst can be employed in any of the conventional types or structures known to the art. It may be employed in the form of extrudates, pills, pellets, granules, broken fragments, or various special shapes. In an embodiment, consideration of the use of the catalysts in the reactive distillation system and/or a mass transfer surface within the distillation column may be taken into account when determining a suitable shape. For example, the catalyst may have a shape similar to or included in a suitable packing material or suitable for insertion in a structured packing. When the dehydrogenation catalyst is used with one or more side reactions, the catalyst may be disposed within a reaction zone, and the feed may be passed therethrough in the liquid, vapor, or mixed phase, and in either upward or downward, or inward or outward flow.

The dehydrogenation and dimerization catalyst may typically have a range of metal loadings. In an embodiment, the catalyst may have a copper oxide weight loading (i.e., weight percentage) of between about 0.5% and about 80%, between about 10% and about 70%, between about 20% and about 65%, between about 30% and about 60%, or about 40% and about 50%. In an embodiment, the catalyst may have a zinc oxide weight loading of between about 20% and about 60%, between about 30% and about 50%, or between about 40% and about 50%. In an embodiment, the catalyst may have a chromium oxide weight loading of between about 20% and about 60%, or between about 30% and about 50%.

In an embodiment, the catalyst may comprise CuO/ ZrO2/Al2O3. In this embodiment, the catalyst may have a copper oxide weight loading of between about 0.5% and about 80%, between about 10% and about 70%, between about 20% and about 65%, between about 30% and about 50%.
60%, or about 40% and about 50%, and the zinc oxide and alumina may comprise the balance of the weight. In an embodiment, the catalyst may comprise CuO/ZnO/ZrO_2/Al_2O_3, and the catalyst may have a copper oxide weight loading of between about 40% to about 80%, with the remainder of the components forming the balance of the catalyst weight. In an embodiment, the catalyst may comprise CuO/ZnO/ZrO_2/Cr_2O_3, and the catalyst may have a copper oxide weight loading of between about 20% to about 70% and a chromium oxide weight loading between about 30% and about 50%, with the remainder of the components forming the balance of the catalyst weight. In an embodiment, the catalyst comprised an alkaline earth metal and/or alkaline earth metal oxide and copper and/or copper oxide on a support. In this embodiment, the support may comprise silica.

[0073] Any of the materials useful as hydrogenation and dimerization catalysts, may be synthesized using a variety of methods. In an embodiment, the dehydrogenation and dimerization catalyst may be prepared via wet impregnation of a catalyst support. Using the wet-impregnation technique, a metal nitrate dissolved in a suitable solvent may be used to prepare the catalyst, however any soluble compound would be suitable. A sufficient amount of solvent should be used to fully dissolve the metal nitrate and appropriately wet the support. In one embodiment, copper nitrate and ethanol and/or water may be mixed in an amount sufficient such that the copper nitrate dissolves. Additional metal nitrates may also be added to provide a catalyst with additional components. The solution may then be combined with a suitable support material of appropriate particle size. The mixture may then be refluxed at a temperature of approximately 100° C. for approximately several hours (e.g., three to five hours) and then allowed to dry at a temperature of about 110° C. The dried material may then be heated to 200° C. to remove the NO_3 component, and then the materials may be calcined at about 450° C. to about 550° C. at a heating rate of about one to ten °C/min. The amount of metal nitrate used in the wet-impregnation technique can be adjusted to achieve a desired final metal weight loading of the catalyst support.

[0074] When multiple components are used to provide a catalyst disposed on a support, each component can be added via the wet-impregnation technique. The appropriate salts can be dissolved and impregnated on a support in a co-impregnation process or a sequential process. In a co-impregnation process, measured amount of the appropriate plurality of metal salts may be dissolved in a suitable solvent and used to wet the desired catalyst support. The impregnated support can then be dried and calcined to provide a final catalyst with a desired weight loading. In the sequential impregnation process, one or more measured amounts of salts may be dissolved in a suitable solvent and used to wet the desired catalyst support. The impregnated support can then be dried and calcined. The resulting material can then be wetted with one or more additional salts that are dissolved in a suitable solvent. The resulting material can then be dried and calcined again. This process may be repeated to provide a final catalyst material with a desired loading of each component. In an embodiment, a single metal may be added with each cycle. The order in which the metals are added in the sequential process can be varied. Various metal weight loadings may be achieved through the wet-impregnation technique. In an embodiment, the wet-impregnation technique may be used to provide a catalyst having a copper weight loading ranging from about 0.5% and about 50%, with one or more additional components having a weight loading between about 0.1% and about 10%.

[0075] The dehydrogenation and dimerization catalysts may also be prepared via a co-precipitation technique. In this technique, a measured amount of one or more appropriate metal nitrates are dissolved in de-ionized water. The total metal concentration can vary and may generally be between about 1 M and about 3 M. The metal-nitrate solution may then be precipitated through the drop-wise addition of the solution to a stirred, equal volume of a sodium hydroxide solution at room temperature. The sodium hydroxide solution may generally have a concentration of about 4 M, though other concentrations may also be used as would be known to one of skill in the art with the benefit of this disclosure. After addition of the metal nitrate solution, the resulting suspension can be filtered and washed with de-ionized water. The filtered solids can be dried overnight, for example, at a temperature of about 110° C. The resulting mixed metal oxide can then be processed to a desired particle size. For example, the resulting mixed metal oxide can be pressed to a desired form, ground, and then sieved to recover a catalyst material with a particle size in a desired range. Catalysts prepared using the co-precipitation technique may have higher metal loadings than the catalysts prepared using the wet-impregnation technique.

[0076] The catalyst prepared via the co-precipitation technique may be used in the prepared form and/or a catalyst binder can be added to impart additional mechanical strength. In an embodiment, the prepared catalyst may be ground to a fine powder and then stirred into a colloidal suspension (e.g., a colloidal suspension of silica and/or alumina) in an aqueous solution. The resulting suspension may be stirred while being heated and allowed to evaporate to dryness. The heating may take place at about 80° C. to about 130° C. The resulting solid can then be processed to a desired particle size. For example, the resulting solid can be pressed to a desired form, ground, and then sieved to recover a catalyst material with a particle size in a desired range. Alternatively, the colloidal suspension may be added to the 4 M sodium hydroxide precipitation solution prior to addition of the metal nitrate solution in the co-precipitation technique. Various metal weight loadings may be achieved through the co-precipitation technique. In an embodiment, the co-precipitation technique may be used to provide a catalyst having a copper weight loading ranging from about 2% and about 80%, with one or more additional components having a weight loading between about 2% and about 40%.

[0077] The resulting catalyst from either the wet-impregnation technique and/or the co-precipitation technique may be further treated prior to use in the reactive distillation system disclosed herein. In an embodiment, the catalyst may be treated with a sodium carbonate solution for a period of time to improve the selectivity of the catalyst. In this process, the catalyst may be soaked in an aqueous solution of sodium carbonate for a period of time ranging from about 1 hour to about 48 hours, or alternatively about 2 hours to about 24 hours. In an embodiment, the sodium carbonate solution may be a concentration of about 0.2 M. The catalyst may then be filtered and allowed to dry at about room temperature. In an embodiment, the sodium carbonate may comprise from about 0.2 to about 3.0 weight percent of the catalyst after being contacted with the sodium carbonate solution.

[0078] In another treatment process, the catalyst may be reduced with hydrogen prior to use. In this embodiment, the
catalyst may be heated and contacted with hydrogen, which may be flowing over the catalyst, for a period of time suffi-
cient to reduce the catalyst to a desired degree. In an em-

dioment, the catalyst may be contacted with hydrogen at a tem-

terature of about 190° C. to about 240° C. The hydrogen
treatment may be conducted in combination with the sodium
carbonate treatment, and may be performed prior to and/or after the sodium carbonate treatment.

[0079] Without intending to be limited by theory, it is be-
thieved that the production of hydrogen during the de-
hydrogenation and dimerization reaction within the process may result in contact between the dehydrogenation and dimerization catalyst and a hydrogen stream sufficient to at least partially reduce the catalyst. Thus, the process described herein may have the potential for the in-situ reduction of the catalyst during use. This may result in an initial break-in period in which the catalyst conversion and selectivity may change before reaching a steady state conversion and selectivity. This in-situ reduction may be taken into account when considering the degree to which a catalyst should be pre-

[0080] In an embodiment, the dehydrogenation and dimerization catalyst described herein may be capable of achieving a relatively high conversion and/or selectivity of ethanol to ethyl acetate. As used herein, the “conversion” of ethanol to ethyl acetate refers to the amount of ethanol consumed in the conversion reaction as represented by the formula:

\[ x_{\text{ethanol}} = 100 \left( \frac{F_{\text{ethyl acetate}}}{F_{\text{ethanol}}} \right) \]

[0081] where \( F_{\text{ethyl acetate}} \) represents the molar flow rates of ethanol in the reactor effluent (e.g., the product stream comprising the ethyl acetate), and \( F_{\text{ethanol}} \) represents the molar flow rate of ethanol into the reactor inlet. As used herein, the “selectivity” of the conversion refers to the amount of ethanol that is consumed in the conversion reaction that is converted to ethyl acetate as represented by the formula:

\[ s = 100 \left( \frac{F_{\text{ethyl acetate}} + F_{\text{H2}}} {F_{\text{ethanol}}} \right) \]

[0082] The hydrogenation catalyst generally can include a Group VIII metal and/or a Group VI metal. Examples of such a catalyst can include, but is not limited to, Cu, Re, Ni, Fe, Co, Ru, Pd, Rh, Pt, Os, Ir, and alloys or any combination thereof, either alone or with promoters such as W, Mo, Au, Ag, Cr, Zn, Mn, Sn, B, P, Bi, and alloys or any combination thereof. Other effective hydrogenation catalyst materials include either supported nickel or ruthenium modified with rhenium. In an embodiment, the hydrogenation catalyst also includes any one of the supports described below, depending on the desired functionality of the catalyst. The hydrogenation catalysts may be prepared by methods known to those of ordinary skill in the art.

[0083] In an embodiment, the hydrogenation catalyst includes a supported Group VIII metal catalyst and a metal sponge material (e.g., a sponge nickel catalyst). Raney nickel provides an example of an activated sponge nickel catalyst suitable for use in this invention. In an embodiment, the hydrogenation reaction in the invention is performed using a catalyst comprising a nickel-rhenium catalyst or a tungsten-modified nickel catalyst. One example of a suitable catalyst for the hydrogenation reaction of the invention is a carbon-

[0084] In an embodiment, a suitable Raney nickel catalyst may be prepared by treating an alloy of approximately equal amounts by weight of nickel and aluminum with an aqueous alkali solution, e.g., containing about 25 weight % of sodium hydroxide. The aluminum is selectively dissolved by the aqueous alkali solution resulting in a sponge shaped material comprising mostly nickel with minor amounts of aluminum. The initial alloy includes promoter metals (e.g., molybdenum or chromium) in the amount such that 1 to 2 weight % remains in the formed sponge nickel catalyst. In another embodiment, the hydrogenation catalyst is prepared using a solution of ruthenium(III) nitrosyltrihydrate, ruthenium (III) chloride in water to impregnate a suitable support material. The solution is thus dried to form a solid having a water content of less than 1% by weight. The solid is then reduced at atmospheric pressure in a hydrogen stream at 300° C. (uncalcined) or 400° C. (calcined) in a rotary ball furnace for 4 hours. After cooling and rendering the catalyst inert with nitrogen, 3% by volume of oxygen in nitrogen is passed over the catalyst for 2 hours.

[0085] In certain embodiments, the hydrogenation catalyst may include a catalyst support, which may be the same or different than a catalyst support used with the dehydrogenation and dimerization catalyst. In an embodiment, any of the catalyst supports discussed herein may be used to support a hydrogenation catalyst. The hydrogenation catalyst can be employed in any of the conventional types or structures known to the art. In an embodiment, any of the catalyst shapes and/or types discussed herein with respect to the dehydrogenation and dimerization catalyst may be used with the hydro-

[0086] In addition to use of the systems and methods described herein for converting ethanol to ethyl acetate, those systems can also be used in processes with methanol as a feed instead of ethanol, with the production of methyl formate and \( H_2 \) as products according to the following formula:

\[ 2CH_3OH \rightarrow CH_2O + 2H_2 \]

[0087] Such a system and method can utilize selections from the catalysts indicated for use with the ethanol feed. Products can be withdrawn in similar manner as described for the ethanol to ethyl acetate process.
EXAMPLES

[0088] The disclosure having been generally described, the following examples are given as particular embodiments of the disclosure and to demonstrate the practice and advantages thereof. It is understood that the examples are given by way of illustration and are not intended to limit the specification or the claims in any manner.

Example 1
Production of Ethyl Acetate from Ethanol

[0089] A 10 cm diameter distillation column is used, which has been rendered adiabatic by heating casings with temperatures controlled in such a way that the temperature gradient in the column is reproduced. Over a height of 3.5 m, the column is comprised of rectification zone with 8 stages each with a catalytic cell consisting of a cylindrical container with a flat bottom. The bottom of the container is equipped with a grid for retaining the catalyst and also can act as a gas and liquid distributor. The stripping zone is comprised of 12 stages, also with catalyst-containing cells. The rectification section is considered to be above the feed stage and the stripping section is considered to be below the feed stage. Each catalyst cell contains CuO/ZnO/Al2O3. 200 proof ethanol is fed to the 13th stage of the column, starting from the bottom.

[0090] The column is regulated by establishing a reflux ratio which is equal to 0.8, rebol ratio which is equal to 4 and controlling the base temperature at 211°C and the absolute pressure to 20 bar. The reflux stream is mostly ethanol with small amounts of acetaldehyde. Under stabilized conditions, a bottoms stream and a distillate stream are collected with respective throughputs of about 170 g/h and 4 g/h. The bottoms product gives ethyl acetate purity of 98.5% with small amounts of n-butyraldehyde and butan-2-one.

Example 2
Selective Hydrogenation of n-Butyraldehyde and Butan-2-One

[0091] Selective hydrogenation of n-butyraldehyde and butan-2-one in the presence of ethyl acetate was conducted over a hydrogenation catalyst. The reactor was filled with 20 g of 0.1 wt % Pd on silica catalyst. Before the selective hydrogenation reaction, the catalyst was reduced at a temperature of 250°C for 30 minutes. The catalyst reduction was conducted at atmospheric pressure by delivering hydrogen using a mass flow controller. At the end of this procedure, the catalyst was fully reduced.

[0092] The bottoms product from the reactive distillation column, whose composition is given in Table 2, was introduced to a heater at a rate of 30 g/h and mixed with hydrogen prior to admission to the selective hydrogenation reactor. The reaction product was cooled using a jacketed condenser and the liquid condensate was analyzed by gas chromatography. The results are summarized in Table 2, showing n-butyraldehyde and butan-2-one reduced to trace levels.

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>93</td>
<td>92.9</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

TABLE 2

Hydrogenation Feed and Products

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-butyraldehyde</td>
<td>1.5</td>
<td>trace</td>
</tr>
<tr>
<td>butan-2-one</td>
<td>0.5</td>
<td>trace</td>
</tr>
<tr>
<td>2-butanol</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>n-butanol</td>
<td>0.1</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Example 3

Wet-Impregnation Catalyst Preparation

[0093] Various catalysts including CuO/SiO2, CuO/SiO2−Al2O3, CuO/ZnO, CuO/ZrO2, CuO/SiO2−ZrO2, CuO/ZnO/Al2O3, CuO/Cr2O3/BaO, CuO/Cr2O3, and CuO/Al2O3 were prepared via impregnation of the corresponding oxide catalyst support. The preparation involved dissolving 4 grams (g) of Cu(NO)2·2H2O in 30 mL of de-ionized water, which was then added to 30 g of the appropriate oxide support and stirred until well mixed. The impregnated support was then dried at air at 110°C, followed by calcination in air at 450°C. The amount of Cu(NO)2·2H2O was adjusted to achieve a desired final Cu weight loading. Enough water was used to wet the entire oxide support. Copper loadings between 0.5% and 20% by weight were achieved.

Example 4
Co-Impregnation and Sequential Impregnation Catalyst Preparation

[0094] Various catalysts including CuO/ZrO2/SiO2, CuO/ZrO2/SiO2−Al2O3, CuO/MgO/SiO2, CuO/MgO/SiO2−Al2O3, CuO/SrO/SiO2, CuO/BaO/SiO2, and CuO/Na2O/SiO2 were prepared via co-impregnation and sequential impregnation of a silica catalyst support. For the co-impregnation, measured amounts of Cu(NO)2·2H2O and Mn(NO)2·2H2O (M=Mg, Ca, Sr, Ba, or Na; X=1, 2, 4; Y=2-6) were dissolved in de-ionized water. The solution was added to the silica support and stirred until well mixed. The impregnated silica was dried in air at 110°C, followed by calcination in air at 450°C.

[0095] For the sequential impregnation, a measured amount of Mn(NO3)2·YH2O (M=Mg, Ca, Sr, Cr, or Na; X=1 or 2; Y=2-6) was dissolved in de-ionized water. The solution was then added to the silica support and mixed well. The silica was dried at 110°C and then calcined at 450°C in air. This procedure was then repeated using Cu(NO)2·2H2O in place of the first metal nitrate. Copper loadings between 0.5% and 20% by weight and an addition metal loading between 0.1% and 10% by weight were achieved.

Example 5
Co-Precipitation Catalyst Preparation

[0096] Mixed-metal oxide catalysts were prepared via co-precipitation from nitrate solutions. In the co-precipitation synthesis, a measured amount of the appropriate metal nitrate (Cu, Zn, Cr, Al, Cr, Fe, Ni, and/or Ba) was dissolved in de-ionized water (total metal concentration ranges from 1-3 M). The metal-nitrate solution was then precipitated by drop-wise addition to a stirred, equal volume of 4 M aqueous NaOH at room temperature. After addition of all the metal nitrate solution, the suspension was stirred for an additional
hour to ensure complete precipitation of the metals. The precipitated solid was then filtered and washed with excess deionized water. The solids were then dried overnight at 110°C. The resulting mixed metal oxide was then pressed, ground, and sieved to recover a catalyst with particle sizes between 450 and 850 μm. Catalysts prepared in this manner had copper oxide loadings between 40% and 80% by weight. The loadings of other metal oxides ranged from 2% to 40% by weight. In particular, CuO/ZrO₂/ZrO₂/Al₂O₃, and CuO/ZrO₂/ZrO₂/Cr₂O₃ catalysts were found to be especially active and selective for the dehydrogenative dimerization of ethanol, as illustrated below in Example 6.

[0097] In addition to the catalysts prepared above, various catalysts were prepared via co-precipitation and then a binder was incorporated. The catalyst binder was added to the mixed-metal oxide prepared as described above by first grinding the mixed-metal oxide to a fine powder and then stirring it into a colloidal suspension of silica or alumina in water. The resulting suspension was stirred while heating at 80-130°C, to dryness. The resulting solid was then pressed, ground, and sieved to appropriate particle sizes.

Example 6

Dehydrogenative Dimerization of Ethanol

[0098] A portion of the catalysts prepared as described in Examples 3 to 5 were treated with a Na₂CO₃ solution by soaking the catalyst in a 0.2 M aqueous solution of Na₂CO₃ for 2-24 hrs. The catalyst was then filtered and allowed to dry in air at room temperature. Another portion of the catalysts prepared as described in Examples 3 to 5 were reduced in a hydrogen environment at 175-240°C for a period of 4-12 hours. These catalysts were then tested in ethanol dehydrogenation reactions. Conversion and selectivity for gas phase reactions were determined from use in a fixed bed reactor operating at 190-240°C and 1-24 atm. Pure ethanol was fed to the reactor with a weight hourly space velocity (WHSV) between 0.1-1.5 hr⁻¹. Conversion and selectivity for liquid phase and mixed liquid/vapor phase reactions were determined in both a fixed bed reactor, operating at 190°C and at pressures above 25 atm. Liquid phase reactions were also conducted in a batch reactor at 180-200°C and 20-31 atm (the reactor pressure was maintained above the vapor pressure of ethanol at the operating temperature).

[0099] Table 3 shows the conversion and selectivity of the catalysts in a dehydrogenative dimerization reaction conducted in a fixed bed reactor. Conversion (X) and selectivity (S) were calculated from the composition of the reactor effluent as

\[
X_{\text{ethanol}} = 100 \left( \frac{F_{\text{EOH}} - F_{\text{EOH,in}}} {F_{\text{EOH,in}}} \right)
\]

\[
S = 100 \left( \frac{2F_{\text{EOH}} + F_{\text{Acet}}} {F_{\text{EOH,in}} + F_{\text{Acet}}} \right)
\]

[0100] Where \( F_{\text{EOH}} \), \( F_{\text{Acet}} \), and \( F_{\text{Acet}} \) represent the molar flow rates of ethanol, ethyl acetate, and acetaldehyde in the reactor effluent, respectively, and \( F_{\text{EOH,in}} \) represents the molar flow rate of ethanol into the reactor inlet. Acetaldehyde is a reaction intermediate and so was included in the selectivity calculation.

Example 7

Pressure Effects on the Conversion

[0101] A fixed bed reactor operated under similar conditions to those described with respect to Example 6 was used to test the reaction conversion and selectivity of a catalyst under varying reaction pressures. Table 4 shows a typical trend in the conversion and selectivity of these catalysts when operated at elevated pressures. Similar trends were seen for all catalysts tested at elevated pressures.

Example 8

Liquid Phase Reaction

[0103] The dehydrogenative dimerization of ethanol was also conducted in the liquid phase. Reaction temperatures

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Conversion and Selectivity for selected catalysts in a fixed bed reactor at 220°C and 1 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst sample</td>
<td>As prepared</td>
</tr>
<tr>
<td>Pellet catalysts</td>
<td></td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃</td>
<td>18.9</td>
</tr>
<tr>
<td>CuO/Al₂O₃</td>
<td>43.5</td>
</tr>
<tr>
<td>Impregnated catalysts</td>
<td></td>
</tr>
<tr>
<td>CuO/Al₂O₃</td>
<td>19.6</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃</td>
<td>43.0</td>
</tr>
<tr>
<td>CuO/Al₂O₃</td>
<td>50.2</td>
</tr>
<tr>
<td>CuO/Fe₂O₃</td>
<td>19.7</td>
</tr>
<tr>
<td>CuO/Fe₂O₃</td>
<td>41.5</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>40.0</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>3.7</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>33.3</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>25.1</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>21.0</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>19.4</td>
</tr>
<tr>
<td>CuO/Na₂O-SiO₂</td>
<td>39.1</td>
</tr>
<tr>
<td>Co-precipitation catalysts</td>
<td></td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃</td>
<td>8.7</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Na₂CO₃</td>
<td>25.1</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Cr₂O₃</td>
<td>28.8</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Na₂CO₃</td>
<td>37.0</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Cr₂O₃</td>
<td>34.1</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Cr₂O₃</td>
<td>30.7</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Cr₂O₃</td>
<td>24.5</td>
</tr>
<tr>
<td>CuO/ZnO-Al₂O₃-Cr₂O₃</td>
<td>33.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Conversion and Selectivity for CuO/ZnO-ZrO₂/Al₂O₃-Na₂CO₃ (reduced at 240°C in H₂) in a fixed bed reactor at 220°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (atm)</td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>39.0</td>
</tr>
<tr>
<td>9.4</td>
<td>43.6</td>
</tr>
<tr>
<td>14.5</td>
<td>43.3</td>
</tr>
<tr>
<td>21.4</td>
<td>39.3</td>
</tr>
</tbody>
</table>

[0102] As seen by the results in Table 4, operation of catalysts at higher pressures increases the selectivity of the catalyst significantly. Increasing the pressure had little effect on the conversion achieved by the catalysts.
ranged from 180 to 200 °C, and pressures were kept above the vapor pressure of ethanol at the reaction temperature (25-36 atm). Liquid phase reactions were conducted in both a fixed bed reactor and batch reactor. Table 5 shows the results for a CuO/ZnO/Al2O3 catalyst in a batch reactor operating in the liquid phase. During a typical batch reaction, the pressure initially reached the vapor pressure of ethanol and then slowly increased beyond that pressure as the reaction generated H2 gas. The batch reactor results demonstrated that the dehydrogenative dimerization reaction occurs in the liquid phase.

TABLE 5
Conversion and Selectivity for CuO/ZnO/Al2O3 (reduced at 240 °C. in H2) after 2 hrs in a batch reactor.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>X</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>4.4</td>
<td>84.1</td>
</tr>
<tr>
<td>190</td>
<td>6.1</td>
<td>81.5</td>
</tr>
<tr>
<td>200</td>
<td>13.0</td>
<td>96.1</td>
</tr>
</tbody>
</table>

[0104] Based on the results of Examples 3 through 8, it can be seen that a high selectivity to ethyl acetate using the dehydrogenation and dimerization catalysts described herein (e.g., CuO/ZnO/Al2O3/Na2CO3 and/or CuO/ZnO/Al2O3) should enable the use of the system embodiments as illustrated in FIGS. 3, 5 and 7 of the present disclosure. For catalysts where 2 butanone is produced above acceptable levels, the use of the system embodiments as illustrated in FIGS. 4, 6 and 8 of the present disclosure may be used.

Example 9
Effect of Water in the Ethanol Feed

[0105] In this example, the effect of water in the ethanol feed was investigated. A 4 wt % water in ethanol solution was fed to a CuO/ZnO/Al2O3 catalyst in a fixed bed reactor to demonstrate the water tolerance of the catalyst. The reactor was maintained at 21.4 atm and the catalyst was heated to 200-240 °C. Table 6 compares the conversion and selectivity achieved for the 4 wt % water in ethanol and a pure ethanol feed.

TABLE 6
Conversion and selectivity for CuO/ZnO/Al2O3 in a fixed bed reactor operating at 21.4 atm for ethanol feeds with and without water.

<table>
<thead>
<tr>
<th>Pure Ethanol Feed</th>
<th>4% Water in Ethanol Feed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature (°C)</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>240</td>
</tr>
</tbody>
</table>

Example 10
Process Simulation of FIG. 10

[0106] In an example, a process simulation was performed using the Aspen Plus distillation system and product separation system shown in FIG. 10. The simulation was performed using the Aspen Plus V7.1 (Build 23.0.2.4563) software package. The physical properties are provided in degrees Celsius (°C.), psig, pounds per hour (lb/hr), U.S. gallons per minute (USGPM), and British thermal units per hour (Btu/hr). The material streams, their compositions, and the associated unit properties produced by the simulation are provided in Tables 7, 8, and 9 below, respectively.

TABLE 7A
Material Streams

<table>
<thead>
<tr>
<th>Feed Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>111</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>59</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>294</td>
</tr>
<tr>
<td>Molar Flow (lbmol/h)</td>
<td>502.4</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>23142</td>
</tr>
<tr>
<td>Liquid Volume Flow (USGPM)</td>
<td>69.1</td>
</tr>
<tr>
<td>Heat Flow (Btu/hr)</td>
<td>-5,922E7</td>
</tr>
</tbody>
</table>

TABLE 7B
Material Streams

<table>
<thead>
<tr>
<th>Vapor Overhead Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Liquid Stream</td>
</tr>
<tr>
<td>Name</td>
</tr>
<tr>
<td>Vapor Fraction</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
<tr>
<td>Pressure (psig)</td>
</tr>
<tr>
<td>Molar Flow (lbmol/h)</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
</tr>
<tr>
<td>Liquid Volume Flow (USGPM)</td>
</tr>
<tr>
<td>Heat Flow (Btu/hr)</td>
</tr>
</tbody>
</table>

TABLE 7C
Material Streams

<table>
<thead>
<tr>
<th>Overhead Stream</th>
<th>Bottoms Stream</th>
<th>Heavies Product Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>123</td>
<td>124</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>175</td>
<td>208</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>279</td>
<td>285</td>
</tr>
<tr>
<td>Molar Flow (lbmol/h)</td>
<td>1016</td>
<td>236</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>54267</td>
<td>20756</td>
</tr>
<tr>
<td>Liquid Volume Flow (USGPM)</td>
<td>180.2</td>
<td>69.6</td>
</tr>
<tr>
<td>Heat Flow (Btu/hr)</td>
<td>-1.2E8</td>
<td>-4.4E7</td>
</tr>
</tbody>
</table>

TABLE 8A
Stream Compositions

<table>
<thead>
<tr>
<th>Feed Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>111</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethanol)</td>
<td>1</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethyl Acetate)</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (Hydrogen)</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (Butanol)</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (n-butylnicole)</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (butan-2-one)</td>
<td>0</td>
</tr>
</tbody>
</table>
**TABLE 8B**

Stream Compositions

<table>
<thead>
<tr>
<th>Name</th>
<th>Liquid Stream</th>
<th>Bottoms Stream</th>
<th>Vapor Overhead Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>116</td>
<td>119</td>
<td>121</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethanol)</td>
<td>0.69</td>
<td>0.85</td>
<td>0.39</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethyl Acetate)</td>
<td>0.29</td>
<td>0.13</td>
<td>0.32</td>
</tr>
<tr>
<td>Comp Mole Frac (Hydrogen)</td>
<td>0</td>
<td>0</td>
<td>0.13</td>
</tr>
<tr>
<td>Comp Mole Frac (Butanol)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (n-butyraldehyde)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (butan-2-one)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 8C**

Stream Compositions

<table>
<thead>
<tr>
<th>Name</th>
<th>Overhead Stream</th>
<th>Bottoms Stream</th>
<th>Heavy Product Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>123</td>
<td>124</td>
<td>126</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethanol)</td>
<td>0.61</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethyl Acetate)</td>
<td>0.29</td>
<td>0.90</td>
<td>0.57</td>
</tr>
<tr>
<td>Comp Mole Frac (Hydrogen)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (Butanol)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (n-butyraldehyde)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (butan-2-one)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 9**

Unit Properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Separator</th>
<th>Separator</th>
<th>Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120</td>
<td>122</td>
<td>125</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>10</td>
<td>279</td>
<td>338</td>
</tr>
<tr>
<td>Theoretical Stages</td>
<td>30</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Condenser Duty (Btu/hr)</td>
<td>-3.3E7</td>
<td>-2.5E7</td>
<td>-3.3E7</td>
</tr>
<tr>
<td>Reboiler Duty (Btu/hr)</td>
<td>2.2E7</td>
<td>3.6E7</td>
<td>2.9E7</td>
</tr>
</tbody>
</table>

**Example 11**

Process Simulation of FIG. 11

As another example, a similar process simulation was performed using the reactive distillation system and product separation system shown in FIG. 11. The material streams, their compositions, and the associated unit properties produced by the simulation are provided in Tables 10, 11, and 12 below, respectively.

**TABLE 10A**

Material Streams

<table>
<thead>
<tr>
<th>Name</th>
<th>Feed Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128</td>
<td>141</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (° C.)</td>
<td>50</td>
<td>108</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>294</td>
<td>382</td>
</tr>
<tr>
<td>Molar Flow (Ibmol/h)</td>
<td>502.4</td>
<td>893</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>23148</td>
<td>44429</td>
</tr>
</tbody>
</table>

**TABLE 10B**

Material Streams

<table>
<thead>
<tr>
<th>Name</th>
<th>Feed Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128</td>
<td>141</td>
</tr>
<tr>
<td>Liquid Volume Flow (USGPM)</td>
<td>69</td>
<td>140</td>
</tr>
<tr>
<td>Heat Flow (Btu/hr)</td>
<td>-5.9E7</td>
<td>-1E8</td>
</tr>
</tbody>
</table>

**TABLE 10C**

Material Streams

<table>
<thead>
<tr>
<th>Name</th>
<th>Overhead Stream</th>
<th>Bottoms Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>138</td>
<td>139</td>
</tr>
<tr>
<td>Vapor Fraction</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Temperature (° C.)</td>
<td>202</td>
<td>210</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>250</td>
<td>200</td>
</tr>
<tr>
<td>Molar Flow (Ibmol/h)</td>
<td>240</td>
<td>9.7</td>
</tr>
<tr>
<td>Mass Flow (lb/hr)</td>
<td>21101</td>
<td>792</td>
</tr>
<tr>
<td>Liquid Volume Flow (USGPM)</td>
<td>68</td>
<td>2.6</td>
</tr>
<tr>
<td>Heat Flow (Btu/hr)</td>
<td>-4.5E7</td>
<td>-1.5E6</td>
</tr>
</tbody>
</table>

**TABLE 11A**

Stream Compositions

<table>
<thead>
<tr>
<th>Name</th>
<th>Feed Stream</th>
<th>Recycle Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128</td>
<td>141</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethanol)</td>
<td>1.0</td>
<td>0.91</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethyl Acetate)</td>
<td>0</td>
<td>0.09</td>
</tr>
<tr>
<td>Comp Mole Frac (Hydrogen)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (Butanol)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (n-butyraldehyde)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (butan-2-one)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**TABLE 11B**

Stream Compositions

<table>
<thead>
<tr>
<th>Name</th>
<th>Liquid Stream</th>
<th>Vapor Overhead Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>132</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>133</td>
<td>136</td>
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<tr>
<td>Comp Mole Frac (Ethanol)</td>
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<td>Comp Mole Frac (Ethyl Acetate)</td>
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<tr>
<td>Comp Mole Frac (Hydrogen)</td>
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<td>0.73</td>
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TABLE 11B-continued

<table>
<thead>
<tr>
<th>Name</th>
<th>Liquid Stream</th>
<th>Upper Overland Stream</th>
<th>Bottoms Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp Mole Frac (Butanol)</td>
<td>0.01</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (n-butyraldehyde)</td>
<td>0</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Comp Mole Frac (butan-2-one)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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TABLE 11C

<table>
<thead>
<tr>
<th>Name</th>
<th>Overhead Stream</th>
<th>Bottoms Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp Mole Frac (Ethanol)</td>
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<td>0</td>
</tr>
<tr>
<td>Comp Mole Frac (Ethyl Acetate)</td>
<td>0.99</td>
<td>0.57</td>
</tr>
<tr>
<td>Comp Mole Frac (Hydrogen)</td>
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<td>Comp Mole Frac (Butanol)</td>
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</tr>
<tr>
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<td>Comp Mole Frac (butan-2-one)</td>
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TABLE 12

<table>
<thead>
<tr>
<th>Name</th>
<th>Separator 133</th>
<th>Separator 134</th>
<th>Separator 137</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (psig)</td>
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<td>264.5</td>
<td>250</td>
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<td>Theoretical Stages</td>
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<td>32</td>
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<tr>
<td>Condenser Duty (Btu/hr)</td>
<td>-5.6E6</td>
<td>-4E7</td>
<td>2.2E7</td>
</tr>
<tr>
<td>Reboiler Duty (Btu/hr)</td>
<td></td>
<td>4.6E7</td>
<td>2.2E7</td>
</tr>
</tbody>
</table>

[0108] In the preceding discussion and in the claims, the terms “including” and “comprising” are used in an open-ended fashion, and thus should be interpreted to mean “including, but not limited to”. At least one embodiment is disclosed and variations, combinations, and/or modifications of the embodiment(s) and/or features of the embodiment(s) made by a person having ordinary skill in the art are within the scope of the disclosure. Alternative embodiments that result from combining, integrating, and/or omitting features of the embodiment(s) are also within the scope of the disclosure. Where numerical ranges or limitations are expressly stated, such express ranges or limitations should be understood to include iterative ranges or limitations of like magnitude falling within the expressly stated ranges or limitations (e.g., from about 1 to about 10 includes 2, 3, 4, etc.; greater than 0.10 includes 0.11, 0.12, 0.13, etc.). For example, whenever a numerical range with a lower limit, R, and an upper limit, Ru, is disclosed, any number falling within the range is specifically disclosed. In particular, the following numbers within the range are specifically disclosed: R–R(1+k)(Ru–R), wherein k is a variable ranging from 1 percent to 100 percent with a 1 percent increment, i.e., k is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent, . . ., 50 percent, 51 percent, 52 percent, . . ., 95 percent, 96 percent, 97 percent, 98 percent, 99 percent, or 100 percent. Moreover, any numerical range defined by two R numbers as defined in the above is also specifically disclosed. Use of the term “optionally” with respect to any element of a claim means that the element is required, or alternatively, the element is not required, both alternatives being within the scope of the claim. Use of broader terms such as comprises, includes, and having should be understood to provide support for narrower terms such as consisting of, consisting essentially of, and comprised substantially of. Accordingly, the scope of protection is not limited by the description set out above but is defined by the claims that follow, that scope including all equivalents of the subject matter of the claims. Each and every claim is incorporated as further disclosure into the specification and the claims are embodiment(s) of the present invention.

1. A reactive distillation method comprising: introducing an feed stream to a reactive distillation column, wherein the feed stream comprises ethanol; contacting the feed stream with a catalyst in the reactive distillation column during a distillation, wherein the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen; removing ethyl acetate during the distillation from the reactive distillation column as a bottoms stream; and removing hydrogen during the distillation from the reactive distillation column as an overhead stream.

2. The reactive distillation method of claim 1, further comprising: contacting the bottoms stream with a hydrogenation catalyst and hydrogen to hydrogenate at least a portion of the contaminant in the bottoms stream; and separating the hydrogenated portion of the contaminant from the bottoms stream.

3. The reactive distillation method of claim 2, wherein the hydrogenation catalyst comprises a Group VIII metal, a Group VI metal, or any combination thereof.

4. The reactive distillation method of claim 1, wherein the catalyst comprises at least one catalytic component selected from the group consisting of: copper, copper oxide, barium, barium oxide, ruthenium, ruthenium oxide, rhodium, rhodium oxide, platinum, platinum oxide, palladium, palladium oxide, rhenium, rhenium oxide, silver, silver oxide, cadmium, cadmium oxide, zinc, zinc oxide, zirconium, zirconium oxide, gold, gold oxide, thallium, thallium oxide, magnesium, magnesium oxide, manganese, manganese oxide, aluminum, aluminum oxide, chromium, chromium oxide, nickel, nickel oxide, iron, iron oxide, molybdenum, molybdenum oxide, sodium, sodium oxide, carbonate, strontium, strontium oxide, tin, tin oxide, and any mixture thereof.

5. The reactive distillation method of claim 1, wherein the catalyst comprises a support, wherein the support comprises at least one support material selected from the group consisting of: carbon, silica, silica-alumina, alumina, zirconia, titania, ceria, vanadia, nitride, boron nitride, heteropolyacids, hydroxyapatite, zinc oxide, chromia, a zeolite, a carbon nanotube, carbon fullerenes, and any combination thereof.

6. The reactive distillation method of claim 1, wherein the catalyst comprises copper, and wherein the catalyst has a copper weight loading of between about 0.5% and about 80% of the catalyst.

7. The reactive distillation method of claim 1, wherein the catalyst comprises copper oxide and zinc oxide disposed on a support.
8. The reactive distillation method of claim 1, wherein the catalyst comprises copper oxide, zinc oxide, zirconium oxide, and alumina.
9. The reactive distillation method of claim 1, wherein the catalyst comprises copper oxide, zinc oxide, zirconium oxide, and chromium oxide.
10. The reactive distillation method of claim 1, wherein the catalyst comprises:
    an alkaline earth metal or alkaline earth metal oxide,
    copper or copper oxide, and
    a support.
11. The reactive distillation method of claim 1, wherein the catalyst comprises sodium carbonate.
12. The reactive distillation method of claim 1, wherein the catalyst is at least partially reduced in the presence of hydrogen.
13. The reactive distillation method of claim 1, wherein a conversion of ethanol in the feed stream is at least about 10%.
14. The reactive distillation method of claim 13, wherein a selectivity of the conversion of ethanol to ethyl acetate is at least about 60%.
15. The reactive distillation method of claim 1, further comprising:
    removing a side stream from the reactive distillation column,
    and
    contacting the side stream with a second catalyst, wherein the side stream reacts in the presence of the second catalyst to produce ethyl acetate.
16. The reactive distillation method of claim 1, wherein a liquid portion of the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen.
17. A reactive distillation system comprising:
    a reactive distillation column comprising:
    a dehydrogenation catalyst located generally centrally in the column,
    an ethanol feed in fluid communication with the reactive distillation column and configured to pass ethanol over the dehydrogenation catalyst,
    an overhead product hydrogen removal passage, and a bottoms product ethyl acetate removal passage;
    a product separation system comprising an inlet configured to receive the bottoms product from the reactive distillation column, an ethyl acetate product removal passage, and an ethyl acetate removal passage; and
    a recycle line coupling the ethyl acetate removal passage from the product separation system and an inlet to the reactive distillation column.
18. The reactive distillation system of claim 17, further comprising a dehydrogenation catalyst positioned to contact a liquid product following passage over the dehydrogenation catalyst.
19. The reactive distillation system of claim 17, wherein the product separation system further comprises at least one of a lights product removal passage or a heavies product removal passage.
20. The reactive distillation system of claim 17, wherein the reactive distillation column comprises a batch reactor configured to contact a liquid ethanol feed with the dehydrogenation catalyst and remove hydrogen during the contacting of the liquid ethanol feed with the dehydrogenation catalyst.
21. A reactive distillation method comprising:
    introducing an feed stream to a reactive distillation column, wherein the feed stream comprises ethanol;
    contacting the feed stream with a catalyst in the reactive distillation column during a distillation, wherein the feed stream reacts in the presence of the catalyst to produce a reaction product comprising ethyl acetate and hydrogen;
    separating bottoms stream during the distillation from the reactive distillation column, wherein the bottoms stream comprises ethyl acetate and ethanol;
    separating a recycle stream from the bottoms stream, wherein the recycle stream comprises at least a portion of the ethanol from the bottoms stream; and
    recycling the recycle stream to the reactive distillation column.
22. The reactive distillation method of claim 21, further comprising:
    separating the bottoms stream into an overhead stream and
    the recycle stream at a first pressure, wherein the overhead stream comprises ethanol and ethyl acetate; and
    separating the overhead stream into an ethyl acetate product stream at a second pressure, wherein the second pressure is greater than the first pressure.
23. The reactive distillation method of claim 22, further comprising:
    combining the ethanol stream with the bottoms stream in the separation of the bottoms stream into the overhead stream and the recycle stream.
24. The reactive distillation method of claim 22, further comprising:
    separating at least one byproduct from the recycle stream after separation of the recycle stream from the bottoms stream and prior to recycling the recycle stream to the reactive distillation column.
25. The reactive distillation method of claim 21, further comprising:
    separating the bottoms stream into a product stream and the recycle stream; and
    separating the product stream into a byproduct stream and
    an ethyl acetate product stream.
26. A reactive distillation system comprising:
    a reactive distillation column configured to separate ethanol from ethyl acetate,
    wherein the reactive distillation column comprises:
    an ethanol feed configured to pass a feed stream comprising ethanol into the reactive distillation column, an overhead product hydrogen removal passage, and a bottoms product ethyl acetate removal passage;
    a side reactor in fluid communication with the reactive distillation column, wherein the side reactor comprises a dehydrogenation catalyst;
    an inlet in fluid communication with the side reactor and the reactive distillation column, wherein the inlet is configured to pass a fluid comprising ethanol from the reactive distillation column over the dehydrogenation catalyst to produce ethyl acetate, and
    an outlet in fluid communication with the side reactor and the reactive distillation column, and configured to pass the fluid from an outlet of the side reactor to the reactive distillation column.
27. The reactive distillation system of claim 26, wherein at least one of the reactive distillation column or the side reactor comprises a hydrogenation catalyst.
28. The reactive distillation system of claim 27, wherein the reactive
distillation system further comprises:
a hydrogen feed in fluid communication configured to pass hydrogen over at least a portion of the hydrogenation catalyst.

29. The reactive distillation system of claim 26, further comprising:
a second side reactor in fluid communication with the reactive distillation column, wherein the side reactor comprises a second catalyst,
a second inlet in fluid communication with the second side reactor and the reactive distillation column, and configured to pass a second fluid from the reactive distillation column over the second catalyst, and
a second outlet in fluid communication with the second side reactor and the reactive distillation column, and configured to pass the second fluid from an outlet of the second side reactor to the reactive distillation column.

30. The reactive distillation system of claim 29, wherein the second catalyst comprises a hydrogenation catalyst.

31. The reactive distillation system of claim 29, wherein the second catalyst comprises a hydrogenation catalyst that is the same as the dehydrogenation catalyst in the side reactor.

32. The reactive distillation system of claim 29, wherein the second catalyst comprises a second dehydrogenation catalyst that is different than the dehydrogenation catalyst in the side reactor.

33. The reactive distillation system of claim 29, wherein the side reactor and the second side reactor are configured to each provide a different catalyst holdup.

34. A reactive distillation process comprising:
introducing a feed stream to a reactive distillation column,
wherein the feed stream comprises ethanol;
contacting a first fluid drawn from the reactive distillation column with a dehydrogenation catalyst in a side reactor,
producing a reaction product comprising ethyl acetate in response to contacting the first fluid with the dehydrogenation catalyst in the side reactor;
introducing ethyl acetate to the reactive distillation column from the side reactor during the distillation;
removing ethyl acetate during the distillation from the reactive distillation column as a bottoms stream; and
removing hydrogen during the distillation from the reactive distillation column as an overhead stream.

35. The reactive distillation process of claim 34, wherein at least one of the reactive distillation column or the side reactor comprises a hydrogenation catalyst.

36. The reactive distillation process of claim 35, further comprising:
introducing a second feed stream to a reactive distillation column, wherein the second feed stream comprises hydrogen; and
contacting the hydrogen with the hydrogenation catalyst during the reactive distillation process.

37. The reactive distillation process of claim 35, wherein producing a reaction product comprising ethyl acetate further produces by-products, and wherein the reactive distillation process further comprises:
hydrogenating at least a portion of the by-products over the hydrogenation catalyst to produce hydrogenated by-products.

38. The reactive distillation process of claim 34, further comprising:
contacting a second fluid drawn from the reactive distillation column with a second catalyst in a second side reactor.

39. The reactive distillation process of claim 38, wherein the second catalyst comprises at least one of dehydrogenation catalyst or a hydrogenation catalyst.
A method of purifying an ethyl acetate stream comprises contacting an inlet stream with a solvent, transferring at least a portion of the impurity compound from the inlet stream into the solvent to form an extract and a purified product, separating the extract from the purified product, separating the portion of the impurity compound from the extract, forming an impurities stream and a regenerated solvent, and recycling at least a portion of the regenerated solvent to contact the inlet stream. The inlet stream comprises ethyl acetate and an impurity compound, and the extract comprises the solvent and the portion of the impurity compound transferred from the inlet stream.
Figure 1: Reactive residue curve maps at pressures of 1 atm and 5 atm.
Figure 2: Reactive residue curve maps at pressures of 10 atm and 20 atm.
Figure 3: Single feed reactive distillation column schematic.
Figure 4: Schematic for a reactive distillation system with subsequent product hydrogenation.
Figure 5: Double feed reactive distillation column schematic with an upper feed of ethanol and lower feed of hydrogen.
Figure 6: Double feed reactive distillation column schematic using dual catalyst beds with an upper feed of ethanol and lower feed of hydrogen.
Figure 7: Side reactor configuration (a) upward flow feed to side reactor (b) downward flow feed to side reactor.
Figure 8: Double Side reactor configuration (a) upward flow feed to multiple side reactors (b) downward flow feed to multiple side reactors.
Figure 12. Schematic for Stripping Process
Various Extraction Curves with Varying NaHSO₃ Concentration and Volume

Cumulative volume of NaHSO₃ solution, ml vs. 2-butanone concentration w/v%
ETHYL ACETATE PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of and claims priority to U.S. patent application Ser. No. 12/925,460 filed on Oct. 20, 2010 to Sagar B. Gadewar and entitled “Ethyl Acetate Production,” which is a Non- Provisional application of and claims priority to U.S. Provisional Application No. 61/253,349, filed Oct. 20, 2009 to Sagar B. Gadewar and entitled “Ethyl Acetate Production,” both of which are incorporated herein by reference in their entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

REFERENCE TO A MICROFICHE APPENDIX

[0003] Not applicable.

BACKGROUND

[0004] The following discussion is provided solely to assist the understanding of the reader, and does not constitute an admission that any of the information discussed or references cited constitute prior art to the present invention.

[0005] Ethyl acetate can be produced from acetaldehyde according to the Tischenko reaction:

\[ 2\text{CH}_3\text{CHO} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5 \]

[0006] When acetaldehyde is produced from ethanol, ethyl acetate can be produced from ethanol according to the following reaction:

\[ 2\text{CH}_3\text{OH} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5 + 2\text{H}_2 \]

[0007] Alternatively, ethanol can react with acetaldehyde according to the following reaction:

\[ \text{C}_2\text{H}_5\text{OH} + \text{CH}_3\text{CHO} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5 + \text{H}_2 \]


[0009] U.S. Pat. No. 4,996,007 describes a process for the oxidation of primary alcohols to aldehydes, esters and acids. A primary alcohol is reacted with oxygen, with a catalyst selected from ruthenium, rhodium, platinum, palladium, rhodium and mixtures thereof, with the option of quaternary C1 to C20 alkyl ammonium co-catalyst, and dihydrodihydroxy- or the mixture thereof as an oxygen activator.

[0010] In U.S. Pat. No. 4,220,803 catalytic dehydrogenation of ethanol for the production of acetaldehyde and acetic acid using a supported copper oxide essentially free of barium is proposed.

[0011] U.S. Pat. No. 4,052,424 suggested a silver-cadmium alloy catalyst for use in production of alkyl alkanate esters, by contacting a primary alkyl in the vapor phase with the catalyst at a temperature of about 250° C. and 600° C.

[0012] In U.S. Pat. No. 4,440,946 there is described a process for producing a carboxylate ester which comprises contacting a mixture of alcohol and aldehyde in the vapor phase with a co-precipitate composition comprising silver-cadmium-zinc-zirconium which is substantially in the free metal form.

[0013] Use of the Tischenko reaction for the production of mixed esters from aldehydes is described in U.S. Pat. No. 3,714,236.

[0014] U.S. Pat. No. 5,334,751 describes production of ethyl acrylate by reaction of ethanol and oxygen in the presence of a solid catalyst that contains crystalline TiP2O5 and has the formula Pd₃M₂TIP₂O₈, where M is Cd, Au, Zn, Ti, or an alkali metal or alkaline earth metal, a is 0.3, b is 0.5-2.5, x has a value to satisfy the valencies, and Ti and P of the crystalline TiP2O5 represent part of the crystalline TiP2O5.


[0016] Production of esters from primary alcohols by dehydrogenation using bromous acid or a salt thereof in acid medium is described in JP-A-59/025334.

[0017] In SU-A-362814 there is described a process for production of ethyl acetate by dehydrogenation of ethanol at 180° C. to 300° C. in the presence of a copper catalyst containing zinc as an activator with an ethanol feed rate of 250 to 700 liters per liter of catalyst per hour.

[0018] The dehydrogenation of ethanol to form ethyl acetate is described in GB-A-287846. This proposes use of a dehydrogenating agent, such as a copper catalyst, a temperature of from 250° C. to 500° C., and a pressure of more than 10 atmospheres (1.013x10⁶ Pa).

[0019] Vapor phase contact of ethanol at a temperature above its critical temperature with a catalyst comprising copper and a diffusely reducible oxide, such as zinc oxide or manganese oxide, is proposed in GB-A-312345, use of a temperature of 375° C. and a pressure of 4000 psi (27.58 Mpa) being suggested.

[0020] GB-A-470773 teaches a process for conversion of ethanol to ethyl acetate by dehydrogenating ethanol over a catalyst consisting of a reduced metal, for example, copper on insulatian earth with 10% uranium oxide as promoter, maintained at a temperature of 220° C. to 260° C., removing by condensation some of the gas-vapor product rich in hydrogen resulting from the reaction, and returning the gaseous remainder rich in hydrogen to the catalyzing zone.

[0021] EP-A-0151886 describes a process for the preparation of C₂⁺ esters of alkylcarboxylic acids from C₂⁺ primary alcohols which comprises contacting a vaporous mixture containing a primary C₂⁺ alkanol and hydrogen in an alkanol: hydrogen molar ratio of from 1:1 to about 1000:1 at a combined partial pressure of alkanol and hydrogen of about 0.1 bar (103 Pa) up to about 40 bar (4x10⁷ Pa) and at a temperature in the range of from about 180° C. to about 300° C. in a catalytic reaction zone with a catalyst consisting essentially of a reduced mixture of copper oxide and zinc oxide, and recovering a reaction product mixture containing a primary C₂⁺ alkanol ester of an alkylcarboxylic acid which ester contains twice as many carbon atoms as the primary C₂⁺ alkanol.

[0022] In EP-A-0201105 there is described a method for converting primary alcohols, such as ethanol, to the corresponding alkane esters which involves the regulation of the mole feed ratio of hydrogen gas to alkanol in the reaction zone of a copper-chromite containing catalyst.
One method of separating ethyl acetate from ethanol and water involves extractive distillation with an extractive agent comprising polyethylene glycol and diethylene glycol, diethylene glycol, or triethylene glycol as described in U.S. Pat. No. 4,569,726 or with an extractive agent containing dimethyl sulphoxide as described in U.S. Pat. No. 4,379,028.

Separation of ethyl acetate from a composition comprising ethyl acetate, ethanol and water is described in JP-A-05/185392 by feeding the composition to a distillation column to obtain a quasi-azeotropic mixture comprising ethyl acetate, ethanol and water, condensing it, separating the condensate into an organic layer and an aqueous layer, returning the organic layer to the column, and recovering ethyl acetate as a bottom product from the column.

EP-A-0331021 describes how carbonylation of olefins to produce monocarboxylate esters causes formation of aldehydes and acetals as byproducts. Monocarboxylate esters produced in this way are subjected to a three step purification process involving treatment with a strongly acidic agent, followed by hydrogenation and distillation. The initial treatment with a strongly acidic agent is intended to convert acetals to vinyl ethers and aldehydes and acetals to aldehydes. The subsequent hydrogenation step then converts these compounds to byproducts which are more easily separated from the desired monocarboxylate ester.

EP-A-0101916 contains a similar disclosure regarding carbonylation of olefins to give monocarboxylate esters. It proposes treatment of the monocarboxylate ester with hydrogen at elevated temperature in the presence of an acidic ion exchanger or zeolite doped with one or more metals of Group VIII of the Periodic Table, followed by hydrogenation. It is stated that acetals present as byproducts are converted to vinyl ethers which are converted by hydrogenation to low boiling esters or the aldehydes and acetals are converted to high boilers by an aldol reaction. Unsaturated ketones are converted to saturated ketones.

U.S. Pat. No. 4,435,595 describes the use of reactive distillation to produce high-purity methyl acetate, by esterifying methanol and acetic acid. The process provides for the use of acetic acid and methanol which flows in counter-current through a single reactive distillation column in the presence of an acid catalyst. The acetic acid, in addition to being a reagent, also acts as an extracting agent for the non-reacted methanol and for the water which has been produced. Therefore, the methyl acetate is separated continuously from the acid and removed from the top of the column.

SUMMARY

In an embodiment, a method of purifying an ethyl acetate stream comprises contacting an inlet stream with a solvent, transferring at least a portion of the impurity compound from the inlet stream into the solvent to form an extract and a purified product, separating the extract from the purified product, separating the portion of the impurity compound from the extract, forming an impurity stream and a regenerated solvent, and recycling at least a portion of the regenerated solvent to contact the inlet stream. The inlet stream comprises ethyl acetate and an impurity compound, and the extract comprises the solvent and the portion of the impurity compound transferred from the inlet stream.

In an embodiment, a reactive distillation system for producing high purity ethyl acetate from ethanol comprises a reactive distillation column, an extraction unit, and a stripping unit. The reactive distillation column comprises a dehydrogenation catalyst, an ethanol inlet configured to pass an ethanol feed over the dehydrogenation catalyst, a top product gaseous hydrogen removal passage, and a bottoms product liquid ethyl acetate removal passage. The extraction unit is configured to receive a liquid ethyl acetate product stream from the reactive distillation column through the bottoms product liquid ethyl acetate removal passage, contact a liquid solvent feed stream with the liquid ethyl acetate product stream, provide an extract stream comprising a portion of any impurities in the liquid ethyl acetate product stream, and provide a purified product stream. The stripping unit is configured to receive the extract stream from the extraction unit, separate the portion of the impurities from the extract stream, provide an outlet impurities stream, and provide a regenerated solvent stream back to the extraction unit as at least a portion of the liquid solvent feed stream.

In an embodiment, a reactive distillation process producing high purity ethyl acetate from ethanol comprises feeding a feed stream comprising ethanol to a reactive distillation column, contacting the ethanol with a catalyst, dehydrogenating ethanol over the catalyst in the liquid phase during the distillation process, removing ethyl acetate during the distillation process as a bottoms product, and removing hydrogen during the distillation process as a top product.

These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and the advantages thereof, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description.

FIG. 1 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 1 and 5 atmospheres (atm) for an embodiment.

FIG. 2 shows reactive residue maps for conversion of ethanol to ethyl acetate at pressures of 10 and 20 atm for an embodiment.

FIG. 3 shows a simplified schematic of a reactive distillation system according to an embodiment.

FIG. 4 shows a simplified schematic of a reactive distillation system according to another embodiment.

FIG. 5 shows a simplified schematic of a reactive distillation system according to still another embodiment.

FIG. 6 shows a simplified schematic of a reactive distillation system according to yet another embodiment.

FIGS. 7(a) and 7(b) shows a simplified schematic of a reactive distillation system according to an embodiment.

FIGS. 8(a) and 8(b) shows a simplified schematic of a reactive distillation system according to another embodiment.

FIG. 9 illustrates a schematic flow diagram of a reactive distillation system with a recycle according to an embodiment.

FIG. 10 illustrates a schematic flow diagram of a product separation system according to an embodiment.

FIG. 11 illustrates a schematic flow diagram of a product separation system according to another embodiment.

FIG. 12 illustrates a schematic flow diagram of a stripping section according to another embodiment.

FIG. 13 illustrates a schematic co-current extraction flow scheme according to an embodiment.
[0046] FIG. 14 illustrates a schematic counter-current extraction flow scheme according to an embodiment.

[0047] FIG. 15 illustrates a schematic cross-current extraction flow scheme according to an embodiment.

[0048] FIG. 16 illustrates a chart demonstrating the results of an extraction of 2-butane from ethyl acetate.

[0049] FIG. 17 illustrates another chart demonstrating the results of an extraction of 2-butane from ethyl acetate.

[0050] FIG. 18 illustrates another chart demonstrating the results of an extraction of 2-butane from ethyl acetate using several extracting solution compositions.

DETAILED DESCRIPTION

[0051] A reactive distillation system and process are disclosed herein for producing high purity ethyl acetate from ethanol. This process is beneficial as it provides an improved commercial method of upgrading ethanol to ethyl acetate, a more valuable product. This improved commercial process may be used where there is a supply and/or a surplus supply of ethanol. Further, this process reduces and/or eliminates the need for a separate acetaldehyde or acetic acid plant to provide the precursors for the ethyl acetate production process.

The raw material may comprise only ethanol, which may present an advantage relative to other processes requiring multiple feedstocks. In addition, bio-derived ethanol may be used to allow the process to be operated from renewable ethanol sources. Further, the present system and method may utilize base-metal catalysts, which may be less expensive than the precious metal-based catalysts of other ethyl acetate production routes. Such catalysts can comprise copper, and may be composed of copper oxide mixed with one or more additional metals and/or metal oxides. The present systems and methods may allow for a one-step ethyl acetate production process, which may be advantageous relative to other processes that require further steps to purify the ethyl acetate product, including a selective removal of 2-butane, which forms a low boiling azeotrope with ethyl acetate. Each of these advantages may be provided in a process that can also be less expensive than alternative processes by ethyl acetate production from ethanol.

[0052] In an embodiment, the present systems and methods can provide a route to ethyl acetate by dehydrogenation and dimerization of ethanol which is capable of yielding high purity ethyl acetate from ethanol feed streams containing significant amounts of byproducts or impurities. One issue in the production of ethyl acetate by dehydrogenation of ethanol is that the reaction product mixture is commonly a complex mixture including esters, alcohols, aldehydes and ketones. From a distillative separation point of view, the mixture is further complicated due to the presence of azeotropes. The reaction product mixture commonly contains components with boiling points close to ethyl acetate (such as n-butyraldehyde and/or butan-2-one), including components which can form azeotropes with ethyl acetate, and/or other components of the mixture. This may present a challenge when high purity ethyl acetate is desired.

[0053] In chemical processing, chemical reaction and the purification of the desired products by distillation may be carried out sequentially. The performance of this chemical process structure may be improved by the integration of reaction and distillation in a single being multifunctional process unit. This integration concept is called “reactive distillation.” As advantages of this integration, chemical equilibrium limitations may be overcome, higher selectivities may be achieved, and the heat of reaction may be used in situ for distillation, auxiliary solvents may be avoided, and/or azeotropic and/or closely boiling mixtures may be more easily separated. Increased process efficiency and reduction in overall capital costs may result from the use of this approach.

[0054] A reactive distillation system comprises at least one separator and/or reactor (e.g., a distillation tower, side reactor, etc.) in which a reaction is occurring. In general, suitable separators may include any process equipment suitable for separating at least one inlet stream into a plurality of effluent streams having different compositions, states, temperatures, and/or pressures. For example, the separator may be a column having trays, packing, or some other type of complex internal structure. Examples of such columns include scrubbers, strippers, absorbers, adsorbers, packed columns, and distillation columns having valve, sieve, or other types of trays. Such columns may employ weirs, downspouts, internal baffles, temperature control elements, and/or pressure control elements. Such columns may also employ some combination of reflux condensers and/or reboilers, including intermediate stage condensers and reboilers. In an embodiment, the reactive distillation system described herein may comprise a distillation tower having at least one catalyst disposed therein.

The catalyst may take a variety of forms, and the separator may comprise any combination of catalyst and separator structures. For example, the separator may comprise sequential layers of catalysts and distillation packing and/or the packing may comprise catalytic elements such as pellets that act as a structured packing. In some embodiments, the reactive distillation system described herein may comprise a distillation tower comprising one or more side reactors comprising at least one catalyst disposed therein, where the one or more side reactors are coupled to and are in fluid communication with the distillation tower.

[0055] As indicated above, the present systems and methods provide for the production of ethyl acetate from ethanol at a relatively low cost, along with a plant or distillation system with significantly reduced complexity using reactive distillation. The present disclosure further provides an improved process for the production of high purity ethyl acetate from ethanol, or from a feedstock comprising a major proportion of ethanol and a minor proportion of impurities such as isopropanol and iso-butanol. While not commonly present in ethanol feed streams, impurities that can poison the particular catalyst used should be limited, avoided and/or removed. For example, sulfur or nitrogen heterocyclic compounds can frequently act as catalyst poisons and, if present, should be removed before introducing the ethanol feed stream to the reactive distillation column. In an embodiment, the ethanol feed may comprise water. The presence of water in the ethanol feed does not severely reduce the performance of the catalysts, which can tolerate up to 5% water by weight in the ethanol. Ethanol conversion is reduced when using an ethanol source with significant water content, but the reaction selectivity increases. The use of an ethanol feed comprising a small amount of water may be advantageous by allowing for the use a potentially less expensive ethanol source in the form of the ethanol/water azeotrope (about 4.4% water by weight). The effects of water are demonstrated in the Examples described herein.

[0056] Ethyl acetate can be produced from ethanol according to the following reactions:

\[ C_2H_5OH \rightarrow CH_3COOH + H_2 \]

\[ CH_3COOH + CH_3OH \rightarrow CH_3COOC_2H_5 + H_2O \]
The Tishchenko reaction may also provide a potential reaction route for the production of ethyl acetate from ethanol:

\[ \text{C}_2\text{H}_5\text{OH} \rightarrow \text{CH}_3\text{CHO} + \text{H}_2 \]

\[ 2\text{CH}_3\text{CHO} \rightarrow \text{CH}_3\text{COOC}_2\text{H}_5 \]

In an embodiment, ethanol reacts in a single continuous reactive distillation column which provides sufficient residence time to achieve a relatively high conversion of ethanol. In an embodiment, the reactive distillation column may be configured to provide a conversion of ethanol of at least about 10% and a selectivity of at least about 60%, as described in more detail herein. Table 1 shows the effect of pressure on the boiling point of the pure components and azeotrope in the mixture. The azeotrope between ethanol and ethyl acetate is substantially avoided above a pressure of 13 atm.

TABLE 1

<table>
<thead>
<tr>
<th>Boiling point of reaction components.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling Point, °C</td>
</tr>
<tr>
<td>P = 1 atm</td>
</tr>
<tr>
<td>P = 5 atm</td>
</tr>
<tr>
<td>P = 10 atm</td>
</tr>
<tr>
<td>P = 20 atm</td>
</tr>
<tr>
<td>P = 30 atm</td>
</tr>
<tr>
<td>P = 40 atm</td>
</tr>
<tr>
<td>Hydrogen</td>
</tr>
<tr>
<td>-161</td>
</tr>
<tr>
<td>-137.6</td>
</tr>
<tr>
<td>-123.7</td>
</tr>
<tr>
<td>-106.5</td>
</tr>
<tr>
<td>-94.3</td>
</tr>
<tr>
<td>-84.5</td>
</tr>
<tr>
<td>Acetaldehyde</td>
</tr>
<tr>
<td>20.4</td>
</tr>
<tr>
<td>71.9</td>
</tr>
<tr>
<td>101.1</td>
</tr>
<tr>
<td>136.4</td>
</tr>
<tr>
<td>160.7</td>
</tr>
<tr>
<td>180</td>
</tr>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>78.3</td>
</tr>
<tr>
<td>125.2</td>
</tr>
<tr>
<td>150.2</td>
</tr>
<tr>
<td>179</td>
</tr>
<tr>
<td>198</td>
</tr>
<tr>
<td>212.7</td>
</tr>
<tr>
<td>Ethyl acetate</td>
</tr>
<tr>
<td>77.7</td>
</tr>
<tr>
<td>136</td>
</tr>
<tr>
<td>160.5</td>
</tr>
<tr>
<td>210.3</td>
</tr>
<tr>
<td>238.4</td>
</tr>
<tr>
<td>260.7</td>
</tr>
<tr>
<td>Ethanol/Ethyl acetate azeotrope</td>
</tr>
<tr>
<td>71.7</td>
</tr>
<tr>
<td>123.5</td>
</tr>
<tr>
<td>150.1</td>
</tr>
<tr>
<td>No Azeo</td>
</tr>
<tr>
<td>No Azeo</td>
</tr>
<tr>
<td>No Azeo</td>
</tr>
</tbody>
</table>

[0058] Residue curve maps can be used to indicate feasible product compositions for distillation columns. In the presence of reaction along with separation, reactive residue curve maps can be used to determine feasible products from a reactive distillation column. Reactive residue curve maps at a pressure of 1 atm and 5 atm respectively are shown in FIG. 1. The stable nodes in the diagram are ethanol and ethyl acetate, and, therefore, it is possible to design a reactive distillation column where either ethanol or ethyl acetate can be obtained as the bottoms product. Hydrogen is an unstable node in the diagram and can be obtained as the distillate. Acetaldehyde and the ethanol/ethyl acetate azeotrope are saddle points in the diagram.

[0059] Reactive residue curve maps at pressures of 10 atm and 20 atm respectively are shown in FIG. 2. The reactive residue curve maps for any pressure above 20 atm are substantially similar to the reactive residue curve map at 20 atm. In view of the reactive residue maps discussed above, a set of reactive distillation systems effective to produce high purity ethyl acetate from ethanol have been designed. The reactive distillation column can have single or multiple feed locations.

Reactive Distillation Column Configurations

[0061] The present systems and methods provide a reactive distillation system in which ethanol may be the sole or primary component of the feed. In some embodiments, the ethanol feed is used in combination with a separate, second feed of hydrogen. Reference to a "single feed" to a reactive distillation column means that the column has only one chemical feed stream supplying intended reactant(s) to the column. Nonetheless, such a single feed distillation column may have multiple entry points for the reactant, or recycling feed streams where a part of the reactant liquid or a partial distillate is drawn from the column and fed back into the column at a different point, e.g., to achieve improved separation and/or more complete reaction. A "single ethanol feed" thus refers to a single feed stream, in which ethanol is the sole or at least the primary constituent. In contrast, the term "dual feed" in the context of a distillation column refers to two separate chemical feed streams. For example, in some of the present embodiments, dual feeds are an ethanol feed and a separate hydrogen feed. The term "reactive distillation column" is used conventionally to refer to a distillation column in which both reaction and separation is performed. In this case, the primary and desired reaction is the conversion of two ethanol molecules to one ethyl acetate molecule with release of two hydrogen molecules. Thus, the present invention provides systems and methods for the production of ethyl acetate from ethanol which includes reacting ethanol over a suitable dehydrogenation and/or dimerization catalyst, thereby producing ethyl acetate and hydrogen.

[0062] In an embodiment, a single reactive distillation column is used. Hydrogen gas is removed (e.g., continuously) from the top of the reactive distillation column as an overhead stream. Ethyl acetate is removed (e.g., continuously) from the bottom of the column as a bottoms stream. Optionally, contaminating byproducts present following reaction of the ethanol over the dehydrogenation catalyst can be separated from the ethyl acetate product stream. Various byproduct separation schemes are possible including, but not limited to, reacting the byproducts in the product stream over a suitable hydrogenation catalyst in the lower part of the column or in a separate hydrogenation reactor. The hydrogenation can convert difficult to separate byproducts into species which are easier to separate from the ethyl acetate. Consequently, the process also include purifying the ethyl acetate by distilling out resulting hydrogenated byproducts. In some embodiments, an extraction process may be used selectively remove one or more byproducts from the ethyl acetate products stream. Consequently, the process may also include purifying the ethyl acetate by contacting the product stream with an extractant, which can be regenerated and recycled to the extraction system.

[0063] In an embodiment, the reactive distillation column is configured for the dehydrogenation of ethanol with the formation of ethyl acetate. The reaction is accomplished by passing the ethanol feed stream over a dehydrogenation catalyst under conditions where ethyl acetate is formed and hydrogen and ethyl acetate are withdrawn as top and bottoms products respectively. Such product draws drive the thermodynamics of the process toward the desired products. In its
A single feed of ethanol is shown schematically in FIG. 3 can produce hydrogen as a distillate and ethyl acetate as a bottoms product. Column 10 contains a generally central catalyst zone 12, and usually will include a top stage or non-reactive rectifying section 13 and a bottom stage or non-reactive stripping section 15. Ethanol feed 14 is commonly fed to the middle part of the reactive distillation column. Distillate removed at the top of the column is passed through a partial condenser 16, and hydrogen is separated from lower boiling constituents in reflux tank 18. The hydrogen may leave the system as an overhead product stream 19, which in an embodiment may comprise trace amounts of additional components including ethanol, ethyl acetate, and/or one or more reaction byproducts. The condensed lower boiling constituents (i.e., reflux), or at least some portion thereof, can be cycled back to the column for further reaction and/or separation. The bottoms product can be passed through reboiler 20, where a portion of the bottoms product is evaporated and added back to the bottom of the column. The remaining bottoms product may pass out of the system as product stream 22. Alternatively, only a portion of the bottoms product may be passed through reboiler 20, with the vapor portion passing back to the bottom of the column and the remainder of the bottoms product being combined with any bottoms product bypassing the reboiler 20 and passing out of the system as product stream 22 for further processes and/or use as a final product. The product stream 22 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction. The column reflux and reboil ratios are maintained such that essentially pure ethyl acetate is obtained as the bottoms product. In an embodiment, the bottoms product stream 22 may comprise greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

During operation, the reactants and products flow through the reactor/column reacting and flashing along the length of the reactor/column. In an embodiment, the reaction of the reactants and/or products may occur in the catalyst zone 12, and the reactions may occur in the vapor and/or liquid phase. While not intending to be limited by theory, it is believed that the dehydrogenative dimerization of ethanol to ethyl acetate may occur over the dehydrogenation and dimerization catalysts described herein in the liquid phase. It has not been previously recognized that the dehydrogenation and dimerization conversion of ethanol to ethyl acetate would occur in the liquid phase. The use of a liquid phase reaction may allow for reactive distillation to be effectively used for converting ethanol into ethyl acetate and hydrogen. Specific catalysts useful in the reactive distillation systems and methods disclosed herein are discussed in more detail below. Ethyl acetate and hydrogen are produced due to the reaction over the dehydrogenation and dimerization catalyst. Byproducts including, but not limited to, aldehydes, such as acetaldehyde, n-butyaldehyde, and/or crotonaldehyde; ethers, such as ethyl ether and n-butyl ether; ethyl acetate; ketones such as 2-butanone, acetone; and other alcohols, such as isobutanol, 2-butanol, 2-ethylbutanol, n-hexanol, and/or 2-ethylhexanol may also be produced during the reaction. The removal of the overhead stream 19 comprising hydrogen, which may occur by flashing, increases the extent of reaction. In general, the hydrogen concentration increases from the middle part of the column towards the top of the column. At pressures of about 13 bar or lower, as ethyl acetate is formed from the reactants, an azo trope between ethyl acetate and ethanol occurs. This azo trope may result in the overhead product 19 that leaves the top of the reactive distillation column 10 containing ethanol/ethyl acetate and/or acetaldehyde in addition to hydrogen. A partial condenser 16 allows hydrogen to be removed as a distillate, while acetaldehyde and ethanol are recycled back to the top of the reactive distillation column. At a pressure above about 13 atm, the ethyl acetate and ethanol azeotrope disappears, which improves the operation of the reactive distillation column.

The column 10 can be operated at any suitable pressure between about 1 atm and about 80 atm. In an embodiment, the column 10 may be operated at a pressure ranging from about 1 atm to about 5 atm, about 5 atm to about 10 atm, about 7 atm to about 12 atm, about 13 atm to about 15 atm, about 13 atm to about 20 atm, about 15 atm to about 20 atm, about 15 atm to about 30 atm, about 20 atm to about 30 atm, about 20 atm to about 50 atm, about 30 atm to about 40 atm, about 40 atm to about 50 atm, or about 50 atm to about 60 atm, about 60 atm to about 70 atm, about 60 atm to about 80 atm, or about 70 atm to about 80 atm. In an embodiment, the reactive distillation is performed at a pressure where ethanol/ethyl acetate azeotrope is not present. The temperature profile in the column is dictated by the mixture boiling point along the height of the column. In an embodiment the temperature within the column may range from about 100 °C to about 350 °C, alternatively about 150 °C to about 250 °C. The column 10 may comprise any number of stages equivalent to a number of theoretical stages sufficient to effect the reaction and separation of ethyl acetate to a desired purity. In an embodiment, the number of stages or the number of height equivalents of a theoretical plate (HETP) may range from about 1 to about 100, including for example from about 1 to about 10, about 10 to about 20, about 10 to about 50, about 20 to about 30, about 20 to about 70, about 30 to about 40, about 30 to about 50, about 30 to about 100, about 50 to about 100, or about 70 to about 100. As described in more detail below, a relatively high conversion of ethanol to products can be achieved by the counter-current flow of reactants and products in addition to overcoming the reaction equilibrium by removal of products through the concurrent distillation within the column 10.

In an embodiment, the systems and methods may also include hydrogenating contaminants or reaction byproducts in the bottoms stream or in the reacted liquid after it has passed over the dehydrogenation catalyst and separating the hydrogenated contaminants or byproducts from the ethyl acetate. As noted above, aldehydes and/or ketones such as n-butyraldehyde and butan-2-one may be produced as byproducts in the reaction. These byproducts boil at temperatures close to the boiling point of ethyl acetate and may be difficult to separate from ethyl acetate. FIG. 4 shows a process schematic where the bottoms product 22 from the reactive distillation column 10 illustrated in FIG. 3 is sent to a hydro-
generation reactor 24 comprising a hydrogenation catalyst 26 with a hydrogen co-feed 28. Suitable hydrogenation catalyst(s) may comprise various components and are described in more detail herein. At least a portion of the n-butyraldehyde and/or butan-2-one impurities and/or byproducts can be hydrogenated and can then be separated using a separator 32. The separator 32 may comprise any of the types of separators described herein with respect to the reactive distillation system. Alternatively or in addition to the separators already described, the separator 32 may be a phase separator, which is a vessel that separates an inlet stream into a substantially vapor stream and a substantially liquid stream, such as a knock-out drum, flash drum, reboiler, condenser, or other heat exchanger. Such vessels also may have some internal baffles, temperature control elements, and/or pressure control elements, but generally lack any trays or other type of complex internal structure commonly found in columns. The separator also may be any other type of separator, such as a membrane separator. In a specific embodiment, the separator is a knock-out drum. Finally, the separator may be any combination of the aforementioned separators arranged in series, in parallel, or combinations thereof. In an embodiment, separator 32 comprises a distillation column. The outlet of the hydrogenation reactor 24 may be passed through a heat exchanger 30 (e.g., a condenser) and cooled before entering the separator 32. The heat exchanger 30 may be any equipment suitable for heating or cooling one stream using another stream. Generally, the heat exchanger 30 is a relatively simple device that allows heat to be exchanged between two fluids without the fluids directly contacting each other. Examples of suitable heat exchangers 30 include, but are not limited to, shell and tube heat exchangers, double pipe heat exchangers, plate fin heat exchangers, bayonet heat exchangers, reboilers, condensers, evaporators, and air coolers. In the case of air coolers, one of the fluids comprises atmospheric air, which may be forced over tubes or coils using one or more fans.

The bottoms product stream 36 from the separator 32 may comprise ethyl acetate and may have a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight. Unconverted hydrogen and the hydrogenated byproducts may be removed as an overhead product 34, and may be used, for example, as fuel or as a feed to one or more processes. In an embodiment, the separator 32 may be operated between a pressure of 1 atm and 80 atm.

In an embodiment, the bottoms product stream 36 may pass to another separator. The separator may then separate the bottoms product stream into an ethyl acetate stream and a byproduct stream comprising one or more heavier hydrogenation products produced in the hydrogenation reactor 26. This separation scheme may allow the resulting ethyl acetate stream to have a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

In another embodiment of the invention, the reactive distillation column has two feeds. Ethanol may be fed to the upper part of the column (upper feed), and hydrogen may be fed to the lower part of the column (lower feed). A schematic for the double feed reactive distillation column is schematically illustrated in FIG. 5. This system includes column 40 containing catalyst 42 in catalyst zone 44, and commonly may include a top stage or non-reactive rectifying section 50 and a bottom stage or non-reactive stripping section 52. In the illustrated system, ethanol feed 46 is delivered at or near the top of the catalyst zone 44, and the hydrogen feed 48 is delivered at or near the bottom of catalyst zone 44. It should be recognized columns can be designed with the ethanol feed 46 location in other locations, e.g., within the catalyst zone 44 but above the hydrogen feed 48, such as from the approximate middle of the catalyst zone 44 to the top of the column 40. Similarly, columns with the hydrogen feed 48 in other locations can also be designed, e.g., with the hydrogen feed 48 from the approximate middle of the catalyst zone 44 to the bottom of the column 40 or even higher within the catalyst zone 44 but below the ethanol feed 46. In an embodiment, the ethanol feed 46 and the hydrogen feed 48 are separated sufficiently to allow byproduct hydrogenation to be substantially completed before hydrogen from the feed reaches substantial concentrations of ethanol being dehydrogenated. Ethanol reacts over the catalyst producing ethyl acetate and hydrogen. Examples of suitable dehydrogenation and dimerization catalysts are described in more detail herein.

Due to boiling point differences, hydrogen moves towards the top of the column 40 and ethyl acetate moves towards the bottom of the column 40. Acetaldehyde may be produced during the reaction and may move up in the column 40. At least a portion of the acetaldehyde, if present, can be condensed in condenser 54 (e.g., a partial condenser, or a total condenser), passed through reflux tank 56, and recycled back to column 40 as reflux. A product stream 59 comprising hydrogen is taken out as distillate from the reflux tank 56. A part of the bottom draw is taken out as the ethyl acetate product stream 58, while the remaining part is passed through reboiler 60 to be recycled to the column 40. In an embodiment, the bottom draw may be passed through a reboiler (e.g., similar to reboiler 60) and optionally passed to a separator where the vapor portion may pass to the column 40 while at least a portion of the remainder is taken out as the ethyl acetate product stream 58. The stream passing through the reboiler 60 provides the evaporation effect and vapor flow for operating the column 40. The product stream 58 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction.

Byproducts such as n-butyraldehyde and butan-2-one produced in the reaction may have boiling points close to the boiling point of ethyl acetate. The lower hydrogen feed 48 is useful in hydrogenating the by-products to produce components that can be separated easily from ethyl acetate. The ratio of the hydrogen feed to the ethanol feed can be adjusted to minimize the amount of close boiling byproducts, while not excessively reducing ethyl acetate to ethanol. In an embodiment, the molar ratio of hydrogen to ethanol ranges from about 1:10 to about 10000:1, e.g., from about 1:10 to about 1:1, from about 1:1 to about 5:1, from about 1:1 to about 10:1, from about 5:1 to about 25:1, from about 5:1 to about 50:1, from about 1:1 to about 100:1, from about 50:1 to about 200:1, from about 50:1 to about 400:1, from about 100:1 to about 500:1, from about 100:1 to about 1000:1, from about 200:1 to about 1000:1, or from about 500:1 to about 1000:1. Hydrogen product from the reaction leaves at the top of the column. In an embodiment, the column 40 may operate at any of the conditions (e.g., operating pressure, operating temperature, etc.) discussed herein with respect to column 10 in FIG. 3. In addition, the column 40 may have any number of stages, and in an
embodiment, the column 40 may have a number of stages as described with respect to column 10 in FIG. 3.

[0073] As schematically illustrated in FIG. 6, the reactive distillation column 70 has two feeds 90, 82 and uses two catalyst zones, identified as an upper zone 72 containing Catalyst A 74 and a lower catalyst zone 76 containing Catalyst B 78. Ethanol feed 80 is fed to the upper part of the column 70 (upper feed). Hydrogen feed 82 is fed to the lower part of the column 70 (lower feed). The molar ratio of ethanol to hydrogen may fall within any of the ranges described above with respect to FIG. 5 (e.g., from about 1:10 to about 1000:1, and all sub-ranges). Ethanol may react over the upper catalyst (Catalyst A 74) producing ethyl acetate and hydrogen. Examples of suitable upper catalysts are described in more detail herein with respect to the dehydrogenation and dimerization catalysis. As with previous schematic designs shown, the column 70 will usually include a top stage or non-rective rectifying section 71 and a bottom stage or non-reactive stripping section 79.

[0074] Due to boiling point differences, hydrogen moves towards the top of the column 70 and ethyl acetate moves towards the bottom of the column 70. Acetaldehyde may be produced during the reaction and may move up in the column 70. At least a portion of the acetaldehyde, if present, can be condensed in condenser 84 and recycled back to the reaction zone through reflux tank 86. Byproducts such as n-butylaldehyde and butan-2-one produced in the reaction can have boiling points close to the boiling point of ethyl acetate. The lower hydrogen feed is useful in hydrogenating the by-products over the lower catalyst (Catalyst B) to produce components that can be separated easily from ethyl acetate. Examples of hydrogenation catalysts (Catalyst B) are described in more detail herein. A product stream 88 comprising hydrogen from the reaction leaves at the top of the column 70. A portion of the bottom draw is taken out as the ethyl acetate product stream 92, while the remaining portion is passed through reboiler 90 to be recycled to the column 70. In an embodiment, the bottom draw may be passed through a reboiler (e.g., similar to reboiler 90) and optionally passed to a separator where the vapor portion may pass to the column 70 while at least a portion of the remainder is taken out as the ethyl acetate product stream 92. The stream passing through the reboiler 90 provides the evaporation effect and vapor flow for operating the column 70. The product stream 92 may comprise the ethyl acetate produced in the column along with unreacted ethanol and potentially any side products produced by the reaction. Subsequent purification of product stream 92 comprising ethyl acetate may be needed to remove the dehydrogenated byproducts from the ethyl acetate, e.g., using a separator such as that as shown in FIG. 4 as separator 32, which in an embodiment may comprise a distillation column.

[0075] In an embodiment, the column 70 may operate at any of the conditions (e.g., operating pressure, operating temperature, etc.) discussed herein with respect to column 10 in FIG. 3. In addition, the column 70 may have any number of stages, and in an embodiment have any number of stages as described with respect to column 10 in FIG. 3.

[0076] In the dual feed systems described above with respect to FIGS. 5 and 6, the hydrogen feed should be at a sufficiently low level that it does not significantly adversely affect the dehydrogenation of ethanol in the zone above, while being effective to hydrogenate the undesirable close boiling point byproducts. Feed rates of hydrogen can be adjusted empirically to optimize this balance. Commonly, the ratio of ethanol:hydrogen will be in a range of about 500:1 to 1:1 molar ratio, more commonly about 500:1 to 10:1 or 500:1 to 100:1.

[0077] In an embodiment, side reactors can be connected to a reactive distillation column to increase the catalyst holdup for improved reactant conversion. In the side reactor embodiment, the side reactor feed is withdrawn from the distillation column and the reactor effluent is returned back to the same column. An adequate amount of catalyst may be arranged in a side reactor system where traditional reactor types and catalyst structures can be used. Also, the reaction conditions within the side reactor such as temperature can be adjusted independently of those prevailing in the distillation column by appropriate heat exchange. In some embodiments, only the side reactor may comprise one or more catalysts, and the column may operate to separate the outlet of the side reactors. In this embodiment, the column may not contain a dehydrogenation catalyst, or in some embodiments, any catalyst at all.

[0078] Schematics for a side reactor reactive distillation column with a single catalyst are shown in FIG. 7. A single side reactor is shown, however, multiple side reactors along the length of the reactive distillation column can be used. FIG. 7(a) shows a feed 93 where the feed 93 to the side reactor 94 is bottom up and vapor phase. The outlet from side reactor 94 is stream 95 which is sent back to the distillation column 40 at any location in the column 40 above the location of feed 93. FIG. 7(b) shows a configuration where the feed 96 to the side reactor 97 is top down and liquid phase. The outlet from side reactor 97 is stream 98 which is sent back to the distillation column 40 at any location in the column 40 below the location of feed 96. The side reactors 94 and 97 each contain catalyst for converting ethanol into ethyl acetate. Examples of suitable catalysts are described in more detail herein.

[0079] The use of a side reactor using a liquid feed may allow for the reaction to occur in the liquid phase. While not intending to be limited by theory, it is believed that the dehydrogenative dimerization of ethanol to ethyl acetate may occur over the dehydrogenation and dimerization catalysts described herein in the liquid phase. As noted above, it has not been previously recognized that the dehydrogenation and dimerization conversion of ethanol to ethyl acetate would occur in the liquid phase. The use of a liquid phase reaction may allow for reactive distillation to be effectively used for converting ethanol into ethyl acetate and hydrogen.

[0080] While illustrated as a bottom up vapor phase design and a top down liquid phase design in FIGS. 7(a) and 7(b), the side reactors 94, 97 may also operate bottom up using a liquid phase draw from the column 40 and top down using a vapor phase draw from the column with the appropriate equipment such as pumps, compressors, valves, piping, etc. In an embodiment, the side reactors 94, 97 may be implemented as a single reactor vessel, or as a plurality of reactor vessels arranged in series and/or parallel. In an embodiment, a plurality of side reactors may be implemented as shown in FIGS. 7(a) and 7(b) along the length of the column as needed. In addition, the catalyst in both the column 40 and the side reactor 94 may convert ethanol into ethyl acetate, though the specific catalysts (e.g., catalyst formaldehyde and/or catalyst component loadings) in each of the column 40 and the side reactor 94, 97 may be the same or different. Suitable catalysts for converting ethanol into ethyl acetate
may be selected based on the expected operating conditions, which may vary between the column 40 and the side reactor 100, 106.

**[0081]** Schematics for a side reactor reactive distillation with two feeds and using two distinct catalyst zones are shown in FIG. 8. A single side reactor is shown for each catalyst zone in the reactive distillation column 70, however, multiple side reactors along the length of the reactive distillation column 70 can be used for each catalyst zone. FIG. 8(a) shows a configuration where the top zone feed 99 to the side reactor 100 is bottom up and vapor phase. The bottom zone feed 102 to another side reactor 103 is also bottom up and vapor phase. The outlet from side reactor 100 is stream 101 which is sent back to the distillation column at any location in the column above the location of feed 99. The outlet from side reactor 103 is stream 104 which is sent back to the distillation column at any location in the column above the location of feed 102. FIG. 8(b) shows a configuration where the top zone feed 105 to the side reactor 106 is top down and liquid phase. The bottom zone feed 108 to another side reactor 109 is also top down and liquid phase. The outlet from side reactor 106 is stream 107 which is sent back to the distillation column at any location in the column below the location of feed 105. The outlet from side reactor 109 is stream 110 which is sent back to the distillation column at any location in the column below the location of feed 108. Examples of suitable catalysts for side reactors 100 and 106 may include any of the dehydration and dimerization catalysts described in more detail herein. Examples of hydrogenation catalysts for side reactors 103 and 109 include any of the hydrogenation catalysts described in more detail herein.

**[0082]** While illustrated as a bottom up vapor phase design and a top down liquid phase design in FIGS. 8(a) and 8(b), the side reactors 100, 103, 106, 109 may also operate bottom up using a liquid phase draw from the column 70 and top down using a vapor phase draw from the column 70 with the appropriate equipment such as pumps, compressors, valves, piping, etc. In an embodiment, the side reactors 100, 103, 106, 109 may be implemented as a single reactor vessel, or as a plurality of reactor vessels arranged in series and/or parallel. In an embodiment, a plurality of side reactors may be implemented as shown in FIGS. 8(a) and 8(b) along the length of the column as needed. In addition, the respective catalysts in the column 70 and/or the side reactors 100, 106 may convert ethanol into ethyl acetate, though the specific catalysts (e.g., catalyst compositions, catalyst forms, and/or catalyst component loadings) in each of the column 40 and the side reactors 100, 106 may be the same or different. Suitable catalysts for converting ethanol into ethyl acetate may be selected based on the expected operating conditions, which may vary between the column 40 and the side reactors 100, 106. Similarly, the respective catalysts in the column 70 and/or the side reactors 103, 109 may comprise hydrogenation catalysts, though the specific catalysts (e.g., catalyst compositions, catalyst forms, and/or catalyst component loadings) in each of the column 70 and the side reactors 103, 109 may be the same or different. Suitable hydrogenation catalysts may be selected based on the expected operating conditions, which may vary between the column 70 and the side reactors 100, 106.

**[0083]** As schematically illustrated in FIG. 9, an ethyl acetate production system 200 may comprise a products separation and/or purification section 212 for use in removing a portion of any byproducts or impurities from the product stream. In some embodiments, the ethyl acetate product stream produced in the processes and systems described herein may comprise one or more impurities. In some embodiments, the ethyl acetate product stream produced in the reactive distillation systems described with respect to FIG. 3-8 may comprise less than about 10 wt. %, less than about 8 wt. %, less than about 6 wt. %, less than about 4 wt. %, less than about 2 wt. %, or less than about 1.5 wt. % impurities, and in some embodiments, more than about 0.1 wt. %, more than about 0.5 wt. %, or more than about 1 wt. %. The products separation section 212 may be configured to provide at least one product stream 216 comprising ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight. At least one additional stream 218 may be produced comprising the remaining components of the product stream 210 from the ethyl acetate production process 206 (e.g., a reactive distillation column as described above). In an embodiment, a plurality of streams can be produced in the separation section comprising a stream 216 predominantly comprising ethyl acetate, and a stream 218 predominantly comprising the impurities removed from the ethyl acetate. In some embodiments, the product stream 216 may undergo further processing to remove one or more impurities. For example, an optional dehydration process may be carried out to remove any water present in the product stream 216.

**[0084]** As schematically illustrated in FIG. 9, a system 200 for producing ethyl acetate may comprise a feed stream 202 comprising ethanol that can be fed to the reactive distillation system 206. In an embodiment, the reactive distillation system 206 may comprise any of the reactive distillation systems described with respect to FIG. 3-8 herein. The reactive distillation system may produce an overhead product stream 208 and a bottoms product stream 210. The overhead product stream 208 may comprise hydrogen along with trace amounts of other light components (e.g., ethanol, etc.) and may generally correspond to any of the streams 19, 59, and/or 88 as illustrated in FIGS. 3-8. Similarly, the bottoms product stream 210 may comprise at least an ethyl acetate, at least a portion of any unreacted ethanol, and/or additional reaction products (e.g., byproducts, impurities, etc.), and the bottoms product stream 210 may generally correspond to any of the streams 22, 36, 58, and/or 92 as illustrated in FIGS. 3-8.

**[0085]** A products separation section 212 may comprise the bottoms product stream 210 from the reactive distillation system 206. The products separation section 212 may comprise any number or type of separation units, which may employ pressure- or temperature-swing distillation, pressure- or temperature-swing adsorption, membrane-based separation, cryogenic distillation, extraction, and/or any other suitable separation technology, all of which may be used to generate a desired product distribution. The products separation section 212 may generally produce an ethyl acetate product stream 216. The ethyl acetate product stream 216 may comprise ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight. In addition to the ethyl acetate product stream 216, one or more additional streams may be produced by the products separation section 212. In an embodiment, an impurities stream 218 may be produced. The impurities stream 218 may comprise...
one or more reaction products (e.g., butanol, one or more aldehydes and/or ketones, etc.). Each of the potential product streams 216, 218 may exit the system as separate product streams and/or exit the system 200 for use as fuel and/or as a feed to additional downstream processes. While illustrated as separate streams 216, 218 one or more of these streams may exit the system 200 as a combined product stream.

[0086] In an embodiment as shown in FIG. 10, the separation section 212 may comprise an extraction process 300 for removing a portion of the impurities in the product stream 210. For example, an extraction process 300 may be used to separate at least a portion of one or more byproducts from the ethyl acetate in the product stream 210, thereby improving the quality and value of the ethyl acetate product stream. In this embodiment, the separation section 212 used to carry out the extraction process 300 may be the same or similar to the separation section described above with respect to FIG. 9. The extraction process 300 generally comprises an extraction section 250 in which the product stream 210 is contacted with a solvent in a solvent stream 254 to transfer or remove at least a portion of the impurities from the product. The extract stream 256 comprising the impurities transferred from the product can then be regenerated in a stripping section 252, which generally involves separating the impurities from the solvent to allow the impurities to be removed from the system and the solvent to be recycled.

[0087] The extraction process 300 may receive the bottoms product stream 210 from a reactive distillation system, which may comprise any of the reactive distillation systems described with respect to FIG. 3-8 herein. The extraction process 300 may comprise the extraction section 250 in which the bottoms product stream 210 is contacted with a solvent in a solvent stream 254. In an embodiment, the extraction section 250 comprises a liquid-liquid contact vessel suitable for contacting two liquid streams. Suitable vessels and extraction section 250 configurations are described in more detail herein. The solvent may draw a portion of one or more impurities from the bottoms product stream 210 into the solvent phase. The bottoms product stream 210 having the portion of the impurities removed may then exit the extraction section 250 as a purified product stream 216. The extract stream 256 comprising the solvent and the portion of the impurity compound transferred from the bottoms product stream 210 may then exit the extraction section 250 as an extract stream 256.

[0088] An optional drying section 258 may serve to remove any remaining solvent or a component of a solvent (e.g., water from an aqueous solvent) from the purified product stream 216. The resulting dried purified product stream 260 may then leave the system as the final product stream. Any suitable drying units may be used to remove at least a portion of the solvent from the purified product stream 216. Suitable drying units may include, but are not limited to, industrial dehydration units comprising adsorbents such as Zeolites, alumina, silica, and other drying agents arranged in a pressure and/or temperature swing configuration, and/or liquid absorption (e.g., liquid-liquid extraction, gas-liquid extraction, etc.) using a drying agent. The purified product stream 216 and/or the dried purified product stream 260 may comprise ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

[0089] In order to separate the impurities from the solvent, the extract stream 256 may be transferred to a stripping section 252. In an embodiment, the impurities may be removed using vapor-liquid stripping, heating, liquid-liquid phase separation, flashing and/or distillation, and/or any other suitable technique. Suitable vessels and stripping section 252 configurations are described in more detail herein. As shown in FIG. 10, the stripping section 252 may result in the separation of the impurities from the extract stream 256, thereby producing a liquid impurities stream 218 and/or a vapor impurities stream 262, and a regenerated solvent stream 254. In some embodiments, different components of the impurities may leave the separation section 212 as either a vapor or a liquid, including those generated by the solvent and/or any reactions within the separation section 212. The solvent may be regenerated by removing at least a portion of the impurities in the stripping section 252. In some embodiments, only a portion of any extracted impurities can be removed in the stripping section 252, and the resulting regenerated solvent stream 254 may comprise a minor amount of impurities. The regenerated solvent stream 254 may be recycled to the extraction section 250 to serve as the solvent. In some embodiments, a new solvent stream (e.g., a makeup solvent stream) may enter the extraction section separately or with the regenerated solvent stream 254 to serve as the solvent in the extraction section 250. The liquid impurities stream 218 and/or vapor impurities stream 262 may exit the system for various downstream uses. In an embodiment, the impurities stream may comprise commercially valuable chemicals that can be transferred for sale. In some embodiments, the impurities may be further separated before being sold, or alternatively, the impurities can be used as fuel or any other suitable use.

[0090] When used with the ethyl acetate production systems and processes described herein, the solvent used in the extraction process 300 may be selected to remove the expected impurities within the ethyl acetate product stream (e.g., bottoms product stream 210). As noted above, the synthesis of ethyl acetate by consecutive dehydration and condensation of ethanol to ethyl acetate is accompanied by the formation of relatively small amounts of byproducts. At least a portion of the byproducts comprising various aldehydes, ketones, and the like can be removed to improve the quality and purity of the ethyl acetate. In an embodiment, the extraction process 300 can be used to selectively extract at least a portion of the byproducts that may be present in the ethyl acetate. In an embodiment, the solvent may be configured to selectively react with and extract the impurities in the ethyl acetate. For example, the solvent may comprise one or compounds configured to reversibly react with the impurities, thereby allowing the reaction to remove the impurities from the ethyl acetate in the extraction section 250 and then be reversed to release the impurities in the stripping section 252.

[0091] In an embodiment, the solvent may comprise a fluid comprising one or more extracting agents. In an embodiment, the extracting agent may comprise a nucleophilic compound that can react with aldehydes and/or ketones to form a corresponding adduct. The resulting reaction products may have an increased solubility in the aqueous fluid, thereby allowing the adducts to leave the ethyl acetate product stream 210 and enter the solvent stream 254 to form the extract stream 256. Within the stripping section 252, the adduct equilibrium may be shifted to release the extracting agents from the impurities. The impurities may then be separated from the solvent comprising the extracting agents using any suitable separation technique such as vaporization and/or liquid-separation.
Various extracting agents can be used in the aqueous solvent. In an embodiment, the extracting agents can comprise sulfur and/or nitrogen. Suitable extracting agents can include, but are not limited to, hydrazine (NH₂H₂), hydroxyamine (NH₂OH), semicarbazide (H₂N=NH–CO–NH₂), phenylhydrazine (C₆H₅NH₂), phenylhydroxyamine (C₆H₅NH–OH), sodium hydrogen sulfite (NaHSO₃), sodium hydrogen sulfite (Na₂SO₃), sodium sulfite (Na₂SO₄), salts thereof, aqueous solutions thereof, and any combinations thereof. While any of these extracting agents can be used, reference will be made to sodium hydrogen sulfite in the following discussion as an example.

In an embodiment, an aqueous solution of sodium hydrogen sulfite can be used as a solid, which usually comprises a mixture of NaHSO₃ and Na₂SO₃. An aqueous solution can be made from the solid, and the use of an aqueous solution of sodium hydrogen sulfite provides an inexpensive, low toxicity solution that can serve as the solvent in the extraction process. In this embodiment, the aqueous solution can include sodium sulfite (Na₂SO₄). Sodium sulfite can be used by directly dissolving sodium sulfite in a solvent, or sodium hydroxide (NaOH) can be added to sodium hydrogen sulfite as a solid or in solution. Further, a mixture of sodium hydrogen sulfite and sodium sulfite can be used in an aqueous solution of sodium hydrogen sulfite to form the sulfite ion (SO₃²⁻). Thus any soluble hydrosulfite and/or sulfite compound can also be used in similar manner regardless of the counter ion. For example, hydrosulfite compounds including Na⁺, NH₃⁺ salts can also be used along with or in place of sodium hydrogen sulfite.

The aqueous solution comprising the hydrosulfite ion reacts reversibly with aldehydes and ketones such as 2-butanone, acetone, acetaldehyde, thereby rendering them more water soluble as sodium salts of hydrosulfite adducts of the compounds. For example, the following reaction may take place when the aqueous solution comprising the hydrosulfite ion is contacted with a fluid comprising a ketone (e.g., 2-butanone) as follows:

\[
\text{Na}^+\text{HSO}_3^- + \text{CH}_3\text{CH} = \text{O} + \text{CH}_3\text{CH}_2\text{C(OH)} \\
\rightarrow \text{Na}^+\text{HSO}_3^-\text{CH}_3\text{CH} = \text{O}^-\text{CH}_3\text{CH}_2\text{C(OH)}
\]

The resulting sodium salt of the 2-butanone sulfonate adduct has higher solubility in water compared to ethyl acetate thus leading to partial extraction of 2-butanone from the organic (ethyl acetate) phase, thereby increasing the ethyl acetate phase purity. The resulting adduct may be formed by various aldehydes and/or ketones, thereby providing for the ability to selectively improve the removal efficiency of the impurities in the ethyl acetate production process during the extraction process.

Within the extraction process, various factors may affect the extraction efficiency of the solvent within the extraction section including the concentration of the extracting agent in the solvent, the ratio of the solvent to the ethyl acetate product, and the temperature at which the extraction takes place. With respect to the concentration of the extracting agent in the solvent, there are several considerations that can have an affect on the concentration of the compound in the solvent. In general, a higher concentration of the extracting agent (e.g., NaHSO₃) in the aqueous fluid can reduce the ethyl acetate solubility in the solvent. However, as the concentration of the extracting agent rises above a certain amount, the resulting adduct may precipitate out of solution. Such precipitation may complicate a continuous process in terms of solids handling equipment. In general, the amount of the extracting agent in the aqueous fluid should be sufficient to provide an excess of the ions in solution but less than an amount that would result in precipitation of the resulting adduct in the extract, which indicates that the solubility limit of the adduct has been reached. Thus, the concentration of the extracting agent in the solvent may vary based on the concentration of the impurities in the ethyl acetate product stream. In an embodiment, the concentration of the extracting agent (e.g., sodium hydrogen sulfite) in the aqueous solution can vary. In an embodiment, the extracting agent can comprise sodium hydrogen sulfite, and the amount of sodium hydrogen sulfite in the aqueous solution can vary and generally range from about 50 grams to about 420 grams, from about 300 grams to about 420 grams of solid (e.g., a mixture of NaHSO₃ and Na₂SO₄ per liter of water. When the extracting agent is sodium hydrogen sulfite, the concentration may generally range from about 5 to about 42 grams per 100 milliliters of solution, or from about 50 to about 42 grams per 100 milliliters of solution at about 68°F (about 20°C). In an embodiment, the extracting agent may be provided in the form of sodium sulfite and/or a hydrate thereof, and the concentration may generally range from about 5 to about 68 grams per 100 milliliters of solution when the sodium sulfite is provided as sodium sulfite heptahydrate. The concentration of the extracting agent may vary based on the composition of the extracting agent, the form in which it is provided, the temperature of the solution, the composition of the solution, and the like.

With respect to the temperature at which the extraction process takes place, it has been discovered that the aqueous solvent generally increases at a lower temperature relative to a higher temperature extraction. Accordingly, lowering the temperature of the extraction process may result in a greater amount of the impurities being transferred from the ethyl acetate product to the solvent stream. In general, the extraction section may operate within a temperature range of between about 10°C to about 70°C, from about 15°C to about 60°C, or from about 20°C to about 50°C.

Once the aqueous solvent contacts the ethyl acetate product stream (e.g., bottoms product stream) in the extraction step, the aqueous fluid comprising the adducts can be separated from the organic ethyl acetate phase using liquid-liquid separation. The separated extract stream can then be used to perform an additional extraction of impurities from an ethyl acetate product stream and/or the extract can be transferred to the stripping section for regeneration. In general, the extract stream comprising the adducts can be treated in the stripping section to separate the organic compounds (e.g., the impurities, any dissolved ethyl acetate, etc.) from the aqueous solvent comprising the extracting agent. For example, the extract stream may be heated to reverse the adduct formation, and the organic phase can then be separated from the aqueous solution. In some embodiments, the adducts may be separated by crystallization followed by a subsequent treatment of the precipitated solids.

When the adducts remain dissolved in the aqueous fluid, the adducts can be decomposed by heating to reverse the equilibrium and release the impurities (e.g., the aldehydes/ketones) while regenerating the aqueous solution comprising...
the extracting agent for reuse. The impurities can then be separated using evaporation, distillation, and/or liquid-liquid phase separation. In an embodiment, the aqueous solution (e.g., the extract stream 256) may comprise the excess of sodium hydrogen sulfite, the dissolved sodium hydrogen sulfite adducts, and some amount dissolved ethyl acetate. The solution can be regenerated by heating the solution to a temperature suitable to reverse the adduct formation equilibrium. In an embodiment in which the nucleophile compound comprises sodium hydrogen sulfite, the regeneration can be achieved by heating the solution to a temperature between about 45°C and about 100°C. At this temperature, the sodium hydrogen sulfite adduct decomposes to release the impurities and the NaHSO3. The released impurities and any dissolved ethyl acetate can be separated from the aqueous solution and collected. In some embodiments, the organic compounds can be vaporized (e.g., in a flash tank) or distilled from the aqueous solution, and/or alternatively, the organic compounds can be separated based on a liquid-liquid phase separation. The remaining aqueous solution may comprise the regenerated solvent for use in the extraction process 300.

In an embodiment, the separation process within the stripping section 252 may result in some minor amount of the organic compounds remaining in the aqueous solvent.

During the heating process some amount of the extracting agent may decompose to form an additional impurity. For example, when the extracting agent comprises sodium hydrogen sulfite, heating may result in some sulfur dioxide being lost due to decomposition. The decomposition products can be captured using an aqueous NaHSO3 solution or an aqueous caustic solution (e.g., NaOH), which may be advantageous in preventing the release of the decomposition products to the atmosphere. The regenerated solvent solution in the stream 354 may have higher or lower extracting agent concentration than desired. The concentration may be adjusted through the addition of water, solid extracting agent, or an extracting agent solution until the desired concentration is reached.

In some embodiments, the adducts can be removed from the extract stream 256 by crystallization. For example, the adducts can be separated from the extract stream 256 by forming a sodium ketone/aldehyde hydrosulfite adduct crystals. If the adducts are crystallized out of solution, the resulting crystals can be separated physically. The crystals can then be heated to reverse the adduct formation. In an embodiment, the crystals may be dissolved in an aqueous solution prior to heating to reverse the adduct formation. The resulting organic impurities can then be separated from the extracting agent and any aqueous solution.

The extraction process can be carried out using various configurations and designs. An embodiment of an extraction process 350 is schematically illustrated in FIG. 11. In this embodiment, a product stream 310 is fed to the extraction section 302. The product stream may generally correspond to any of the streams 22, 36, 58, and 72 as illustrated in FIGS. 3-8. The product stream 310 may predominantly comprise ethyl acetate, though various byproducts including ketones and/or aldehydes such as 2-butane, acetonitrile and/or acetaldehyde may also be present.

The section 302 also may receive a solvent stream 319. In an embodiment, the solvent stream 319 may comprise an aqueous fluid and an extracting agent as described above. The solvent comprising the extracting agent may comprise an aqueous solution of hydrazine (NH2OH), hydroxylamine (NH2OH), semicarbazide (H2NNHC(O) NH2), phenylhydrazine (C6H5N2H), phenylhydrazonoxime (C6H5NOH), sodium hydrogen sulfite. (NaHSO3, Na2S2O5), sodium sulfite (Na2SO3), salts thereof, aqueous solutions thereof, and any combination thereof. Additional solvents useful with the extraction process can include dichloromethane-ethanol and methyl isobutyl ketone (MIBK). The extraction section 302 may comprise one or more liquid-liquid contact devices configured to contact the two liquid streams 319, 310. Various liquid-liquid contact devices can be used including an extraction column, which may comprise packing material (e.g., structured packing, random packing, trays, etc.) configured to increase mixing and the available contact area for mass transfer between the two liquids. Additional suitable structures can include a series of mixer settlers, sieve trays, a Kerr-McGee extractor, a packed tower, a rotating disk contactor, a Scheibel extractor, a pulsed column, and a centrifugal extractor. The extraction may be carried out in a co-current, counter-current, and/or cross-current flow scheme, each of which is described in more detail below with respect to FIGS. 13, 14, and 15, respectively. In an embodiment, the extraction section can comprise a counter-current flow arrangement between the solvent and product streams.

A contact device within the extraction section may comprise a number of stages configured to provide the degree of impurity removal from the product stream 310 and/or a desired purity of the purified ethyl acetate product stream. In an embodiment, the contact device, or a plurality of contact devices, can contain between about 1 to about 100 stages, or between about 1 to about 50 stages. The contact device or contact devices may operate at any suitable pressure. In an embodiment, the contact device may operate at a pressure ranging from about 1 atm to about 80 atm, and a temperature of between about 10°C to about 70°C, from about 15°C to about 60°C, or from about 20°C to about 50°C.

Within the extraction section 302, at least a portion of the impurities may be transferred to the solvent. In an embodiment, the extracting agent may react with a portion of the impurities in the product stream 310 to form an adduct and improve the solubility of the impurity in the solvent phase. Once the product stream 310 and the solvent stream 319 have been contacted and separated within the extraction section 302, a purified product stream 216 and an extract stream 256 may exit the extraction section 302. The purified product stream 216 may have an increased purity of ethyl acetate relative to the entering product stream 310. As described above, the purified product stream 216 may pass to a drying unit to further remove any solvent to further purify the purified product stream. In an embodiment, the purified product stream 216 and/or a dried, purified product stream may comprise ethyl acetate having a purity of greater than about 90%, greater than about 95%, greater than about 96%, greater than about 97%, greater than about 98%, greater than about 99%, or greater than about 99.5% ethyl acetate by weight.

The extract stream 256 may comprise the solvent and the impurities removed from the product stream 310. The extract stream 256 may pass to the stripping section 304. In an embodiment, the extract stream 256 may comprise a solvent fluid, the adducts formed by the reaction between the extracting agent and the impurities, any excess extracting agent, and potentially some amount of dissolved ethyl acetate. The stripping section 304 may comprise one or more separation devices configured to separate the impurities from the solvent.
and any extracting agent. Various separation devices can be used including phase separators and liquid-liquid separators. In an embodiment, the separation device within the stripping section 304 may comprise a flash tank. In this embodiment, the extract stream 256 may enter the flash tank, be heated to a temperature sufficient to dissociate the adduct, and evaporate at least a portion of any impurities and dissolved ethyl acetate. The flash tank may operate at a pressure ranging from about 1 atm to about 80 atm, and a temperature of between about 70°C to about 120°C, or from about 85°C to about 100°C. In some embodiments, the separation device may comprise a distillation column. The extract stream 256 can be heated within the distillation column to dissociate the adducts into the impurities and the extracting agent within the solvent. The impurities may then be separated by distillation. The distillation column may comprise about 1 to about 100 stages, or about 1 to about 50 stages. The distillation column may operate at a pressure ranging from about 1 atm to about 80 atm. The temperature and pressure may be selected based on the equilibrium on each stage within the distillation column. In an embodiment, the temperature within the column may range from about 50°C to about 200°C, or from about 70°C to about 150°C.

In an embodiment, the stripping section 304 may operate at a vacuum pressure relative to atmospheric pressure. A lower operating pressure is generally expected to reduce the temperature at which the solvent can be separated from the impurities when the adducts are dissociated. In an embodiment, the stripping section may operate at a pressure ranging from about 0.001 atm to about 1 atm and at a temperature of between about 45°C and about 100°C. In general, the solvent and/or extracting agent may break down during the heating process in the stripping section, potentially releasing contaminants into the vapor stream. By operating at a reduced pressure, and resulting reduced temperature, the rate of solvent and/or extracting agent loss may be reduced. For example, by lowering the temperature at which the stripping occurs, the rate at which any hydroxylsulfite/sulfite in solution breaks down to form sulfur dioxide can be reduced or limited.

When the stripping section 304 comprises a phase separator, an overhead product stream 306 may exit the stripping section 304 and pass to a condenser 308. The overhead stream 306 may comprise the separated impurities, dissolved ethyl acetate, and potentially minor amount of water and decomposition products resulting from a breakdown of the extracting agent. Within the condenser 308, the temperature of the overhead stream 306 may be reduced to condense the impurities into a liquid, which may leave the condenser 308 as an impurities stream 312. The impurities stream 312 may exit the system for sale, or use as fuel, and/or as a feed to one or more suitable downstream processes. Any remaining gases may exit the condenser as an off-gas stream 310. The off-gas stream 310 may comprise a portion of the vaporized impurities, ethyl acetate, and any decomposition products from the solvent. The off-gas stream 310 can be vented to the atmosphere or a flare, or as shown in FIG. 11, recycled to be combined with the regenerated solvent stream 307. The regenerated solvent stream 307 may leave the stripping section 304 as a bottoms stream and pass to the contactor 314. The off-gas stream 310 may then be re-absorbed within the contactor 314. The combined regenerated solvent stream 254 may pass to a heat exchanger 316, which may comprise any of the types of heat exchangers described herein. The regenerated solvent stream 254 may be cooled within the heat exchanger 316 to a temperature suitable to allow the extracting agent within the solvent to form an adduct with any corresponding impurities in the product stream 310. The cooled, regenerated solvent stream 254 may then be combined with an optional solvent make-up stream 318 to form the solvent stream 319. The make-up stream may include the solvent comprising the extracting agent in any suitable concentration. In an embodiment, the make-up stream may serve to adjust the concentration of the extracting agent within the solvent stream 319 to a desired level.

In some embodiments, the stripping section 304 may comprise a liquid-liquid separator. The liquid-liquid separator may operate at a pressure ranging from about 1 atm to about 80 atm. The extract stream 256 may be heated to a temperature in the range of between about 40°C to about 120°C, or from about 45°C to about 100°C, within the separator, which may be sufficient to dissociate the adduct. The impurities may then form an organic liquid phase that is at least partially insoluble in the aqueous solvent. The resulting phases may be separated in a liquid-liquid phase separation device, such as a settling tank or settling tower. Suitable draw points may be used to provide a regenerated solvent stream 307 and an organics stream 306. The organics stream 306 may leave the system without any further separation or processing. The liquid-liquid separator may comprise a gas vent suitable for passing any off-gases back to the contactor 314. The aqueous phase may leave the liquid-liquid separator as the regenerated solvent stream 307 and pass back to the extractor through the contactor 314 and heat exchanger 316 as described above.

FIG. 12 illustrates an embodiment of a stripping section 354 that is similar to the stripping section 304 described with respect to FIG. 11. In the interest of clarity, similar components will not be described. The stripping section 354 may comprise any of the separation devices operating at any of the operating conditions as described above with respect to FIG. 11, and the stripping section 354 can be used with the remaining components of the extraction process 350 illustrated in FIG. 11. The stripping section 354 differs from the stripping section 304 of FIG. 11 in that a purge gas stream 364 can be introduced into the stripping section 354, which can aid in the extraction of the impurities from the solvent solution. In an embodiment, the purge gas can comprise a gas having a boiling point significantly below that of the impurities, and the purge gas may have a low solubility in the solvent and/or impurities to aid in separation from the solvent and impurities. The purge gas can include, but is not limited to, nitrogen, oxygen, argon, helium, hydrogen, carbon dioxide, and any combination thereof (e.g., air). The use of the purge gas may aid in removing the impurities from the extract stream 256 while maintaining a relatively low stripping temperature. The use of the low temperature may aid in limiting or reducing the breakdown of the solvent and/or extracting agent, which can potentially result in the generation of pollutants.

The extract stream 256 can be introduced into the stripping section 354 and can include a solvent fluid, the adducts formed by the reaction between the extracting agent and the impurities, any excess extracting agent, and potentially some amount of dissolved ethyl acetate. As the liquid extract stream 256 flows through the stripping section, a purge gas stream 364 can be introduced into the lower portion of the stripping section 354. The ratio of the purge gas volumetric flow rate to the extract stream volumetric flow rate can
range from about 1,000:1 to about 1:100, and the ratio may be based on the amount of impurities present in the extract stream, the conditions within the stripping section 354, and/or the solubility of the impurities in the purge gas. The extract stream 256 can be heated to a temperature in the range of about 45°C to about 100°C before and/or within the stripping section 354, resulting in at least a partial dissociation of the adducts. Vapor-liquid stripping can then take place between the impurities released from the adducts and the purge gas. Since the impurities would generally have a lower boiling point than the solvent, the impurities could expect to be stripped into the purge gas stream.

[0111] The stripping section 354 can have an overhead product stream 356 that can pass to a cooler 358 and into a separator 360. The overhead stream 356 may comprise the purge gas, impurities stripped by the purge gas, and potentially minor amount of solvent, ethyl acetate, and decomposition products resulting from a breakdown of the extracting agent. Within the cooler 358, the temperature of the overhead stream 356 may be reduced to condense the impurities into a liquid, which may then pass to the separator 360 and leave as an impurities stream 362. The impurities stream 362 may exit the system for sale, for use as fuel, and/or as a feed to one or more suitable downstream processes. The purge gas may not condense and may pass out of the separator 360 as the purge gas stream 364 for recycle to the stripping section 354. The purge gas stream 364 may comprise a minor amount of the impurities, the solvent, and the decomposition products, that can reach an equilibrium in the process due to the recycling of the purge gas stream 364. The regenerated solvent stream 370 can be processed and/or recycled as described with respect to the regenerated solvent stream in FIG. 11.

[0112] The extraction section may comprise a number of flow configurations. The extraction may be carried out in a co-current, counter-current, and/or cross-current flow scheme, as schematically illustrated in FIGS. 13, 14, and 15, respectively. An embodiment of a co-current extraction scheme is illustrated in FIG. 13. In this embodiment, the extraction section may comprise a plurality of stages 402, 404, 406. For each stage 402, 404, 406, the product stream 310 and the solvent stream 319 may enter the stage and flow together through the stage. The solvent and product may be separated within the stage, for example using a settler/phase separator. Each phase may then pass to the next stage as separate phases. Alternatively, the combined fluids may pass to the next stage as a single stream. In general, the co-current flow of solvent and product may allow the two streams to reach an equilibrium, and therefore, the co-current flow may only provide an extraction equivalent to a single theoretical stage. However, additional stages may be useful in practice to provide additional residence/contact time to approach the equilibrium concentrations and mass transfer of the impurities from the ethyl acetate product into the solvent phase. The solvent phase may be separated from the product phase within the last stage or within a separator downstream of the last stage to produce the extract stream 256 and the purified product stream 216. While illustrated as separate stages 402, 404, 406, the stages may be present in a single physical vessel. Further, while three stages 402, 404, 406 are shown in FIG. 13, less than three stages or more than three stages may be used. In an embodiment, the number of stages may be between about 1 and about 50 stages.

[0113] An embodiment of a counter-current extraction scheme is illustrated in FIG. 14. In this embodiment, the extraction section may comprise a plurality of stages 408, 410, 412. The product stream 310 may enter at a first of the stages and the solvent stream 319 may enter the last stage and flow countercurrently through each stage. The phases may be arranged to allow the phases to flow countercurrently based on density differences, with the organic product phase flow upwards and the aqueous solvent phase flow downwards. The countercurrent flow of the product and solvent may result in the most efficient extraction and mass transfer of the three flow schemes. The solvent phase may be separated from the product phase within the first stage 408 to allow the extract stream 256 to leave the extraction section 302. Similarly, the product phase may be separated from the solvent phase within the last stage 412 to allow the purified product stream 216 to leave the extraction section 302. While illustrated as separate stages 408, 410, 412, the stages may be present in a single physical vessel. Further, while three stages 408, 410, 412 are shown in FIG. 14, less than three stages or more than three stages may be used. In an embodiment, the number of stages may be between about 1 and about 50 stages.

[0114] An embodiment of a cross-current extraction scheme is illustrated in FIG. 15. In this embodiment, the extraction section may comprise a plurality of stages 414, 416, 418. The product stream 310 may enter at a first of the stages and progress through each stage 414, 416, 418. The solvent stream 319 can be divided into portions 420, 422, 424, which may have the same or different flow rate. The portions 420, 422, 424 may pass to each stage 414, 416, 418, respectively, to contact the product within each stage 414, 416, 418. Within each stage 414, 416, 418, the solvent phase may be separated from the product phase, and the solvent phase portions may be recombined to form extract stream 256. The solvent phase may pass out of the last stage 418 as the purified product stream 216. The use of the cross-current flow configuration may allow the concentration of the impurities in the ethyl acetate product stream to be decreased in each stage. In an embodiment, the cross-current extraction scheme may comprise separate vessels (e.g., contactors, settlers, etc.) for each stage. In some embodiments, the stages may be present in a single physical vessel with internal contactors and separators. Further, while three stages 408, 410, 412 are shown in FIG. 15, less than three stage or more than three stages may be used. In an embodiment, the number of stages may be between about 1 and about 50 stages.

[0115] While described separately, the extraction section 302 may comprise any combination of the embodiments illustrated in FIGS. 13, 14, and 15. For example, each stage of the cross-current flow scheme may comprise a co-current or counter-current individual flow scheme. Various other combinations may also be possible.

Dehydrogenation and Dimerization Catalysts

[0116] Suitable dehydrogenation and dimerization catalysts are capable of converting at least a portion of the alcohol (e.g., ethanol) in a feed stream to a higher valued product such as ethyl acetate. Any catalyst capable of carrying out a dehydrogenation and dimerization reaction may be used alone or in combination with additional catalytic materials in the reactors. In an embodiment, suitable dehydrogenation and dimerization catalysts can generally comprise metals and/or oxides of copper, barium, rhenium, rhodium, platinum, palladium, rhenium, silver, cadmium, zinc, zirconium, gold, palladium, magnesium, manganese, aluminum, chromium, nickel, iron, molybdenum, sodium, strontium, tin, and mixtures thereof.
In many cases, the catalyst material will be provided on a support material. The catalyst can be treated with a carbonate (e.g., sodium carbonate), amines with hydrogen, and/or other suitable treatments prior to use.

[0017] In certain embodiments, the dehydrogenation and dimerization catalyst may include a catalyst support. The catalyst support stabilizes and supports the catalyst. The type of catalyst support used depends on the chosen catalyst and the reaction conditions. Suitable supports may include, but are not limited to, carbon, silica, silica-alumina, alumina, zirconia, titania, ceria, vanadia, nitride, boron nitride, heteropolyacids, hydroxypatite, zinc oxide, chromia, zeolites, carbon nanotubes, carbon fullerenes, and any combination thereof.

[0018] The dehydrogenation and dimerization catalyst can be employed in any of the conventional types or structures known to the art. It may be employed in the form of extrudates, pills, pellets, granules, broken fragments, or various special shapes. In an embodiment, consideration of the use of the catalyst in the reactive distillation system and/or as a mass transfer surface within the distillation column may be taken into account when determining a suitable shape. For example, the catalyst may have a shape similar to structured packing material or suitable for insertion in a structured packing. When the dehydrogenation catalyst is used with one or more side reactors, the catalyst may be disposed within a reaction zone, and the feed may be passed therethrough in the liquid, vapor, or mixed phase, and in either upward or downward, or inward or outward flow.

[0019] The dehydrogenation and dimerization catalyst may typically have a range of metal loadings. In an embodiment, the catalyst may have a copper oxide weight loading (i.e., weight percentage) of between 0.5% and about 90%, between about 10% and about 70%, between about 20% and about 65%, between about 30% and about 60%, or about 40% and about 50%. In an embodiment, the catalyst may have a zinc oxide weight loading of between 20% and about 60%, between about 30% and about 50%, and about 40% and about 50%. In an embodiment, the catalyst may have a chromium oxide weight loading of between 20% and about 60%, or between about 30% and about 50%, and about 40% and about 50%. In an embodiment, the catalyst may have a copper oxide weight loading between 20% and about 60%, or between about 30% and about 50%, and about 40% and about 50%.

[0020] In an embodiment, the catalyst may comprise CuO/ZnO/Al₂O₃. In this embodiment, the catalyst may have a copper oxide weight loading of between about 0.5% and about 90%, about 10% and about 70%, between about 20% and about 65%, between about 30% and about 60%, or about 40% and about 50%, and the zinc oxide and alumina may comprise the balance of the weight. In an embodiment, the catalyst may comprise CuO/ZnO/Al₂O₃ and the catalyst may have a copper oxide weight loading of between about 40% and about 90%, with the remainder of the components forming the balance of the catalyst weight. In an embodiment, the catalyst may comprise CuO/ZnO/Al₂O₃, and the catalyst may have a copper oxide weight loading of between about 20% to about 90% and a chromium oxide weight loading between about 30% and about 50%, with the remainder of the components forming the balance of the catalyst weight. In an embodiment, the catalyst may comprise Cr₂O₃/Al₂O₃. In an embodiment, the catalyst comprises an alkaline earth metal and/or alkaline earth metal oxide and/or copper oxide on a support. In this embodiment, the support may comprise silica.

[0021] Any of the materials useful as hydrogation and dimerization catalysts, may be synthesized using a variety of methods. In an embodiment, the dehydrogenation and dimerization catalyst may be prepared via a wet impregnation of a catalyst support. Using the wet-impregnation technique, a metal nitrate dissolved in a suitable solvent may be used to prepare the catalyst, however any soluble compound would be suitable. A sufficient amount of solvent should be used to fully dissolve the metal nitrate and appropriately wet the support. In one embodiment, copper nitrate and ethanol and/or water may be mixed in an amount sufficient such that the copper nitrate dissolves. Additional metal nitrates may also be added to provide a catalyst with additional components. The solute may then be combined with a suitable support material of appropriate particle size. The mixture may then be refluxed at a temperature of approximately 100° C. for approximately several hours (e.g., three to five hours) and then allowed to dry at a temperature of about 110°C. The dried material may then be heated to 200° C. to remove the NO₃ component, and then the materials may be calcined at about 450°C. to about 550°C. at a heating rate of about one to ten °C/min. The amount of metal nitrate used in the wet-impregnation technique can be adjusted to achieve a desired final metal weight loading of the catalyst support.

[0022] When multiple components are used to provide a catalyst disposed on a support, each component can be added via the wet-impregnation technique. The appropriate salts can be dissolved and impregnated on a support in a co-impregnation process or a sequential process. In a co-impregnation process, measured amount of the appropriate plurality of metal salts may be dissolved in a suitable solvent and used to wet the desired catalyst support. The impregnated support can then be dried and calcined to provide a final catalyst with a desired weight loading. In the sequential impregnation process, one or more measured amounts of salts may be dissolved in a suitable solvent and used to wet the desired catalyst support. The impregnated support can then be dried and calcined again. This process may be repeated to provide a final catalyst material with a desired loading of each component. In an embodiment, a single metal may be added with each cycle. The order in which the metals are added in the sequential process can be varied. Various metal weight loadings may be achieved through the wet-impregnation technique. In an embodiment, the wet-impregnation technique may be used to provide a catalyst having a copper weight loading ranging from about 0.5% and about 50%, with one or more additional components having a weight loading between about 0.1% and about 10%.

[0023] The dehydrogenation and dimerization catalysts may also be prepared via a co-precipitation technique. In this technique, a measured amount of one or more appropriate metal nitrates (or other appropriate metal salts) are dissolved in de-ionized water. The total metal concentration can vary and may generally be between about 1 M and about 3 M. The metal-nitrate solution may then be precipitated through the drop-wise addition of the solution to a stirred, equal volume of a sodium hydroxide solution at room temperature. The sodium hydroxide solution may generally have a concentration of about 4M, though other concentrations may also be used as would be known to one of skill in the art with the benefit of this disclosure. After addition of the metal nitrate solution, the resulting suspension can be filtered and washed with de-ionized water. The filtered solids can be dried over-
night, for example, at a temperature of about 110°C. The resulting mixed metal oxide can then be processed to a desired particle size. For example, the resulting mixed metal oxide can be pressed to a desired form, ground, and then sieved to recover a catalyst material with a particle size in a desired range. Catalysts prepared using the co-precipitation technique may have higher metal loadings than the catalysts prepared using the wet-impregnation technique.

[0124] The catalyst prepared via the co-precipitation technique may be used in the prepared form and/or a catalyst binder can be added to impart additional mechanical strength. In an embodiment, the prepared catalyst may be ground to a fine powder and then stirred into a colloidal suspension (e.g., a colloidal suspension of silica and/or alumina) in an aqueous solution. The resulting suspension may be stirred while being heated and allowed to evaporate to dryness. The heating may take place at about 80°C to about 130°C. The resulting solid can then be processed to a desired particle size. For example, the resulting solid can be pressed to a desired form, ground, and then sieved to recover a catalyst material with a particle size in a desired range. Alternatively, the colloidal suspension may be added to the 4M sodium hydroxide precipitation solution prior to addition of the metal nitrate solution in the co-precipitation technique. Various metal weight loadings may be achieved through the co-precipitation technique. In an embodiment, the co-precipitation technique may be used to provide a catalyst having a copper weight loading ranging from about 2% and about 80%, with one or more additional components having a weight loading between about 2% and about 40%.

[0125] The resulting catalyst from either the wet-impregnation technique and/or the co-precipitation technique may be further treated prior to use in the reactive distillation system disclosed herein. In an embodiment, the catalyst may be treated with a sodium carbonate solution for a period of time to improve the selectivity of the catalyst. In this process, the catalyst may be soaked in an aqueous solution of sodium carbonate for a period of time ranging from about 1 hour to about 48 hours, or alternatively about 2 hours to about 24 hours. In an embodiment, the sodium carbonate solution may have a concentration of about 0.2 M. The catalyst may then be filtered and allowed to dry at about room temperature. In an embodiment, the sodium carbonate may comprise from about 0.2 to about 3.0 weight percent of the catalyst after being contacted with the sodium carbonate solution.

[0126] In another treatment process, the catalyst may be reduced with hydrogen prior to use. In this embodiment, the catalyst may be heated and contacted with hydrogen, which may be flowing over the catalyst, for a period of time sufficient to reduce the catalyst to a desired degree. In an embodiment, the catalyst may be contacted with hydrogen at a temperature of about 190°C to about 240°C. The hydrogen treatment may be conducted in combination with the sodium carbonate treatment, and may be performed prior to and/or after the sodium carbonate treatment.

[0127] Without intending to be limited by theory, it is believed that the production of hydrogen during the dehydrogenation and dimerization reaction within the process may result in contact between the dehydrogenation and dimerization catalyst and a hydrogen stream sufficient to at least partially reduce the catalyst. Thus, the process described herein may have the potential for the in-situ reduction of the catalyst during use. This may result in an initial break-in period in which the catalyst conversion and selectivity may change before reaching a steady state conversion and selectivity. This in-situ reduction may be taken into account when considering the degree to which a catalyst should be pre-reduced with hydrogen.

[0128] In an embodiment, the dehydrogenation and dimerization catalyst described herein may be capable of achieving a relatively high conversion and/or selectivity of ethanol to ethyl acetate. As used herein, the “conversion” of ethanol to ethyl acetate refers to the amount of ethanol consumed in the conversion reaction as represented by the formula:

$$X_{\text{ethanol}} = 100 \left( \frac{F_{\text{EOH}} - F_{\text{EHO}}}{F_{\text{EOH}}} \right)$$

where $F_{\text{EOH}}$ represents the molar flow rate of ethanol in the reactor effluent (e.g., the product stream comprising the ethyl acetate), and $F_{\text{EHO}}$ represents the molar flow rate of ethanol into the reactor inlet. As used herein, the “selectivity” of the conversion refers to the amount of ethanol that is consumed in the conversion reaction that is converted to ethyl acetate as represented by the formula:

$$s = 100 \left( \frac{2F_{\text{EOH}} + F_{\text{EAO}}}{F_{\text{EOH}} - F_{\text{EHO}}} \right)$$

where $F_{\text{EAO}}$ and $F_{\text{EHO}}$ represent the molar flow rate of ethyl acetate and acetaldehyde in the reactor effluent (e.g., the product stream comprising the ethyl acetate), respectively, and the remaining terms are the same as described above with respect to the conversion of ethanol.

In an embodiment, the dehydrogenation and dimerization catalyst described herein may be capable of achieving a conversion of ethanol in the reactive distillation process described herein of at least about 10%, at least about 20%, at least about 30%, at least about 40%, or at least about 50%. In an embodiment, the dehydrogenation and dimerization catalyst described herein may be capable of achieving a selectivity of ethyl acetate in the reactive distillation process described herein of at least about 60%, at least about 70%, at least about 80%, at least about 85%, at least about 90%, at least about 95%, or at least about 96%.

Hydrogenation Catalysts

[0129] The hydrogenation catalyst generally can include a Group VIII metal and/or a Group VI metal. Examples of such a catalyst can include, but is not limited to, Cu, Re, Ni, Fe, Co, Ru, Pd, Rh, Pt, Os, Ir, and alloys or any combination thereof, either alone or with promoters such as W, Mo, Au, Ag, Cr, Zn, Mn, Sn, B, P, Bi, and alloys or any combination thereof. Other effective hydrogenation catalyst materials include either supported nickel or ruthenium modified with rhenium. In an embodiment, the hydrogenation catalyst also includes any one of the supports described below, depending on the desired functionality of the catalyst. The hydrogenation catalysts may be prepared by methods known to those of ordinary skill in the art.

[0130] In an embodiment, the hydrogenation catalyst includes a supported Group VIII metal catalyst and a metal sponge material (e.g., a sponge nickel catalyst). Raney nickel provides an example of an activated sponge nickel catalyst suitable for use in this invention. In an embodiment, the
hydrogenation reaction in the invention is performed using a catalyst comprising a nickel-rhenium catalyst or a tungsten-modified nickel catalyst. One example of a suitable catalyst for the hydrogenation reaction of the invention is a carbon-supported nickel-rhenium catalyst.

[0131] In an embodiment, a suitable Raney nickel catalyst may be prepared by treating an alloy of approximately equal amounts by weight of nickel and aluminum with an aqueous alkali solution, e.g., containing about 25 weight % of sodium hydroxide. The aluminum is selectively dissolved by the aqueous alkali solution resulting in a sponge shaped material comprising mostly nickel with minor amounts of aluminum. The initial alloy includes promoter metals (e.g., molybdenum or chromium) in the amount such that 1 to 2 weight % remains in the formed sponge nickel catalyst. In another embodiment, the hydrogenation catalyst is prepared using a solution of ruthenium(III) nitrosyl nitrate, ruthenium (III) chloride in water to impregnate a suitable support material. The solution is then dried to form a solid having a water content of less than 1% by weight. The solid is then reduced at atmospheric pressure in a hydrogen stream at 300°C (uncalcined) or 400°C (calcined) in a rotary ball furnace for 4 hours. After cooling and rendering the catalyst inert with nitrogen, 5% by volume of oxygen in nitrogen is passed over the catalyst for 2 hours.

[0132] In certain embodiments, the hydrogenation catalyst may include a catalyst support, which may be the same or different than a catalyst support used with the dehydrogenation and dimerization catalyst. In an embodiment, any of the catalyst supports discussed herein may be used to support a hydrogenation catalyst. The hydrogenation catalyst can be employed in any of the conventional types or structures known to the art. In an embodiment, any of the catalyst shapes and/or types discussed herein with respect to the dehydrogenation and dimerization catalyst may be used with the hydrogenation catalyst.

Production of Methyl Formate from Methanol

[0133] In addition to use of the systems and methods described herein for converting ethanol to ethyl acetate, those systems can also be used in processes with methanol as a feed instead of ethanol, with the production of methyl formate and H₂ as products according to the following formula:

\[ \text{CH₃OH} \rightarrow \text{HCOOH} + \text{H₂} \]

[0134] Such a system and method can utilize selections from the catalysts indicated for use with the ethanol feed. Products can be withdrawn in similar manner as described for the ethanol to ethyl acetate process.

EXAMPLES

[0135] The disclosure having been generally described, the following examples are given as particular embodiments of the disclosure and to demonstrate the practice and advantages thereof. It is understood that the examples are given by way of illustration and are not intended to limit the specification or the claims in any manner.

Example 1

Production of Ethyl Acetate from Ethanol

[0136] A 10 cm diameter distillation column is used, which has been rendered adiabatic by heating casings with temperatures controlled in such a way that the temperature gradient in the column is reproduced. Over a height of 3.5 m, the column is comprised of rectification zone with 8 stages each with a catalytic cell consisting of a cylindrical container with a flat bottom. The bottom of the container is equipped with a grid for retaining the catalyst and also can act as a gas and liquid distributor. The stripping zone is comprised of 12 stages, also with catalyst-containing cells. The rectification section is considered to be above the feed stage and the stripping section is considered to be below the feed stage. Each catalytic cell contains CuO/ZnO/Al₂O₃, 200 proof ethanol is fed to the 13th stage of the column, starting from the bottom.

[0137] The column is regulated by establishing a reflux ratio which is equal to 0.8, reboil ratio which is equal to 4 and controlling the base temperature to 211°C and the absolute pressure to 20 bar. The reflux stream is mostly ethanol with small amounts of acetaldehyde. Under stabilized conditions, a bottoms stream and a distillate stream are collected with respective throughputs of about 170 g/h and 4 g/h. The bottom product gives ethyl acetate purity of 98.5% with small amounts of n-butyraldehyde and butan-2-one.

Example 2

Selective Hydrogenation of n-butyraldehyde and butan-2-one

[0138] Selective hydrogenation of n-butyraldehyde and butan-2-one in the presence of ethyl acetate was conducted over a hydrogenation catalyst. The reactor was filled with 20 g of 0.1 wt % Pd on silica catalyst. Before the selective hydrogenation reaction, the catalyst was reduced at a temperature of 250°C for 30 minutes. The catalyst reduction was conducted at atmospheric pressure by delivering hydrogen using a mass flow controller. At the end of this procedure, the catalyst was fully reduced.

[0139] The bottoms product from the reactive distillation column, whose composition is given in Table 2, was introduced to a heater at a rate of 30 g/h and mixed with hydrogen prior to admission to the selective hydrogenation reactor. The reaction product was cooled using a jacketed condenser and the liquid condensate was analyzed by gas chromatography. The results are summarized in Table 2, showing n-butyraldehyde and butan-2-one reduced to trace levels.

<table>
<thead>
<tr>
<th>Component</th>
<th>Feed</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>93</td>
<td>92.0</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>Iso-propanol</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>n-butyraldehyde</td>
<td>1.3</td>
<td>trace</td>
</tr>
<tr>
<td>butan-2-one</td>
<td>0.5</td>
<td>trace</td>
</tr>
<tr>
<td>2-butanol</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>n-butanol</td>
<td>0</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Example 3

Wet-Impregnation Catalyst Preparation

[0140] Various catalysts including CuO/SiO₂, CuO/SiO₂-Al₂O₃, CuO/ZnO, CuO/ZrO₂, CuO/SiO₂-ZrO₂,
CuO/ZnO/Al2O3, CuO/Cr2O3/Al2O3, and CuO/Cr2O3 were prepared via impregnation of the corresponding oxide catalyst support. The preparation involved dissolving 4 grams (g) of Cu(NO3)2·2.5H2O in 30 mL of de-ionized water, which was then added to 30 g of the appropriate oxide support and stirred until well mixed. The impregnated support was then dried in air at 110°C, followed by calcination in air at 450°C. The amount of Cu(NO3)2·2.5H2O was adjusted to achieve a desired final Cu weight loading. Enough water was used to wet the entire oxide support. Copper loadings between 0.5% and 20% by weight were achieved.

Example 4

Co-Impregnation and Sequential Impregnation Catalyst Preparation

Various catalysts including CuO/ZnO/SiO2, CuO/ ZrO2/SiO2, CuO/MgO/SiO2, CuO/Co/SiO2, CuO/SiO2, CuO/Al2O3, and CuONa2O/SiO2 were prepared via co-impregnation and sequential impregnation of a silica catalyst support. For the co-impregnation, measured amounts of Cu(NO3)2·2.5H2O and M(NO3)2·YH2O (M=Zn, Sr, Mg, Ca, Sr, Ca, or Na; X=1 or 2; Y=2-6) were dissolved in de-ionized water. The solution was added to the silica support and stirred until well mixed. The impregnated silica was dried in air at 110°C, followed by calcination in air at 450°C.

For the sequential impregnation, a measured amount of M(NO3)2·YH2O (M=Zn, Sr, Mg, Ca, Sr, Ca, or Na; X=1 or 2; Y=2-6) was dissolved in de-ionized water. The solution was then added to the silica support and mixed well. The silica was dried at 110°C and then calcined at 450°C in air. This procedure was then repeated using Cu(NO3)2·2.5H2O in place of the first metal nitrate. Copper loadings between 0.5% and 20% by weight and an addition metal loading between 0.1% and 10% by weight were achieved.

Example 5

Co-Precipitation Catalyst Preparation

Mixed-metal oxide catalysts were prepared via co-precipitation from nitrate solutions. In the co-precipitation synthesis, a measured amount of the appropriate metal nitrate (Cu, Zn, Zr, Al, Cr, Fe, Ni, and/or Ba) was dissolved in de-ionized water (total metal concentration ranges from 1-3 M). The metal-nitrate solution was then precipitated by drop-wise addition to a stirred, equal volume of 4 M aqueous NaOH at room temperature. After addition of all of the metal nitrate solution, the suspension was stirred for an additional hour to ensure complete precipitation of the metals. The precipitated solid was then filtered and washed with excess de-ionized water. The solids were then dried overnight at 110°C.

The resulting mixed metal oxide was then pressed, ground, and sieved to recover a catalyst with particle sizes between 450 and 850 μm. Catalysts prepared in this manner had copper oxide loadings between 40% and 80% by weight. The loadings of other metal oxides ranged from 2% to 40% by weight. In particular, CuO/ZnO/ZrO2/Al2O3, and CuO/ZnO/ ZrO2/Cr2O3 catalysts were found to be especially active and selective for the dehydrogenative dimerization of ethanol, as illustrated below in Example 6.

In addition to the catalysts prepared above, various catalysts were prepared via co-precipitation and then a binder was incorporated. The catalyst binder was added to the mixed-metal oxide prepared as described above by first grinding the mixed-metal oxide to a fine powder and then stirring it into a colloidal suspension of silica or alumina in water. The resulting suspension was stirred while heating at 80-130°C to dryness. The resulting solid was then pressed, ground, and sieved to appropriate particle sizes.

Example 6

Dehydrogenative Dimerization of Ethanol

A portion of the catalysts prepared as described in Examples 3 to 5 were treated with a Na2CO3 solution to soak the catalyst in a 0.2 M aqueous solution of Na2CO3 for 2-24 hrs. The catalyst was then filtered and allowed to dry in air at room temperature. Another portion of the catalysts prepared as described in Examples 3 to 5 were reduced in a hydrogen environment at 175-240°C for a period of 4-12 hours. These catalysts were then tested in ethanol dehydrogenation reactions. Conversion and selectivity for gas phase reactions were determined from use in a fixed bed reactor operating at 190-240°C and 1-24 atm. Pure ethanol was fed to the reactor with a weight hourly space velocity (WHSV) between 0.1-1.5 hr⁻¹. Conversion and selectivity for liquid phase and mixed liquid/vapor phase reactions were determined in a fixed bed reactor, operating at 190-240°C and at pressures above 25 atm. Liquid phase reactions were also conducted in a batch reactor at 180-200°C and 20-31 atm (the reactor pressure was maintained above the vapor pressure of ethanol at the operating temperature).

Table 3 shows the conversion and selectivity of the catalysts in a dehydrogenative dimerization reaction conducted in a fixed bed reactor. Conversion (X) and selectivity (S) were calculated from the composition of the reactor effluent as

\[
X_{\text{react}} = \frac{F_{\text{EALD}} - F_{\text{EALD}}}{F_{\text{EALD}}} \\
S = \frac{2F_{\text{EALD}} + F_{\text{EAL}}}{F_{\text{EALD}} - F_{\text{EALD}}}
\]

where \(F_{\text{EALD}}\) and \(F_{\text{EAL}}\) represent the molar flow rates of ethanol, ethyl acetate, and acetaldehyde in the reactor effluent, respectively, and \(F_{\text{EALD}}\) represents the molar flow rate of ethanol into the reactor inlet. Acetaldehyde is a reaction intermediate and so was included in the selectivity calculation.

<table>
<thead>
<tr>
<th>Catalyst sample</th>
<th>As prepared/received</th>
<th>Reduced in H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet catalysts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuO/ZnO/Al2O3</td>
<td>18.9</td>
<td>35.0</td>
</tr>
<tr>
<td>CuO/Cr2O3/Al2O3</td>
<td>43.5</td>
<td>84.6</td>
</tr>
<tr>
<td>Impregnated catalysts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuO/SiO2</td>
<td>19.6</td>
<td>49.2</td>
</tr>
<tr>
<td>CuO/Al2O3</td>
<td>43.0</td>
<td>87.0</td>
</tr>
<tr>
<td>CuO/Al2O3</td>
<td>50.2</td>
<td>47.3</td>
</tr>
</tbody>
</table>

TABLE 3

Conversion and Selectivity for selected catalysts in a fixed bed reactor at 220°C and 1 atm
Example 7
Pressure Effects on the Conversion

[0147] A fixed bed reactor operated under similar conditions to those described with respect to Example 6 was used to test the reaction conversion and selectivity of a catalyst under varying reaction pressures. Table 4 shows a typical trend in the conversion and selectivity of these catalysts when operated at elevated pressures. Similar trends were seen for all catalysts tested at elevated pressures.

<table>
<thead>
<tr>
<th>Catalyst sample</th>
<th>As prepared/received</th>
<th>Reduced in H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO/ZnO</td>
<td>19.7</td>
<td>65.5</td>
</tr>
<tr>
<td>CuO/ZnO</td>
<td>41.5</td>
<td>63.4</td>
</tr>
<tr>
<td>CuO/SiO₂</td>
<td>33.3</td>
<td>29.0</td>
</tr>
<tr>
<td>CuO/ZnO/SiO₂</td>
<td>25.1</td>
<td>31.5</td>
</tr>
<tr>
<td>CuO/ZnO/Al₂O₃</td>
<td>31.0</td>
<td>33.6</td>
</tr>
<tr>
<td>CuO/ZnO/SiO₂</td>
<td>19.4</td>
<td>95.9</td>
</tr>
<tr>
<td>CuO/ZnO</td>
<td>39.1</td>
<td>58.7</td>
</tr>
</tbody>
</table>

Example 8
Liquid Phase Reaction

[0149] The dehydrogenative dimerization of ethanol was also conducted in the liquid phase. Reaction temperatures ranged from 180 to 200°C, and pressures were kept above the vapor pressure of ethanol at the reaction temperature (25-36 atm). Liquid phase reactions were conducted in both a fixed bed reactor and batch reactor. Table 5 shows the results for a CuO/ZnO/Al₂O₃ catalyst in a batch reactor operating in the liquid phase. During a typical batch reaction, the pressure initially reached the vapor pressure of ethanol and then slowly increased beyond that pressure as the reaction generated H₂ gas. The batch reactor results demonstrated that the dehydrogenative dimerization reaction occurs in the liquid phase.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>X</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>4.4</td>
<td>84.1</td>
</tr>
<tr>
<td>190</td>
<td>6.1</td>
<td>81.5</td>
</tr>
<tr>
<td>200</td>
<td>13.0</td>
<td>90.1</td>
</tr>
</tbody>
</table>

Example 9
Effect of Water in the Ethanol Feed

[0150] Based on the results of Examples 3 through 8, it can be seen that a high selectivity to ethyl acetate using the dehydrogenation and dimerization catalysts described herein (e.g., CuO/ZnO/Al₂O₃, CuO/ZnO/Al₂O₃, and CuO/ZnO/Al₂O₃) should enable the use of the system embodiments as illustrated in FIGS. 3, 5 and 7 of the present disclosure. For catalysts where 2-butanone is produced above acceptable levels, the use of the system embodiments as illustrated in FIGS. 4, 6 and 8 of the present disclosure may be used.

Example 10
Impregnated Catalysts

[0152] A catalyst comprising CuO/ZnO/Al₂O₃ was prepared via co-impregnation of an alumina support. As in a typical co-impregnation, measured amounts of CuO, CuO, 5H₂O and ZnO(N₂O₅)₂, 6H₂O were dissolved in an appropriate amount of de-ionized water to fill the pore volume of the alumina support. The solution was added to the alumina support and agitation until the liquid was fully absorbed by the alumina. The impregnated alumina was dried in air at 110°C, followed by calcination in air at 400-600°C, for 2-10 hours. Typical catalyst loadings ranged from 1-50 wt % CuO and 2-40 wt % ZnO, and some of the catalyst weight loadings were about 13 wt % CuO and about 7 wt % ZnO₂.
[0153] The supported CuO/ZrO₂/Al₂O₃ could be treated with a base such as sodium carbonate after the calcination to improve catalyst selectivity. For these catalysts, a volume of an aqueous sodium carbonate solution sufficient to fully sublime the supported catalyst was prepared (0.1-1.0 M). The catalyst was then added to the solution and allowed to cure for 2-12 hours at room temperature. The catalyst was then filtered and washed to remove the excess base, then dried prior to use in a reaction. Bases other than sodium carbonate that could be used include K₂CO₃, Li₂CO₃, Cs₂CO₃, NaOH, Ca(OH)₂, KOH, CsOH, Ba(OH)₂.

[0154] The results of the impregnated catalyst are shown below in Table 7, wherein X and S are based on the formulas provided above in Example 6.

<table>
<thead>
<tr>
<th>Catalyst sample</th>
<th>Co-Precipitation Catalyst</th>
<th>As prepared</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuO/ZrO₂ on Al₂O₃</td>
<td>X</td>
<td>S</td>
</tr>
<tr>
<td>13.8</td>
<td>17.2</td>
<td>96.2</td>
</tr>
<tr>
<td>95.1</td>
<td>17.8</td>
<td>98.6</td>
</tr>
</tbody>
</table>

Example 12

Mixed-metal oxide catalysts comprising CuO/ZrO₂/Al₂O₃ and CuO/ZrO₂ were prepared via co-precipitation from nitrate solutions. As in a typical co-precipitation synthesis, a measured amount of the appropriate metal nitrates were dissolved in de-ionized water (total metal concentration ranges from 0.5-3 M). The metal-nitrate solution was then precipitated by drop-wise addition into a stirred, equal volume of 1-4 M aqueous NaOH. The NaOH solution could be at room temperature or heated up to near boiling. After addition of all the metal nitrate solution, the suspension was stirred for 2-4 hours to ensure complete precipitation of the metal oxides. The precipitated solid was then filtered and washed with excess de-ionized water. The solids were then dried at 110° C, followed by calcination at 220-500° C. Catalysts prepared in this manner had CuO loadings between about 40 to about 80 wt%. The loadings of other metal oxides range from about 2 to about 40 wt%. Other metal salts, such as acetates and carbonates, could be used in place of the nitrates.

[0155] A catalyst binder could be added to the mixed-metal oxide to impart additional mechanical strength. The metal oxide binder would be ground to a fine powder and then stirred into a suspension of the binder. The resulting slurry could then be extruded or pressed, ground, and sieved to appropriate particle sizes. An alternative could include adding the binder material to the NaOH precipitation solution prior to addition of the metal nitrate solution. Binders can include SiO₂, Al₂O₃, bentonite and other clays, hydrotalcite, and Al(OH)₃.

[0156] The results of the co-precipitation catalyst are shown below in Table 8, wherein X and S are based on the formulas provided above in Example 6.

Example 13

The effect of the extraction efficiency with respect to the volume and concentration of the solvent was explored in this example. In this example, the effects on the 2-butane concentration in the ethyl acetate solution were determined using different volumes of solvent as well as different concentrations of the extracting agent in the solvent. The same ethyl acetate solution comprising 1.6 wt % 2-butane was prepared as in Example 12. The starting solvent solution included 30 grams of sodium hydrogen sulftie per 100 milliliters of water. A volume of 75 milliliters of the ethyl acetate solution was first contacted with 25 milliliters of the solvent solution in multiple extraction steps that were carried out as described above in Example 12. The concentration of the 2-butane was measured after each step and the results are shown in FIG. 17. Another volume of 75 milliliters of the ethyl acetate solution was then contacted with 15 milliliters of the solvent solution in multiple extraction steps. A fresh volume of 75 milliliters of the ethyl acetate solution was then contacted in multiple extraction steps with 25 milliliters of the solvent solution that was prepared by diluting 15 milliliters of the original solvent solution (30 grams of sodium hydrogen sulftie per 100 milliliters of water) with 10 milliliters of water. The concentration of the 2-butane was measured after each step and the results are shown in FIG. 17.
The results indicate that smaller volumes with the same concentration of NaHSO₃ (15 ml extraction volumes) is more efficient than larger ones (25 ml as shown in FIG. 16). Furthermore, a dilution of the NaHSO₃ solution yielded improved removal efficiency and reduced tendency to form crystals (FIG. 17). This unexpected results is likely due to the higher solubility of the sodium sulfite 2-butanol adduct in a less concentrated aqueous NaHSO₃ salt solution. Thus we discovered that optimal removal nitrates are not achieved by excessively high concentrations of NaHSO₃, or small extraction volumes but with concentration that is high enough to provide NaHSO₃ excess but not suppress the removal of the sodium sulfite 2-butanol adduct which has to dissolve in the aqueous phase.

Example 14

The effect of the extraction temperature explored in this example. In this example, an identical amount of ethyl acetate was treated with the same amount and the same concentration of the aqueous NaHSO₃ (30 grams of sodium hydrogen sulfite per 100 milliliters of water). The first sample was kept cooled for 2 hours at approximately 4°C. The final concentration of the 2-butanol in the sample maintained at 4°C was measured by a gas chromatographic analysis as 0.08 wt.%. The sample maintained at room temperature (approximately 25°C.) had a final concentration of about 0.18%. Thus, a greater amount of the 2-butanol was transferred from the ethyl acetate sample into the solvent solution in the sample maintained at 4°C than the sample maintained at room temperature.

Example 15

The effect of the use of mixtures of sodium sulfite and sodium hydrogen sulfite was explored in this example. The sodium sulfite solution (Na₂SO₃) was prepared in situ by the addition of NaOH to a solution of NaHSO₃. A stoichiometric amount of NaOH can be used to completely convert an amount of NaHSO₃ into Na₂SO₃. A less than stoichiometric amount of NaOH can be used to create a mixture of Na₂SO₃ and NaHSO₃. Tests were performed with a solution of NaHSO₃ that was neutralized with NaOH to a 50% solution (corresponding to a mixture of 50% Na₂SO₃ and 50% NaHSO₃) as well as a solution of NaHSO₃ that was neutralized with NaOH to a 100% solution (corresponding to substantially pure aqueous Na₂SO₃). Several multi-step extractions were performed on a solution comprising ethyl acetate solution comprising 1.86 wt. % 2-butanol. The results are presented in FIG. 18.

As shown in FIG. 18, each point on the graph represents an extraction, wherein the x-axis represents the cumulative amount of extractant solution used. The starting solution of NaHSO₃ contained approximately 30 grams of NaHSO₃/100 ml. The exact concentration was determined by iodometric titration and the solution was adjusted with 4 M NaOH as needed to achieve the desired neutralization level. Although the tests demonstrate that the performance of the Na₂SO₃ containing extraction was slightly lower, the regeneration of Na₂SO₃ solution is expected to be much more reproducible and with lower potential release of SO₂ gas. A similar performance is expected from corresponding mixtures of NaHSO₃ and Na₂SO₃.

ADDITIONAL EMBODIMENTS

Having described the systems and methods, various embodiments may include, but are not limited to:

In a first embodiment, a method of purifying an ethyl acetate stream comprises contacting an inlet stream with a solvent, transferring at least a portion of the impurity compound from the inlet stream into the solvent to form an extract and a purified product, separating the extract from the purified product, separating the portion of the impurity compound from the extract, and recycling at least a portion of the regenerated solvent to contact the inlet stream. In a second embodiment, the solvent of the first embodiment may comprise an aqueous fluid. In a third embodiment, the method of the first embodiment may include heating the extract after separating the extract from the purified product. Heating the extract can include heating the extract to a temperature between about 85 45° C. and about 100° C. In a fourth embodiment, the solvent of any of the first to third embodiments may include an extracting agent, and the extracting agent may be configured to increase the solubility of the impurity compound in the solvent. In a fifth embodiment, the extracting agent of the fourth embodiment may comprise sodium hydrogen sulfite. In a sixth embodiment, the extracting agent of the fourth embodiment may comprise a compound selected from the group consisting of: hydroxysulfite ion, sulfite ion, hydrazine, hydroxylamine, semicarbazide, phenylhydrazine, phenylhydroxylamine, salts thereof, aqueous solutions thereof, and any combination thereof. In a seventh embodiment, the method of any of the fourth to sixth embodiments may also include reacting the extracting agent and the impurity compound to form an adduct in response to contacting the inlet stream with the solvent. In an eighth embodiment, contacting the portion of the impurity compound from the extract in the seventh embodiment may comprise dissolving the adduct. In a nineth embodiment, the impurity compound of any of the first to eighth embodiments may comprise at least one of a ketone, an aldehyde, or any combination thereof. In a tenth embodiment, the method of any of the first to ninth embodiments may comprise drying the purified product. In an eleventh embodiment, the purified product of any of the first to tenth embodiments may comprise at least about 90% ethyl acetate by weight. In a twelfth embodiment, contacting the inlet stream with the solvent in any of the first to eleventh embodiments may comprise at least one of contacting the inlet stream with the solvent in a counter-current flow, or contacting the inlet stream with the solvent in a cross-current flow. In a thirteenth embodiment, the method of any of the first to twelfth embodiments can also include feeding a feed stream comprising ethanol to a reactive distillation column, contacting the ethanol with a catalyst, dehydrating ethanol over the catalyst, removing ethyl acetate during the distillation process as a liquid bottoms product, removing hydrogen during the distillation process as a gaseous top product, and providing the ethyl acetate as the inlet stream. In a fourteenth embodiment, the catalyst of the thirteenth embodiment may be disposed in a side reactor, and the side reactor may be in fluid communication with the reactive distillation column. In a fifteenth embodiment, the catalyst of the fourteenth embodiment may be disposed in the reactive distillation column. In a sixteenth embodiment, sepa-
rating the portion of the impurity compound from the extract in any of the first to fifteenth embodiments may comprise contacting the extract with a purge gas, transferring at least a portion of the impurity compound from the extract to the purge gas, and separating the purge gas from at least the portion of the impurity compound. In a seventeenth embodiment, separating the portion of the impurity compound from the extract in any of the first to sixteenth embodiments may occur at a pressure of between about 0.001 atm and about 1 atm.

In an eighteenth embodiment, a reactive distillation system for producing high purity ethyl acetate from ethanol comprises a reactive distillation column, an extraction unit, and a stripping unit. The reactive distillation column comprises a dehydrogenation catalyst, an ethanol inlet configured to pass an ethanol feed over the dehydrogenation catalyst, a top product gaseous hydrogen removal passage, and a bottoms product liquid ethyl acetate removal passage. The extraction unit is configured to receive a liquid ethyl acetate product stream from the reactive distillation column through the bottoms product liquid ethyl acetate removal passage, contact a liquid solvent feed stream with the liquid ethyl acetate product stream, provide an extract stream comprising a portion of any impurities in the liquid ethyl acetate product stream, and provide a purified product stream. The stripping unit is configured to receive the extract stream from the extraction unit, separate the portion of the impurities from the extract stream, provide an outlet impurities stream, and provide a regenerated solvent stream back to the extraction unit as at least a portion of the liquid solvent feed stream. In a nineteenth embodiment, the system of the eighteenth embodiment can also include a drying unit, and the drying unit can be configured to receive the purified product stream from the extraction unit, remove at least a portion of any water in the purified product stream, and provide a dried purified product stream. In a twentieth embodiment, the extraction unit of the eighteenth or nineteenth embodiments may be configured to contact the liquid solvent feed stream with the liquid ethyl acetate product stream using a counter-current flow. In a twenty first embodiment, the extraction unit of the eighteenth or nineteenth embodiments may be configured to contact the liquid solvent feed stream with the liquid ethyl acetate product stream using a cross-current flow. In a twenty second embodiment, the extraction unit of any of the eighteenth to twenty first embodiments may comprise a liquid-liquid contact vessel. In a twenty third embodiment, the liquid-liquid contact vessel of the twenty second embodiment may comprise packing. In a twenty fourth embodiment, the stripping unit of any of the eighteenth to twenty third embodiments may comprise a distillation column. In a twenty fifth embodiment, the distillation column of the twenty fourth embodiment may comprise between about 1 and about 50 stages. In a twenty sixth embodiment, the system of any of the eighteenth to twenty fifth embodiments can also include a cooler, and the cooler can be configured to receive the regenerated solvent stream, cool the regenerated solvent stream, and provide the cooled regenerated solvent stream back to the extraction unit. In a twenty seventh embodiment, the system of any of the eighteenth to twenty sixth embodiments may also include at least one sidestream with the reactive distillation column. In a twenty eighth embodiment, the system of the twenty seventh embodiment may also include a second catalyst disposed in the at least one side reactor, wherein the catalyst comprises at least one of a dehydrogenation catalyst or a hydrogenation catalyst.

In a twenty ninth embodiment, a reactive distillation process producing high purity ethyl acetate from ethanol comprises feeding a feed stream comprising ethanol to a reactive distillation column, contacting the ethanol with a catalyst, dehydrogenating ethanol over the catalyst in the liquid phase during the distillation process, removing ethyl acetate during the distillation process as a bottoms product, and removing hydrogen during the distillation process as a top product. In a thirtieth embodiment, the reactive distillation process of the twenty ninth embodiment may also include contacting the bottoms stream with a hydrogenation catalyst and hydrogen, hydrogenating at least a portion of a contaminant in the bottoms stream, and separating the hydrogenated portion of the contaminant from the bottoms stream. In a thirty first embodiment, separating the hydrogenated portion of the contaminant from the bottoms stream in the thirtieth embodiment comprises distilling the hydrogenated portion of the contaminant from the bottoms stream. In a thirty second embodiment, the contacting, the hydrogenating, and the separating in the thirtieth or thirty first embodiments may occur downstream of the reactive distillation column. In a thirty third embodiment, the contaminant of any of the thirtieth to thirty second embodiments may comprise a ketone or an aldehyde. In a thirty fourth embodiment, the reactive distillation process of any of the twentieth to thirty third embodiments may also include extracting at least a portion of a contaminant in the bottoms stream using a solvent to produce an extract stream and a purified product stream, and stripping the portion of the contaminant from the extract stream to produce a contaminant stream and regenerate the solvent stream. In a thirty fifth embodiment, the reactive distillation process of any of the twenty ninth to thirty fourth embodiments may also include contacting a first fluid drawn from the reactive distillation column with the catalyst in a side reactor, and introducing the second fluid to the reactive distillation column during the distillation process. The first fluid may react in the presence of the catalyst to produce a reaction product comprising a second fluid. In a thirty sixth embodiment, the reactive distillation process of the thirty fifth embodiment may also include contacting the bottoms stream with a hydrogenation catalyst and hydrogen, hydrogenating at least a portion of a contaminant in the bottoms stream, and separating the hydrogenated portion of the contaminant from the bottoms stream. In a thirty seventh embodiment, the bottoms product of any of the twenty ninth to thirty seventh embodiments may comprise at least about 90% ethyl acetate. In a thirty eighth embodiment, the feed stream comprising ethanol of any of the twenty ninth to thirty eighth embodiments may be the only feed stream fed to the reactive distillation column. In a thirty ninth embodiment, the catalyst of any of the twenty ninth to thirty ninth embodiments may be disposed within the reactive distillation column. In a forty first embodiment, the reactive distillation process of any of the twenty ninth to forty first embodiments may also include introducing a second feed stream to the reactive distillation column, and contacting the second feed...
3. The method of claim 1, wherein the solvent further comprises an extracting agent, wherein the extracting agent is configured to increase the solubility of the impurity compound in the solvent.

4. The method of claim 3, wherein the extracting agent comprises sodium hydrogen sulfite.

5. The method of claim 3, wherein the extracting agent comprises a compound selected from the group consisting of: hydrosulfite ion, sulfite ion, hydrazine, hydroxylamine, semicarbazide, phenylhydrazine, phenylhydroxylamine, salts thereof, aqueous solutions thereof, and any combination thereof.

6. The method of claim 3, further comprising reacting the extracting agent and the impurity compound to form an adduct in response to contacting the inlet stream with the solvent.

7. The method of claim 6, wherein separating the portion of the impurity compound from the extract comprises dissociating the adduct.

8. The method of claim 1, wherein the impurity compound comprises at least one of a ketone, an aldehyde, or any combination thereof.

9. The method of claim 1, wherein the purified product comprises at least about 90% ethyl acetate by weight.

10. The method of claim 1, wherein contacting the inlet stream with the solvent comprises at least one of contacting the inlet stream with the solvent in a counter-current flow, or contacting the inlet stream with the solvent in a cross-current flow.

11. The method of claim 1, further comprising: feeding a feed stream comprising ethanol to a reactive distillation column; contacting the ethanol with a catalyst; dehydrogenating ethanol over the catalyst; removing ethyl acetate during the distillation process as a liquid bottoms product; removing hydrogen during the distillation process as a gaseous top product; and providing the ethyl acetate as the inlet stream.

12. The method of claim 11, wherein the catalyst is disposed in a side reactor, and wherein the side reactor is in fluid communication with the reactive distillation column.

13. The method of claim 1, wherein separating the portion of the impurity compound from the extract comprises: contacting the extract with a purge gas, transferring at least a portion of the impurity compound from the extract to the purge gas, and separating the purge gas from at least the portion of the impurity compound.

14. The method of claim 1, wherein separating the portion of the impurity compound from the extract occurs at a pressure of between about 0.001 atm and about 1 atm.

15. A reactive distillation system for producing high purity ethyl acetate from ethanol, the system comprising: a reactive distillation column comprising: a dehydrogenation catalyst, an ethanol inlet configured to pass an ethanol feed over the dehydrogenation catalyst, a top product gaseous hydrogen removal passage, and a bottoms product liquid ethyl acetate removal passage; an extraction unit configured to receive a liquid ethyl acetate product stream from the reactive distillation column through the bottoms product liquid ethyl acetate removal passage, contact a liquid solvent feed stream with the liquid ethyl acetate product stream, provide an extract stream comprising a portion of any impurities in
the liquid ethyl acetate product stream, and provide a purified product stream; and
a stripping unit configured to receive the extract stream from the extraction unit, separate the portion of the impurities from the extract stream, provide an outlet impurities stream, and provide a regenerated solvent stream back to the extraction unit as at least a portion of the liquid solvent feed stream.

16. The system of claim 15, further comprising a drying unit, wherein the drying unit is configured to receive the purified product stream from the extraction unit, remove at least a portion of any water in the purified product stream, and provide a dried purified product stream.

17. The system of claim 15, wherein the extraction unit comprises a liquid-liquid contact vessel.

18. The system of claim 15, wherein the stripping unit comprises a distillation column.

19. A reactive distillation process producing high purity ethyl acetate from ethanol, comprising:
feeding a feed stream comprising ethanol to a reactive distillation column;
contacting the ethanol with a catalyst;
dehydrogenating ethanol over the catalyst in the liquid phase during the distillation process;
removing ethyl acetate during the distillation process as a bottoms product; and
removing hydrogen during the distillation process as a top product.

20. The reactive distillation process of claim 19, further comprising:
contacting the bottoms stream with a hydrogenation catalyst and hydrogen;
hydrogenating at least a portion of a contaminant in the bottoms stream; and
separating the hydrogenated portion of the contaminant from the bottoms stream.

21. The reactive distillation process of claim 20, wherein the contacting, the dehydrogenating, and the separating occur downstream of the reactive distillation column.

22. The reactive distillation process of claim 19, further comprising:
extracting at least a portion of a contaminant in the bottoms stream using a solvent to produce an extract stream and a purified product stream; and
stripping the portion of the contaminant from the extract stream to produce a contaminant stream and regenerate the solvent stream.

23. The reactive distillation process of claim 19, further comprising:
contacting a first fluid drawn from the reactive distillation column with the catalyst in a side reactor, wherein the first fluid reacts in the presence of the catalyst to produce a reaction product comprising a second fluid; and
introducing the second fluid to the reactive distillation column during the distillation process.

24. The reactive distillation process of claim 23, further comprising:
increasing a contact time between the ethanol and the catalyst; and
improving a conversion of ethyl acetate to ethyl acetate in response to increasing the contact time between the ethanol and the catalyst.

25. The reactive distillation process of claim 23, further comprising:
contacting the bottoms stream with a hydrogenation catalyst and hydrogen;
hydrogenating at least a portion of a contaminant in the bottoms stream; and
separating the hydrogenated portion of the contaminant from the bottoms stream.

26. The reactive distillation process of claim 19, wherein the bottoms product comprises at least about 90% ethyl acetate.

* * * * *
SAFETY DATA SHEET

1. Identification

Product Name: Ethanol, Anhydrous (Histological)
Cat No.: A405-20; A405F-1GAL; A405P-4
Synonyms: Grain alcohol, denatured; Ethyl alcohol, denatured; Ethyl hydroxide, denatured.
Recommended Use: Laboratory chemicals.
Uses advised against: Not for food, drug, pesticide or biocidal product use

Company
Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) Identification

This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Flammable liquids Category 2
Serious Eye Damage/Eye irritation Category 2
Specific target organ toxicity (single exposure) Category 1
Target Organs - Central nervous system (CNS), Optic nerve, Respiratory system.
Specific target organ toxicity - (repeated exposure) Category 1
Target Organs - Kidney, Liver, spleen, Blood.

Label Elements

Signal Word: Danger

Hazard Statements
Highly flammable liquid and vapor
Causes serious eye irritation
Causes damage to organs
Causes damage to organs through prolonged or repeated exposure
3. Composition/Information on Ingredients

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>64-17-5</td>
<td>91-92</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>67-56-1</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>108-10-1</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>141-78-6</td>
<td>1-2</td>
</tr>
<tr>
<td>Hexane</td>
<td>110-54-3</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Toluene</td>
<td>108-88-3</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Ligroine</td>
<td>8032-32-4</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

4. First-aid measures

General Advice: If symptoms persist, call a physician.
Eye Contact
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

Skin Contact
Wash off immediately with plenty of water for at least 15 minutes. If skin irritation persists, call a physician.

Inhalation
Move to fresh air. If not breathing, give artificial respiration. Get medical attention if symptoms occur.

Ingestion
Clean mouth with water and drink afterwards plenty of water.

Most important symptoms and effects
None reasonably foreseeable. Breathing difficulties. Inhalation of high vapor concentrations may cause symptoms like headache, dizziness, tiredness, nausea and vomiting

Notes to Physician
Treat symptomatically

5. Fire-fighting measures

Suitable Extinguishing Media
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

Unsuitable Extinguishing Media
Water may be ineffective, Do not use a solid water stream as it may scatter and spread fire

Flash Point
13.9 °C / 57 °F

Method -
No information available

Autoignition Temperature
362.8 °C / 685 °F

Explosion Limits
Upper 18.0 vol %
Lower 3.3 vol %

Sensitivity to Mechanical Impact
No information available

Sensitivity to Static Discharge
No information available

Specific Hazards Arising from the Chemical
Flammable. Vapors may form explosive mixtures with air. Vapors may travel to source of ignition and flash back. Containers may explode when heated. Vapors may form explosive mixtures with air.

Hazardous Combustion Products
Carbon monoxide (CO) Carbon dioxide (CO2)

Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPA
Health
Flammability
Instability
Physical hazards
3
3
0
N/A

6. Accidental release measures

Personal Precautions
Use personal protective equipment. Ensure adequate ventilation.

Environmental Precautions
Should not be released into the environment. See Section 12 for additional ecological information.

Methods for Containment and Clean Up
Soak up with inert absorbent material. Keep in suitable, closed containers for disposal.

7. Handling and storage

Handling
Wear personal protective equipment. Ensure adequate ventilation. Do not get in eyes, on skin, or on clothing. Avoid ingestion and inhalation.
8. Exposure controls / personal protection

Exposure Guidelines

<table>
<thead>
<tr>
<th>Component</th>
<th>ACGIH TLV</th>
<th>OSHA PEL</th>
<th>NIOSH IDLH</th>
<th>Mexico OEL (TWA)</th>
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</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>STEL: 1000 ppm</td>
<td>(Vacated) TWA: 1000 ppm</td>
<td>IDLH: 3300 ppm</td>
<td>TWA: 1000 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) TWA: 1900 mg/m³</td>
<td>TWA: 1000 ppm</td>
<td>TWA: 1900 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 1900 mg/m³</td>
<td>TWA: 200 ppm</td>
<td></td>
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<tr>
<td>Methyl alcohol</td>
<td>TWA: 200 ppm</td>
<td>(Vacated) TWA: 200 ppm</td>
<td>IDLH: 6000 ppm</td>
<td>TWA: 200 ppm</td>
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<tr>
<td></td>
<td>STEL: 250 ppm</td>
<td>(Vacated) STEL: 250 ppm</td>
<td>TWA: 200 ppm</td>
<td>TWA: 260 mg/m³</td>
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<tr>
<td></td>
<td>Skin</td>
<td>(Vacated) STEL: 325 mg/m³</td>
<td>TWA: 260 mg/m³</td>
<td>TWA: 250 ppm</td>
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<tr>
<td></td>
<td></td>
<td>TWA: 200 ppm</td>
<td>TWA: 325 mg/m³</td>
<td>STEL: 310 mg/m³</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>TWA: 20 ppm</td>
<td>(Vacated) TWA: 50 ppm</td>
<td>IDLH: 500 ppm</td>
<td>TWA: 50 ppm</td>
</tr>
<tr>
<td></td>
<td>STEL: 75 ppm</td>
<td>(Vacated) TWA: 205 mg/m³</td>
<td>TWA: 50 ppm</td>
<td>TWA: 205 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 300 mg/m³</td>
<td>TWA: 75 ppm</td>
<td>STEL: 307 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 100 ppm</td>
<td>STEL: 300 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>TWA: 400 ppm</td>
<td>(Vacated) TWA: 400 ppm</td>
<td>IDLH: 2000 ppm</td>
<td>TWA: 400 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) TWA: 1400 mg/m³</td>
<td>TWA: 400 ppm</td>
<td>TWA: 1400 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 1400 mg/m³</td>
<td>TWA: 200 ppm</td>
<td></td>
</tr>
<tr>
<td>Hexane</td>
<td>TWA: 50 ppm</td>
<td>(Vacated) TWA: 50 ppm</td>
<td>IDLH: 1100 ppm</td>
<td>TWA: 50 ppm</td>
</tr>
<tr>
<td></td>
<td>Skin</td>
<td>(Vacated) TWA: 180 mg/m³</td>
<td>TWA: 50 ppm</td>
<td>TWA: 180 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 500 ppm</td>
<td>TWA: 180 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>TWA: 20 ppm</td>
<td>(Vacated) TWA: 100 ppm</td>
<td>IDLH: 500 ppm</td>
<td>TWA: 50 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) TWA: 375 mg/m³</td>
<td>TWA: 50 ppm</td>
<td>TWA: 188 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ceiling: 300 ppm</td>
<td>TWA: 100 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 150 ppm</td>
<td>TWA: 375 mg/m³</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 560 mg/m³</td>
<td>STEL: 150 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 200 ppm</td>
<td>STEL: 560 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Lignoine</td>
<td>(Vacated) TWA: 300 ppm</td>
<td>(Vacated) TWA: 1350 mg/m³</td>
<td>TWA: 350 mg/m³</td>
<td>TWA: 300 ppm</td>
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<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 400 ppm</td>
<td>Ceiling: 1800 mg/m³</td>
<td>TWA: 1350 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 1800 mg/m³</td>
<td></td>
<td>STEL: 400 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>STEL: 1800 mg/m³</td>
</tr>
</tbody>
</table>

Legend

ACGIH - American Conference of Governmental Industrial Hygienists
OSHA - Occupational Safety and Health Administration
NIOSH IDLH: The National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health

Engineering Measures

Ensure adequate ventilation, especially in confined areas. Use explosion-proof electrical/ventilating/lighting/equipment. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection

Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA’s eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.

Skin and body protection

Long sleeved clothing.
Respiratory Protection
Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.

Hygiene Measures
Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Physical State</th>
<th>Appearance</th>
<th>Odor</th>
<th>Odor Threshold</th>
<th>pH</th>
<th>Melting Point/Range</th>
<th>Boiling Point/Range</th>
<th>Flash Point</th>
<th>Evaporation Rate</th>
<th>Flammability (solid,gas)</th>
<th>Flammability or explosive limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liquid</td>
<td>Clear</td>
<td>No information available</td>
<td>No information available</td>
<td>&lt; -90 °C / -130 °C</td>
<td>No information available</td>
<td>13.9 °C / 57 °F</td>
<td>3.6 (Butyl acetate = 1.0)</td>
<td>Not applicable</td>
<td>Upper: 18.0 vol %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower: 3.3 vol %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vapor Pressure: 48 mmHg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vapor Density: 1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Specific Gravity: 0.785 - 0.792</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Solubility: Soluble in water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Partition coefficient; n-octanol/water: No data available</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Autoignition Temperature: 362.8 °C / 685 °F</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Decomposition Temperature: No information available</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Viscosity: No information available</td>
</tr>
</tbody>
</table>

10. Stability and reactivity

Reactive Hazard
None known, based on information available

Stability
Stable under normal conditions.

Conditions to Avoid

Incompatible Materials
Strong oxidizing agents, Acids, Acid anhydrides, Acid chlorides, Peroxides, Alkali metals

Hazardous Decomposition Products
Carbon monoxide (CO), Carbon dioxide (CO₂)

Hazardous Polymerization
Hazardous polymerization does not occur.

Hazardous Reactions
None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information
Oral LD50
Based on ATE data, the classification criteria are not met. ATE > 2000 mg/kg.

Dermal LD50
Based on ATE data, the classification criteria are not met. ATE > 2000 mg/kg.

Vapor LC50
Based on ATE data, the classification criteria are not met. ATE > 20 mg/l.

Component Information

<table>
<thead>
<tr>
<th>Component</th>
<th>LD50 Oral (Mouse)</th>
<th>LD50 Dermal</th>
<th>LC50 Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>3450 mg/kg</td>
<td>Not listed</td>
<td>20000 ppm/10H ( Rat )</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td><strong>Calc. ATE 60 mg/kg</strong></td>
<td><strong>Calc. ATE 60 mg/kg</strong></td>
<td><strong>Calc. ATE 0.6 mg/L (vapours) or 0.5 mg/L (mists)</strong></td>
</tr>
<tr>
<td></td>
<td>LD50 &gt; 1187 – 2769 mg/kg ( Rat )</td>
<td>LD50 = 17100 mg/kg ( Rabbit )</td>
<td>LC50 = 128.2 mg/L ( Rat ) 4 h</td>
</tr>
</tbody>
</table>
### Ethanol, Anhydrous (Histological)

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>IARC</th>
<th>NTP</th>
<th>ACGIH</th>
<th>OSHA</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>64-17-5</td>
<td>Group 1</td>
<td>Known</td>
<td>A3</td>
<td>X</td>
<td>Not listed</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>67-56-1</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>108-10-1</td>
<td>Group 2B</td>
<td>Not listed</td>
<td>A3</td>
<td>X</td>
<td>Not listed</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>141-78-6</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Hexane</td>
<td>110-54-3</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Toluene</td>
<td>108-88-3</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Ligroine</td>
<td>8032-32-4</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>A3</td>
</tr>
</tbody>
</table>

**IARC** (International Agency for Research on Cancer)
- Group 1 - Carcinogenic to Humans
- Group 2A - Probably Carcinogenic to Humans
- Group 2B - Possibly Carcinogenic to Humans

**NTP** (National Toxicity Program)
- Known - Known Carcinogen
- Reasonably Anticipated - Reasonably Anticipated to be a Human Carcinogen

**ACGIH** (American Conference of Governmental Industrial Hygienists)
- A1 - Known Human Carcinogen
- A2 - Suspected Human Carcinogen
- A3 - Animal Carcinogen
- ACGIH (American Conference of Governmental Industrial Hygienists)
- Mexico - Occupational Exposure Limits - Carcinogens
- A1 - Confirmed Human Carcinogen
- A2 - Suspected Human Carcinogen
- A3 - Confirmed Animal Carcinogen
- A4 - Not Classifiable as a Human Carcinogen
- A5 - Not Suspected as a Human Carcinogen

### Toxicologically Synergistic Products
- No information available

### Delayed and immediate effects as well as chronic effects from short and long-term exposure

#### Irritation
- Severe eye irritant

#### Sensitization
- No information available

#### Carcinogenicity
- The table below indicates whether each agency has listed any ingredient as a carcinogen.

#### Mutagenic Effects
- Mutagenic effects have occurred in experimental animals.

#### Reproductive Effects
- No information available.

#### Developmental Effects
- No information available.

#### Teratogenicity
- No information available.

#### STOT - single exposure
- Central nervous system (CNS) Optic nerve Respiratory system

#### STOT - repeated exposure
- Kidney Liver spleen Blood

#### Aspiration hazard
- No information available

#### Symptoms / effects, both acute and delayed
- Inhalation of high vapor concentrations may cause symptoms like headache, dizziness, tiredness, nausea and vomiting

#### Endocrine Disruptor Information
- No information available
Other Adverse Effects

The toxicological properties have not been fully investigated.

### 12. Ecological information

**Ecotoxicity**

Contains a substance which is toxic to aquatic organisms. The product contains following substances which are hazardous for the environment.

<table>
<thead>
<tr>
<th>Component</th>
<th>Freshwater Algae</th>
<th>Freshwater Fish</th>
<th>Microtox</th>
<th>Water Flea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>EC50 (72h) = 275 mg/L (Chlorella vulgaris)</td>
<td>Fathead minnow (Pimephales promelas) LC50 = 14200 mg/L/96h</td>
<td>Photobacterium phosphoreum;EC50 = 34634 mg/L/30 min Photobacterium phosphoreum;EC50 = 35470 mg/L/5 min</td>
<td>EC50 = 9268 mg/L/48h EC50 = 10800 mg/L/24h</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td></td>
<td>Pimephales promelas: LC50 &gt; 10000 mg/L 96h</td>
<td>EC50 = 39000 mg/L 25 min EC50 = 40000 mg/L 15 min EC50 = 43000 mg/L 5 min</td>
<td>EC50 &gt; 10000 mg/L 24h</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>EC50: 400 mg/L/96h</td>
<td>LC50: 496 - 514 mg/L, 96h flow-through (Pimephales promelas)</td>
<td>EC50 = 79.6 mg/L 5 min</td>
<td>EC50: 4280.0 mg/L/24h EC50: 170 mg/L/48h EC50: 4280.0 mg/L/24h</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>EC50 = 3300 mg/L/48h</td>
<td>Fathead minnow; LC50: 230 mg/L/96h Gold orfe; LC50: 270 mg/L/48h</td>
<td>EC50 = 1180 mg/L 5 min EC50 = 1500 mg/L 15 min EC50 = 5870 mg/L 15 min EC50 = 7400 mg/L 2 h</td>
<td>EC50 = 717 mg/L/48h</td>
</tr>
<tr>
<td>Hexane</td>
<td>Not listed</td>
<td>LC50: 2.1 - 2.98 mg/L, 96h flow-through (Pimephales promelas)</td>
<td>Not listed</td>
<td>EC50: 3.87 mg/L/48h</td>
</tr>
<tr>
<td>Toluene</td>
<td>EC50: = 12.5 mg/L, 72h static (Pseudokirchneriella subcapitata) EC50: &gt; 433 mg/L, 96h (Pseudokirchneriella subcapitata)</td>
<td>50-70 mg/L LC50 96 h 5-7 mg/L LC50 96 h 15-19 mg/L LC50 96 h 28 mg/L LC50 96 h 12 mg/L LC50 96 h</td>
<td>EC50 = 19.7 mg/L 30 min</td>
<td>EC50: = 11.5 mg/L, 48h (Daphnia magna) EC50: 5.46 - 9.83 mg/L, 48h Static (Daphnia magna)</td>
</tr>
<tr>
<td>Lignoone</td>
<td>EC50: = 4700 mg/L, 72h (Pseudokirchneriella subcapitata)</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

**Persistence and Degradability** Persistence is unlikely based on information available.

**Bioaccumulation/Accumulation** No information available.

**Mobility** Will likely be mobile in the environment due to its volatility.

<table>
<thead>
<tr>
<th>Component</th>
<th>log Pow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>-0.32</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>-0.74</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>1.19</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>0.6</td>
</tr>
<tr>
<td>Hexane</td>
<td>4.11</td>
</tr>
<tr>
<td>Toluene</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### 13. Disposal considerations

**Waste Disposal Methods** Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

<table>
<thead>
<tr>
<th>Component</th>
<th>RCRA - U Series Wastes</th>
<th>RCRA - P Series Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl alcohol - 67-56-1</td>
<td>U154</td>
<td>-</td>
</tr>
<tr>
<td>Methylisobutyl ketone - 108-10-1</td>
<td>U161</td>
<td>-</td>
</tr>
</tbody>
</table>
14. Transport information

DOT

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1170</td>
<td>ETHANOL</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

TDG

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1170</td>
<td>ETHANOL</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

IATA

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1170</td>
<td>ETHANOL</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

IMDG/IMO

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1170</td>
<td>ETHANOL</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

15. Regulatory information

All of the components in the product are on the following Inventory lists: Australia Complete Regulatory Information contained in following SDS's X = listed China Canada The product is classified and labeled according to EC directives or corresponding national laws The product is classified and labeled in accordance with Directive 1999/45/EC Europe TSCA Korea Philippines U.S.A. (TSCA) Canada (DSL/NDSL) Europe (EINECS/ELINCS/NLP) Australia (AICS) Korea (ECL) China (IECSC) Japan (ENCS) Philippines (PICCS)

International Inventories

<table>
<thead>
<tr>
<th>Component</th>
<th>TSCA</th>
<th>DSL</th>
<th>NDSL</th>
<th>EINECS</th>
<th>ELINCS</th>
<th>NLP</th>
<th>PICCS</th>
<th>ENCS</th>
<th>AICS</th>
<th>IECSC</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>200-578-6</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td></td>
</tr>
<tr>
<td>Methyl alcohol</td>
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<td>200-659-8</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<td></td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>203-550-1</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</tr>
<tr>
<td>Ethyl acetate</td>
<td>X</td>
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<td>-</td>
<td>205-500-4</td>
<td>-</td>
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<td>Hexane</td>
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<td>203-776-7</td>
<td>438-390-3</td>
<td>X</td>
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<td>Toluene</td>
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<td>-</td>
<td>203-625-9</td>
<td>-</td>
<td>X</td>
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<tr>
<td>Lignoene</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>232-453-7</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<td></td>
</tr>
</tbody>
</table>

Legend:
X - Listed
E - Indicates a substance that is the subject of a Section 5(e) Consent order under TSCA.
F - Indicates a substance that is the subject of a Section 5(f) Rule under TSCA.
N - Indicates a polymeric substance containing no free-radical initiator in its inventory name but is considered to cover the designated polymer made with any free-radical initiator regardless of the amount used.
P - Indicates a commenced PMN substance
R - Indicates a substance that is the subject of a Section 6 risk management rule under TSCA.
S - Indicates a substance that is identified in a proposed or final Significant New Use Rule
T - Indicates a substance that is the subject of a Section 4 test rule under TSCA.
UX - Indicates a substance exempt from reporting under the Inventory Update Rule, i.e. Partial Updating of the TSCA Inventory Data Base Production and Site Reports (40 CFR 710(B)).
Y1 - Indicates an exempt polymer that has a number-average molecular weight of 1,000 or greater.
Y2 - Indicates an exempt polymer that is a polyester and is made only from reactants included in a specified list of low concern reactants that comprises one of the eligibility criteria for the exemption rule.

U.S. Federal Regulations
Ethanol, Anhydrous (Histological)

TSCA 12(b) Not applicable

SARA 313

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
<th>SARA 313 - Threshold Values %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl alcohol</td>
<td>67-56-1</td>
<td>&lt;5</td>
<td>1.0</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>108-10-1</td>
<td>1.0-2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Hexane</td>
<td>110-54-3</td>
<td>&lt;1</td>
<td>1.0</td>
</tr>
<tr>
<td>Toluene</td>
<td>108-88-3</td>
<td>&lt;0.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

SARA 311/312 Hazard Categories See section 2 for more information

CWA (Clean Water Act)

<table>
<thead>
<tr>
<th>Component</th>
<th>CWA - Hazardous Substances</th>
<th>CWA - Reportable Quantities</th>
<th>CWA - Toxic Pollutants</th>
<th>CWA - Priority Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>X</td>
<td>1000 lb</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Clean Air Act

<table>
<thead>
<tr>
<th>Component</th>
<th>HAPS Data</th>
<th>Class 1 Ozone Depletors</th>
<th>Class 2 Ozone Depletors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl alcohol</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hexane</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OSHA Occupational Safety and Health Administration
Not applicable

CERCLA

<table>
<thead>
<tr>
<th>Component</th>
<th>Hazardous Substances RQs</th>
<th>CERCLA EHS RQs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl alcohol</td>
<td>5000 lb</td>
<td></td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>5000 lb</td>
<td></td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>5000 lb</td>
<td></td>
</tr>
<tr>
<td>Hexane</td>
<td>5000 lb</td>
<td></td>
</tr>
<tr>
<td>Toluene</td>
<td>1000 lb 1 lb</td>
<td></td>
</tr>
</tbody>
</table>

California Proposition 65 Ethyl alcohol is only a considered a Proposition 65 developmental hazard when it is ingested as an alcoholic beverage This product contains the following proposition 65 chemicals

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>California Prop. 65</th>
<th>Prop 65 NSRL</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>64-17-5</td>
<td>Development (alcoholic beverages only)</td>
<td>-</td>
<td>Developmental</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>67-56-1</td>
<td>Developmental</td>
<td>-</td>
<td>Developmental</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>108-10-1</td>
<td>Developmental</td>
<td>-</td>
<td>Developmental</td>
</tr>
<tr>
<td>Toluene</td>
<td>108-88-3</td>
<td>Developmental</td>
<td>-</td>
<td>Developmental</td>
</tr>
</tbody>
</table>

U.S. State Right-to-Know Regulations

<table>
<thead>
<tr>
<th>Component</th>
<th>Massachusetts</th>
<th>New Jersey</th>
<th>Pennsylvania</th>
<th>Illinois</th>
<th>Rhode Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl alcohol</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Methyl alcohol</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Methylisobutyl ketone</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ethyl acetate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Hexane</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Toluene</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Lignoine</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

U.S. Department of Transportation
Ethanol, Anhydrous (Histological)

Reportable Quantity (RQ): N
DOT Marine Pollutant N
DOT Severe Marine Pollutant N

U.S. Department of Homeland Security
This product does not contain any DHS chemicals.

Other International Regulations
Mexico - Grade Serious risk, Grade 3

16. Other Information

Prepared By Regulatory Affairs
Thermo Fisher Scientific
Email: EMSDS.RA@thermofisher.com

Creation Date 09-Jul-2009
Revision Date 18-Jan-2018
Print Date 18-Jan-2018
Revision Summary This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer
The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

End of SDS
SAFETY DATA SHEET

Product Name: Ethyl acetate
Cat No.: BP1125-1; BP1125-4
CAS-No: 141-78-6
Synonyms: Acetic acid ethyl ester
Recommended Use: Laboratory chemicals.
Uses advised against: Not for food, drug, pesticide or biocidal product use

Company
importer/Distributor: Fisher Scientific
112 Colonnade Road,
Ottawa, ON K2E 7L6,
Canada
Tel: 1-800-234-7437

Manufacturer: Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

WHMIS 2015 Classification: Classified as hazardous under the Hazardous Products Regulations (SOR/2015-17)

Flammable liquids: Category 2
Serious Eye Damage/Eye Irritation: Category 2
Specific target organ toxicity (single exposure): Category 3
Target Organs - Central nervous system (CNS).
Health Hazards Not Otherwise Classified: Category 1
Prolonged or repeated contact may dry skin and cause irritation or cracking

Label Elements

Signal Word: Danger

Hazard Statements
Highly flammable liquid and vapor
Causes serious eye irritation
May cause drowsiness and dizziness
Prolonged or repeated contact may dry skin and cause irritation or cracking
Precautionary Statements

Prevention
Keep away from heat, hot surfaces, sparks, open flames and other ignition sources. No smoking
Keep container tightly closed
Ground/bond container and receiving equipment
Use explosion-proof electrical/ventilating/lighting/equipment
Use only non-sparking tools
Take precautionary measures against static discharges
Do not breathe dust/fumes/gas/mist/vapours/spray
Wash face, hands and any exposed skin thoroughly after handling
Use only outdoors or in a well-ventilated area
Wear protective gloves/protective clothing/eye protection/face protection

Response
IF ON SKIN (or hair): Take off immediately all contaminated clothing. Rinse skin with water/ shower
IF INHALED: Remove person to fresh air and keep comfortable for breathing
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
Call a POISON CENTER/ doctor if you feel unwell
In case of fire: Use dry sand, dry chemical or alcohol-resistant foam to extinguish

Storage
Store in a well-ventilated place. Keep container tightly closed
Store locked up

Disposal
Dispose of contents/container to an approved waste disposal plant

3. Composition/Information on Ingredients

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>141-78-6</td>
<td>&gt;95</td>
</tr>
</tbody>
</table>

4. First-aid measures

General Advice
If symptoms persist, call a physician.

Eye Contact
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

Skin Contact
Wash off immediately with plenty of water for at least 15 minutes. If skin irritation persists, call a physician.

Inhalation
Move to fresh air. If not breathing, give artificial respiration. Get medical attention if symptoms occur.

Ingestion
Clean mouth with water and drink afterwards plenty of water.

Most important symptoms/effects
Breathing difficulties. May cause central nervous system depression: Inhalation of high vapor concentrations may cause symptoms like headache, dizziness, tiredness, nausea and vomiting

Notes to Physician
Treat symptomatically
5. Fire-fighting measures

Suitable Extinguishing Media  Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

Unsuitable Extinguishing Media  Water may be ineffective, Do not use a solid water stream as it may scatter and spread fire

Flash Point  
-4 °C / 24.8 °F

Method -  Closed cup

Autoignition Temperature  427 °C / 800.6 °F

Explosion Limits

Upper  11.5 vol %
Lower  2.0 vol %

Oxidizing Properties  Not oxidising

Sensitivity to Mechanical Impact  No information available
Sensitivity to Static Discharge  No information available

Specific Hazards Arising from the Chemical

Flammable. Risk of ignition. Vapors may form explosive mixtures with air. Vapors may travel to source of ignition and flash back. Containers may explode when heated.

6. Accidental release measures

NFPA  

Health  2  Flammability  3  Instability  0  Physical hazards  N/A

Personal Precautions  Use personal protective equipment. Ensure adequate ventilation.

Environmental Precautions  Should not be released into the environment. See Section 12 for additional ecological information.

Methods for Containment and Clean Up  Soak up with inert absorbent material. Keep in suitable, closed containers for disposal.

7. Handling and storage

Handling  Ensure adequate ventilation. Wear personal protective equipment. Do not get in eyes, on skin, or on clothing. Avoid ingestion and inhalation.

Storage  Flammables area. Keep away from heat and sources of ignition. Keep container tightly closed in a dry and well-ventilated place.

8. Exposure controls / personal protection

Exposure Guidelines

<table>
<thead>
<tr>
<th>Component</th>
<th>Alberta</th>
<th>British Columbia</th>
<th>Ontario TWA/ET</th>
<th>Quebec</th>
<th>ACGIH TLV</th>
<th>OSHA PEL</th>
<th>NIOSH IDLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>TWA: 400 ppm TWA: 1440 mg/m³</td>
<td>TWA: 150 ppm</td>
<td>TWA: 400 ppm TWA: 1440 mg/m³</td>
<td>TWA: 400 ppm</td>
<td>TWA: 400 ppm (Vacated)</td>
<td>TWA: 1400 mg/m³</td>
<td>TWA: 400 ppm</td>
</tr>
</tbody>
</table>

Page 3 / 7
Ethyl acetate

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACGIH - American Conference of Governmental Industrial Hygienists</td>
</tr>
<tr>
<td>OSHA - Occupational Safety and Health Administration</td>
</tr>
<tr>
<td>NIOSH IDLH: The National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health</td>
</tr>
</tbody>
</table>

**Engineering Measures**
Ensure adequate ventilation, especially in confined areas. Use explosion-proof electrical/ventilating/lighting/equipment. Ensure that eyewash stations and safety showers are close to the workstation location. Wherever possible, engineering control measures such as the isolation or enclosure of the process, the introduction of process or equipment changes to minimise release or contact, and the use of properly designed ventilation systems, should be adopted to control hazardous materials at source.

**Personal protective equipment**

<table>
<thead>
<tr>
<th>Eye Protection</th>
<th>Goggles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand Protection</td>
<td>Wear appropriate protective gloves and clothing to prevent skin exposure.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glove material</th>
<th>Breakthrough time</th>
<th>Glove thickness</th>
<th>Glove comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butyl rubber</td>
<td>&gt; 120 minutes</td>
<td>0.5 - 0.7 mm</td>
<td>Permeation rate 8 µg/cm²/min</td>
</tr>
<tr>
<td>Nitrile rubber</td>
<td>&lt; 200 minutes</td>
<td></td>
<td>As tested under EN374-3 Determination of Resistance to Permeation by Chemicals</td>
</tr>
</tbody>
</table>

Inspect gloves before use. Observe the instructions regarding permeability and breakthrough time which are provided by the supplier of the gloves. (Refer to manufacturer/supplier for information) gloves are suitable for the task. Chemical compatibility, Dexterity, Operational conditions, User susceptibility, e.g. sensitisation effects, also take into consideration the specific local conditions under which the product is used, such as the danger of cuts, abrasion, gloves with care avoiding skin contamination.

**Respiratory Protection**
No protective equipment is needed under normal use conditions.

**Environmental exposure controls**
No information available.

**Hygiene Measures**
Handle in accordance with good industrial hygiene and safety practice. Keep away from food, drink and animal feeding stuffs. Do not eat, drink or smoke when using this product. Remove and wash contaminated clothing before re-use. Wash hands before breaks and at the end of workday.

**9. Physical and chemical properties**

<table>
<thead>
<tr>
<th>Physical State</th>
<th>Liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Colorless</td>
</tr>
<tr>
<td>Odor</td>
<td>sweet</td>
</tr>
<tr>
<td>Odor Threshold</td>
<td>50 ppm</td>
</tr>
<tr>
<td>pH</td>
<td>No information available</td>
</tr>
<tr>
<td>Melting Point/Range</td>
<td>-83.5 °C / -118.3 °F</td>
</tr>
<tr>
<td>Boiling Point/Range</td>
<td>75 - 78 °C / 167 - 172.4 °F</td>
</tr>
<tr>
<td>Flash Point</td>
<td>-4 °C / 24.8 °F</td>
</tr>
<tr>
<td>Method -</td>
<td>Closed cup</td>
</tr>
<tr>
<td>Evaporation Rate</td>
<td>6.2</td>
</tr>
<tr>
<td>Flammability (solid, gas)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Flammability or explosive limits</td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>11.5 vol %</td>
</tr>
<tr>
<td>Lower</td>
<td>2.0 vol %</td>
</tr>
</tbody>
</table>
10. Stability and reactivity

Reactive Hazard
None known, based on information available.

Stability
Stable under normal conditions.

Conditions to Avoid
Incompatible products. Keep away from open flames, hot surfaces and sources of ignition.

Incompatible Materials
Strong oxidizing agents, Strong acids, Amines, Peroxides

Hazardous Decomposition Products
Carbon monoxide (CO), Carbon dioxide (CO₂)

Hazardous Polymerization
Hazardous polymerization does not occur.

Hazardous Reactions
None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information

<table>
<thead>
<tr>
<th>Component</th>
<th>LD₅₀ Oral</th>
<th>LD₅₀ Dermal</th>
<th>LC₅₀ Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>10,200 mg/kg (Rat)</td>
<td>&gt; 20 mL/kg (Rabbit)</td>
<td>58 mg/l (rat; 8 h)</td>
</tr>
</tbody>
</table>

Toxicologically Synergistic Products
No information available

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation
Irritating to eyes

Sensitization
No information available

Carcinogenicity
The table below indicates whether each agency has listed any ingredient as a carcinogen.

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>IARC</th>
<th>NTP</th>
<th>ACGIH</th>
<th>OSHA</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>141-78-6</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

Mutagenic Effects
No information available

Reproductive Effects
No information available.

Developmental Effects
No information available.

Teratogenicity
No information available.

STOT - single exposure
Central nervous system (CNS)

STOT - repeated exposure
None known
12. Ecological information

Ecotoxicity
Do not empty into drains.

<table>
<thead>
<tr>
<th>Component</th>
<th>Freshwater Algae</th>
<th>Freshwater Fish</th>
<th>Microtox</th>
<th>Water Flea</th>
</tr>
</thead>
</table>
| Ethyl acetate | EC50 = 3300 mg/L/48h | Fathead minnow: LC50: 230 mg/L/96h | EC50 = 1180 mg/L 5 min  
Gold orfe: LC50: 270 mg/L/48h | EC50 = 717 mg/L/48h |
|               |                  |                  |                   |                 |

Persistence and Degradability
Persistence is unlikely based on information available.

Bioaccumulation/ Accumulation
No information available.

Mobility
Will likely be mobile in the environment due to its volatility.

<table>
<thead>
<tr>
<th>Component</th>
<th>log Pow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>0.8</td>
</tr>
</tbody>
</table>

13. Disposal considerations

Waste Disposal Methods
Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

<table>
<thead>
<tr>
<th>Component</th>
<th>RCRA - U Series Wastes</th>
<th>RCRA - P Series Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate - 141-78-6</td>
<td>U112</td>
<td>-</td>
</tr>
</tbody>
</table>

14. Transport information

DOT

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1173</td>
<td>ETHYL ACETATE</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

TDG

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1173</td>
<td>ETHYL ACETATE</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

IATA

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1173</td>
<td>ETHYL ACETATE</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

IMDG/IMO

<table>
<thead>
<tr>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN1173</td>
<td>ETHYL ACETATE</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

15. Regulatory information
Ethyl acetate

All of the components in the product are on the following Inventory lists: X = listed

International Inventories

<table>
<thead>
<tr>
<th>Component</th>
<th>DSL</th>
<th>NDSL</th>
<th>TSCA</th>
<th>EINECS</th>
<th>ELINCS</th>
<th>NLP</th>
<th>PICCS</th>
<th>ENCS</th>
<th>AICS</th>
<th>IECS</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>205-500-4</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Canada

SDS in compliance with provisions of information as set out in Canadian Standard - Part 4, Schedule 1 and 2 of the Hazardous Products Regulations (HPR) and meets the requirements of the HPR (Paragraph 13(1)(a) of the Hazardous Products Act (HPA)).

<table>
<thead>
<tr>
<th>Component</th>
<th>Canada - National Pollutant Release Inventory (NPRI)</th>
<th>Canadian Environmental Protection Agency (CEPA) - List of Toxic Substances</th>
<th>Canada's Chemicals Management Plan (CEPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl acetate</td>
<td>Part 5, Individual Substances</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

16. Other information

Prepared By  
Regulatory Affairs  
Thermo Fisher Scientific  
Email: EMSDS.RA@thermofisher.com

Creation Date  
13-October-2009

Revision Date  
18-January-2018

Print Date  
18-January-2018

Revision Summary  
This document has been updated to comply with the requirements of WHMIS 2015 to align with the Globally Harmonised System (GHS) for the Classification and Labelling of Chemicals.

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End of SDS
Praxair Material Safety Data Sheet
(See section 15, under TSCA, for important restrictions on product use.)

1. Chemical Product and Company Identification

<table>
<thead>
<tr>
<th>Product Name: Hydrogen, compressed (MSDS No. P-4604-G)</th>
<th>Trade Names: Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Name: Hydrogen</td>
<td>Synonyms: Dihydrogen, parahydrogen, refrigerant gas R702, water gas</td>
</tr>
<tr>
<td>Chemical Family: Permanent gas</td>
<td>Product Grades: Industrial, 4.5, 4.5-Zero, 4.5 TOC, 5.0-UHP, 5.0-SPG, 5.5-SPG, 6.0-SPG, 6.0-UHP, and 6.0-Research</td>
</tr>
</tbody>
</table>

Telephone: Emergencies: 1-800-645-4633*
CHEMTREC: 1-800-424-9300*
Routine: 1-800-PRAXAIR
Company Name: Praxair, Inc.
39 Old Ridgebury Road
Danbury, CT 06810-5113

*Calls emergency numbers 24 hours a day only for spills, leaks, fire, exposure, or accidents involving this product. For routine information, contact your supplier, Praxair sales representative, or call 1-800-PRAXAIR (1-800-772-9247).

2. Hazards Identification

**EMERGENCY OVERVIEW**

DANGER! Flammable high-pressure gas.
Can form explosive mixtures with air.
May ignite if valve is opened to air.
Burns with invisible flame.
May cause dizziness and drowsiness.
Self-contained breathing apparatus may be required by rescue workers.
Under ambient conditions, this is a colorless, odorless, tasteless gas.

OSHA REGULATORY STATUS: This material is considered hazardous by the OSHA Hazard Communications Standard (29 CFR 1910.1200).

POTENTIAL HEALTH EFFECTS:

Effects of a Single (Acute) Overexposure

**Inhalation.** Asphyxiant. Effects are due to lack of oxygen. Moderate concentrations may cause headache, drowsiness, dizziness, excitation, excess salivation, vomiting, and unconsciousness. Lack of oxygen can kill.

**Skin Contact.** No harm expected.

**Swallowing.** An unlikely route of exposure; this product is a gas at normal temperature and pressure.

**Eye Contact.** No harm expected.

Effects of Repeated (Chronic) Overexposure. No harm expected.
Other Effects of Overexposure. Hydrogen is an asphyxiant. Lack of oxygen can kill.

Medical Conditions Aggravated by Overexposure. The toxicology and the physical and chemical properties of hydrogen suggest that overexposure is unlikely to aggravate existing medical conditions.

CARCINOGENICITY: This product is not listed by NTP, OSHA, or IARC

POTENTIAL ENVIRONMENTAL EFFECTS: None known. For further information, see section 12, Ecological Information.

3. Composition/Information on Ingredients

See section 16 for important information about mixtures.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CAS NUMBER</th>
<th>CONCENTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1333-74-0</td>
<td>&gt;99%*</td>
</tr>
</tbody>
</table>

*The symbol > means “greater than.”

4. First Aid Measures

INHALATION: Remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, qualified personnel may give oxygen. Call a physician.

SKIN CONTACT: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

SWALLOWING: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

EYE CONTACT: An unlikely route of exposure. This product is a gas at normal temperature and pressure.

NOTES TO PHYSICIAN: There is no specific antidote. Treatment of overexposure should be directed at the control of symptoms and the clinical condition of the patient.

5. Fire Fighting Measures

FLAMMABLE PROPERTIES: Flammable gas. Flame is nearly invisible. Escaping gas may ignite spontaneously. Hydrogen has a low ignition energy. Fireball forms if gas cloud ignites immediately after release. Forms explosive mixtures with air and oxidizing agents.

SUITABLE EXTINGUISHING MEDIA: CO₂, dry chemical, water spray, or fog

PRODUCTS OF COMBUSTION: Water (H₂O)

PROTECTION OF FIREFIGHTERS: DANGER! Flammable high-pressure gas. Evacuate all personnel from danger area. Immediately deluge cylinders with water from maximum distance until cool; then move them away from fire area if without risk. Continue cooling water spray while moving cylinders. Do not extinguish flames emitted from cylinders; allow them to burn out. Self-contained breathing apparatus may be required by rescue workers. On-site fire brigades must comply with OSHA 29 CFR 1910.156.

Specific Physical and Chemical Hazards. Heat of fire can build pressure in cylinder and cause it to rupture. Hydrogen cylinders are equipped with a pressure relief device. (Exceptions may exist where authorized by DOT.) No part of a cylinder should be subjected to a temperature higher than 125°F (52°C). If venting or leaking hydrogen catches fire, do not
extinguish flames. Flammable gas may spread from leak, creating an explosive re-ignition hazard. Vapors can be ignited by pilot lights, other flames, smoking, sparks, heaters, electrical equipment, static discharge, or other ignition sources at locations distant from product handling point. Explosive atmospheres may linger. Before entering area, especially confined areas, check atmosphere with approved explosion meter.

**Protective Equipment and Precautions for Firefighters.** Firefighters should wear self-contained breathing apparatus and full fire-fighting turnout gear.

### 6. Accidental Release Measures

**STEPS TO BE TAKEN IF MATERIAL IS RELEASED OR SPILLED:**

**DANGER!** Flammable high-pressure gas.

**Personal Precautions.** Forms explosive mixtures with air. (See section 5.) Immediately evacuate all personnel from danger area. Use self-contained breathing apparatus where needed. Approach suspected leak area with caution. Remove all sources of ignition if without risk. Reduce gas with fog or fine water spray. Shut off flow if without risk. Ventilate area or move cylinder to a well-ventilated area. Flammable gas may spread from leak. Before entering area, especially confined areas, check atmosphere with an appropriate device.

**Environmental Precautions.** Prevent waste from contaminating the surrounding environment. Keep personnel away. Discard any product, residue, disposable container, or liner in an environmentally acceptable manner, in full compliance with federal, state, and local regulations. If necessary, call your local supplier for assistance.

### 7. Handling and Storage

**PRECAUTIONS TO BE TAKEN IN HANDLING:** *Keep away from heat, sparks, and open flame.* Use only spark-proof tools and explosion-proof equipment. *Protect cylinders from damage.* Use a suitable hand truck to move cylinders; do not drag, roll, slide, or drop. *Hydrogen is the lightest known gas.* It may leak out of systems that are air-tight for other gases and may collect in poorly ventilated upper reaches of buildings. Leak check system with soapy water; never use a flame. *All piped hydrogen systems and associated equipment must be grounded.* Electrical equipment must be non-sparking or explosion-proof. *Do not crack or open hydrogen cylinder valves unless connected to utilization equipment;* escaping gas may ignite spontaneously. Open valve slowly. If valve is hard to open, discontinue use and contact your supplier. Close cylinder valve after each use; keep closed even when empty. *Never attempt to lift a cylinder by its cap;* the cap is intended solely to protect the valve. Never insert an object (e.g., wrench, screwdriver, pry bar) into cap openings; doing so may damage the valve and cause a leak. Use an adjustable strap wrench to remove over-tight or rusted caps. For other precautions in using hydrogen, see section 16.

**PRECAUTIONS TO BE TAKEN IN STORAGE:** *Store and use with adequate ventilation.* Store only where temperature will not exceed 125°F (52°C). *Separate hydrogen cylinders from oxygen, chlorine, and other oxidizers* by at least 20 ft (6.1 m), or use a barricade of noncombustible material. This barricade should be at least 5 ft (1.53 m) high and have a fire resistance rating of at least 1/2 hour. *Always secure cylinders upright to keep them from falling or being knocked over.* Install valve protection cap, if provided, firmly in place by hand when the cylinder is not in use. *Post “No Smoking or Open Flames” signs in storage and use areas.* There must be no sources of ignition. All electrical equipment in storage areas must be explosion-proof. Storage areas must meet national electric codes for Class 1
hazardous areas. **Store full and empty cylinders separately.** Use a first-in, first-out inventory system to prevent storing full cylinders for long periods.

**RECOMMENDED PUBLICATIONS:** For further information on storage, handling, and use, see Praxair publication P-14-153, *Guidelines for Handling Gas Cylinders and Containers*. Obtain from your local supplier. For further information specific to hydrogen, see NFPA 50A, *Standard for Gaseous Hydrogen Systems at Consumer Sites*, published by the National Fire Protection Association, 1 Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101; 1-800-344-3555; www.nfpa.org.

### 8. Exposure Controls/Personal Protection

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>OSHA PEL</th>
<th>ACGIH TLV-TWA (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>N.E.*</td>
<td>Simple asphyxiant</td>
</tr>
</tbody>
</table>
| *N.E.–Not Established.  
IDLH = Not applicable.  |

**ENGINEERING CONTROLS:**

- **Local Exhaust.** An explosion-proof local exhaust system is acceptable. See SPECIAL.
- **Mechanical (General).** Inadequate; see special.
- **Special.** Use only in a closed system.
- **Other.** See special.

**PERSONAL PROTECTIVE EQUIPMENT:**

- **Skin Protection.** Wear work gloves for cylinder handling and metatarsal shoes for cylinder handling. Select in accordance with OSHA 29 CFR 1910.132 and 1910.133. Regardless of protective equipment, never touch live electrical parts.
- **Eye/Face Protection.** Select in accordance with OSHA 29 CFR 1910.133.

### 9. Physical and Chemical Properties

**APPEARANCE:** Colorless gas

**odor:** Odorless

**Odor Threshold:** Not applicable.

**Physical State:** Gas at normal temperature and pressure

**pH:** Not applicable.

**Melting Point** at 1 atm: -434.56°F (-259.2°C)

**Boiling Point** at 1 atm: -422.97°F (-252.76°C)

**Flash Point** (test method): Not available.

**Evaporation Rate** (Butyl Acetate = 1): Not applicable.

**FLAMMABILITY:** Flammable

**FLAMMABLE LIMITS IN AIR, % by volume:**

<table>
<thead>
<tr>
<th>LOWER</th>
<th>UPPER</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0%</td>
<td>75.0%</td>
</tr>
<tr>
<td><strong>LIQUID DENSITY</strong> at boiling point and 1 atm:</td>
<td>4.43 lb/ft³ (70.96 kg/m³)</td>
</tr>
<tr>
<td><strong>VAPOR PRESSURE</strong> at 68°F (20°C):</td>
<td>Not applicable.</td>
</tr>
<tr>
<td><strong>VAPOR DENSITY</strong> at 70°F (21.1°C) and 1 atm:</td>
<td>0.0052 lb/ft³ (0.083 kg/m³)</td>
</tr>
<tr>
<td><strong>SPECIFIC GRAVITY</strong> (H₂O = 1) at 19.4°F (-7°C):</td>
<td>Not available.</td>
</tr>
<tr>
<td><strong>SPECIFIC GRAVITY</strong> (Air = 1) at 32°F (0°C) and 1 atm:</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>SOLUBILITY IN WATER</strong> vol/vol at 60°F (15.6°C) and 1 atm:</td>
<td>0.019</td>
</tr>
<tr>
<td><strong>PARTITION COEFFICIENT</strong>: n-octanol/water:</td>
<td>Not available.</td>
</tr>
<tr>
<td><strong>AUTOIGNITION TEMPERATURE</strong>:</td>
<td>932°F (500°C)</td>
</tr>
<tr>
<td><strong>DECOMPOSITION TEMPERATURE</strong>:</td>
<td>Not available.</td>
</tr>
<tr>
<td><strong>PERCENT VOLATILES BY VOLUME</strong>:</td>
<td>100</td>
</tr>
<tr>
<td><strong>MOLECULAR WEIGHT</strong>:</td>
<td>2.016</td>
</tr>
<tr>
<td><strong>MOLECULAR FORMULA</strong>:</td>
<td>H₂</td>
</tr>
</tbody>
</table>

### 10. Stability and Reactivity

**CHEMICAL STABILITY**: ☑ Unstable ☒ Stable

**CONDITIONS TO AVOID**: None known.

**INCOMPATIBLE MATERIALS**: Oxidizing agents, lithium, halogens

**HAZARDOUS DECOMPOSITION PRODUCTS**: None

**POSSIBILITY OF HAZARDOUS REACTIONS**: ☑ May Occur ☐ Will Not Occur

Flammable gas. Forms explosive mixtures with air and oxidizing agents.

### 11. Toxicological Information

**ACUTE DOSE EFFECTS**: Hydrogen is a simple asphyxiant.

**STUDY RESULTS**: None known.

### 12. Ecological Information

**ECOTOXICITY**: No adverse ecological effects expected.

**OTHER ADVERSE EFFECTS**: Hydrogen does not contain any Class I or Class II ozone-depleting chemicals.
### 13. Disposal Considerations

**WASTE DISPOSAL METHOD:** Do not attempt to dispose of residual or unused quantities. Return cylinder to supplier.

### 14. Transport Information

<table>
<thead>
<tr>
<th>DOT/IMO SHIPPING NAME:</th>
<th>Hydrogen, compressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZARD CLASS:</td>
<td>2.1</td>
</tr>
<tr>
<td>PACKING GROUP/Zone:</td>
<td>NA*</td>
</tr>
<tr>
<td>IDENTIFICATION NUMBER:</td>
<td>UN1049</td>
</tr>
<tr>
<td>PRODUCT RQ:</td>
<td>None</td>
</tr>
</tbody>
</table>

**SHIPPING LABEL(s):** FLAMMABLE GAS

**PLACARD (when required):** FLAMMABLE GAS

*NA-Not applicable.

**SPECIAL SHIPPING INFORMATION:** Cylinders should be transported in a secure position, in a well-ventilated vehicle. Cylinders transported in an enclosed, nonventilated compartment of a vehicle can present serious safety hazards.

Shipment of compressed gas cylinders that have been filled without the owner’s consent is a violation of federal law [49 CFR 173.301(b)].

**MARINE POLLUTANTS:** Hydrogen is not listed as a marine pollutant by DOT.

### 15. Regulatory Information

The following selected regulatory requirements may apply to this product. Not all such requirements are identified. Users of this product are solely responsible for compliance with all applicable federal, state, and local regulations.

**U.S. FEDERAL REGULATIONS:**

**EPA (ENVIRONMENTAL PROTECTION AGENCY)**

**CERCLA:** COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT OF 1980 (40 CFR Parts 117 and 302):

Reportable Quantity (RQ): None

**SARA:** SUPERFUND AMENDMENT AND REAUTHORIZATION ACT:

**SECTIONS 302/304:** Require emergency planning based on Threshold Planning Quantity (TPQ) and release reporting based on Reportable Quantities (RQ) of Extremely Hazardous Substances (EHS) (40 CFR Part 355):

TPQ: None

EHS RQ (40 CFR 355): None

**SECTIONS 311/312:** Require submission of MSDSs and reporting of chemical inventories with identification of EPA hazard categories. The hazard categories for this product are as follows:

IMMEDIATE: No  PRESSURE: Yes

DELAYED: No  REACTIVITY: No

FIRE: Yes

**SECTION 313:** Requires submission of annual reports of release of toxic chemicals that appear in 40 CFR Part 372.

Hydrogen is not subject to reporting under Section 313.
40 CFR 68: RISK MANAGEMENT PROGRAM FOR CHEMICAL ACCIDENTAL RELEASE PREVENTION: Requires development and implementation of risk management programs at facilities that manufacture, use, store, or otherwise handle regulated substances in quantities that exceed specified thresholds. Hydrogen is listed as a regulated substance in quantities of 10,000 lb (4536 kg) or greater.

TSCA: TOXIC SUBSTANCES CONTROL ACT: Hydrogen is listed on the TSCA inventory.

OSHA: OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION:

29 CFR 1910.119: PROCESS SAFETY MANAGEMENT OF HIGHLY HAZARDOUS CHEMICALS: Requires facilities to develop a process safety management program based on Threshold Quantities (TQ) of highly hazardous chemicals. Hydrogen is not listed in Appendix A as a highly hazardous chemical. However, any process that involves a flammable gas on site in one location in quantities of 10,000 lb (4536 kg) or greater is covered under this regulation unless the gas is used as a fuel.

STATE REGULATIONS:

CALIFORNIA: Hydrogen is not listed by California under the SAFE DRINKING WATER AND TOXIC ENFORCEMENT ACT OF 1986 (Proposition 65).

PENNSYLVANIA: Hydrogen is subject to the PENNSYLVANIA WORKER AND COMMUNITY RIGHT-TO-KNOW ACT (35 P.S. Sections 7301-7320).

16. Other Information

Be sure to read and understand all labels and instructions supplied with all containers of this product.

OTHER HAZARDOUS CONDITIONS OF HANDLING, STORAGE, AND USE: Flammable high-pressure gas. Use only in a closed system. Use piping and equipment adequately designed to withstand pressures and temperatures to be encountered. Use a backflow prevention device in the piping. Gas can cause rapid suffocation due to oxygen deficiency. Store and use with adequate ventilation. Never work on a pressurized system. If there is a leak, close the cylinder valve. Blow the system down in a safe and environmentally sound manner in compliance with all federal, state, and local laws; then repair the leak. Never place a compressed gas cylinder where it may become part of an electrical circuit.

Mixtures. When you mix two or more gases or liquefied gases, you can create additional, unexpected hazards. Obtain and evaluate the safety information for each component before you produce the mixture. Consult an industrial hygienist or other trained person when you evaluate the end product. Remember, gases and liquids have properties that can cause serious injury or death.

HAZARD RATING SYSTEMS:

<table>
<thead>
<tr>
<th>NFPA RATINGS:</th>
<th>HMIS RATINGS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEALTH</td>
<td>HEALTH</td>
</tr>
<tr>
<td>FLAMMABILITY</td>
<td>FLAMMABILITY</td>
</tr>
<tr>
<td>INSTABILITY</td>
<td>PHYSICAL HAZARD</td>
</tr>
<tr>
<td>SPECIAL</td>
<td>= None</td>
</tr>
</tbody>
</table>

= 0
= 4
= 0
= 3

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STANDARD VALVE CONNECTIONS FOR U.S. AND CANADA:

**THREADED:**
- 0-3000 psig: CGA-350
- 3301-5500 psig: CGA-695
- 5501-7500 psig: CGA-703

**PIN-INDEXED YOKE:**
Not applicable.

**ULTRA-HIGH-INTEGRITY CONNECTION:**
- CGA-724

Use the proper CGA connections. **DO NOT USE ADAPTERS.** Additional limited-standard connections may apply. See CGA pamphlet V-1 listed below.

Ask your supplier about free Praxair safety literature as referred to in this MSDS and on the label for this product. Further information can be found in the following materials published by the Compressed Gas Association, Inc. (CGA), 4221 Walney Road, 5th Floor, Chantilly, VA 20151-2923; telephone (703) 788-2700, http://www.cganet.com/Publication.asp.

- AV-1 Safe Handling and Storage of Compressed Gases
- G-5 Hydrogen
- G-5.3 Commodity Specification for Hydrogen
- P-1 Safe Handling of Compressed Gases in Containers
- SB-2 Oxygen-Deficient Atmospheres
- V-1 Compressed Gas Cylinder Valve Inlet and Outlet Connections
- — Handbook of Compressed Gases, Fourth Edition
Praxair asks users of this product to study this MSDS and become aware of product hazards and safety information. To promote safe use of this product, a user should (1) notify employees, agents, and contractors of the information in this MSDS and of any other known product hazards and safety information, (2) furnish this information to each purchaser of the product, and (3) ask each purchaser to notify its employees and customers of the product hazards and safety information.
The opinions expressed herein are those of qualified experts within Praxair, Inc. We believe that the information contained herein is current as of the date of this Material Safety Data Sheet. Since the use of this information and the conditions of use of the product are not within the control of Praxair, Inc., it is the user’s obligation to determine the conditions of safe use of the product.
SECTION 1. IDENTIFICATION

Product name: Eastman(TM) Acetaldehyde

Product code: 00160-00, P0016000, P0016001, E0016002, E0016001

Manufacturer or supplier's details

Company name of supplier: Eastman Chemical Company

Address: 200 South Wilcox Drive
          Kingsport TN 37660-5280

Telephone: (423) 229-2000

Emergency telephone: CHEMTREC: +1-800-424-9300, +1-703-527-3887 CCN7321

Recommended use of the chemical and restrictions on use

Recommended use: Chemical intermediate

Restrictions on use: None known.

SECTION 2. HAZARDS IDENTIFICATION

GHS classification in accordance with 29 CFR 1910.1200

Flammable liquids: Category 1

Acute toxicity (Oral): Category 4

Eye irritation: Category 2A

Carcinogenicity: Category 2

Specific target organ systemic toxicity - single exposure: Category 3 (Respiratory system)

GHS label elements

Hazard pictograms:

Signal Word: Danger

Hazard Statements:
- H224 Extremely flammable liquid and vapor.
- H302 Harmful if swallowed.
- H319 Causes serious eye irritation.
- H335 May cause respiratory irritation.
Precautionary Statements:

**Prevention:**
P201 Obtain special instructions before use.
P202 Do not handle until all safety precautions have been read and understood.
P210 Keep away from heat/sparks/open flames/hot surfaces. No smoking.
P233 Keep container tightly closed.
P240 Ground/bond container and receiving equipment.
P241 Use explosion-proof electrical/ventilating/lighting/equipment.
P242 Use only non-sparking tools.
P243 Take precautionary measures against static discharge.
P261 Avoid breathing dust/fume/gas/mist/vapors/spray.
P264 Wash skin thoroughly after handling.
P270 Do not eat, drink or smoke when using this product.
P280 Wear protective gloves/protective clothing/eye protection/face protection.

**Response:**
P301 + P312 + P330 IF SWALLOWED: Call a POISON CENTER/doctor if you feel unwell. Rinse mouth.
P303 + P361 + P353 IF ON SKIN (or hair): Take off immediately all contaminated clothing. Rinse skin with water/shower.
P304 + P340 + P312 IF INHALED: Remove person to fresh air and keep comfortable for breathing. Call a POISON CENTER/doctor if you feel unwell.
P305 + P351 + P338 IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.
P308 + P313 IF exposed or concerned: Get medical advice/attention.
P337 + P313 If eye irritation persists: Get medical advice/attention.
P370 + P378 In case of fire: Use dry sand, dry chemical or alcohol-resistant foam to extinguish.

**Storage:**
P403 + P233 Store in a well-ventilated place. Keep container tightly closed.
P403 + P235 Store in a well-ventilated place. Keep cool.
P405 Store locked up.

**Disposal:**
P501 Dispose of contents/container to an approved waste disposal plant.

Other hazards:
May polymerize resulting in hazardous condition.
May form peroxides of unknown stability.
SECTION 3. COMPOSITION/INFORMATION ON INGREDIENTS

<table>
<thead>
<tr>
<th>Chemical name</th>
<th>CAS-No.</th>
<th>Concentration (% w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetaldehyde</td>
<td>75-07-0</td>
<td>100</td>
</tr>
</tbody>
</table>

SECTION 4. FIRST AID MEASURES

If inhaled: Move to fresh air. Treat symptomatically. If symptoms persist, call a physician.

In case of skin contact: Wash off with soap and water. Remove contaminated clothing and shoes. Get medical attention if symptoms occur.

In case of eye contact: Remove contact lenses, if present and easy to do. Continue rinsing. If eye irritation persists: Get medical advice/attention.

If swallowed: Seek medical advice.

Most important symptoms and effects, both acute and delayed: Harmful if swallowed. Causes serious eye irritation. May cause respiratory irritation. Suspected of causing cancer.

Notes to physician: Treat symptomatically.

SECTION 5. FIRE-FIGHTING MEASURES

Suitable extinguishing media: Alcohol-resistant foam
Carbon dioxide (CO2)
Dry chemical
Water spray

Unsuitable extinguishing media: Water spray jet

Specific hazards during fire fighting: Water may be ineffective. The product will float on water and can be rekindled on surface water.

Further information: Highly flammable liquid and vapor. Use water spray to cool unopened containers.

Special protective equipment for fire-fighters: Wear an approved positive pressure self-contained breathing apparatus in addition to standard fire fighting gear.

SECTION 6. ACCIDENTAL RELEASE MEASURES
SAFETY DATA SHEET

Eastman(TM) Acetaldehyde

Personal precautions, protective equipment and emergency procedures:
Wear appropriate personal protective equipment. Local authorities should be advised if significant spillages cannot be contained.

Environmental precautions:
Avoid release to the environment.

Methods and materials for containment and cleaning up:
Contain spillage, soak up with non-combustible absorbent material, (e.g. sand, earth, diatomaceous earth, vermiculite) and transfer to a container for disposal according to local / national regulations (see section 13). After cleaning, flush away traces with water. Eliminate all ignition sources if safe to do so.

SECTION 7. HANDLING AND STORAGE

Advice on protection against fire and explosion:
None known.

Advice on safe handling:
Do not get in eyes. Avoid contact with skin, eyes and clothing. Do not swallow. Wash thoroughly after handling. Keep away from fire (No Smoking). Keep away from fire, sparks and heated surfaces. Do not use sparking tools.

Conditions for safe storage:
Keep container closed when not in use. Store locked up.

SECTION 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

Ingredients with workplace control parameters

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>CAS-No.</th>
<th>Value type (Form of exposure)</th>
<th>Control parameters / Permissible concentration</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetaldehyde</td>
<td>75-07-0</td>
<td>C</td>
<td>25 ppm</td>
<td>ACGIH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA</td>
<td>200 ppm</td>
<td>OSHA Z-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>360 mg/m3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA</td>
<td>100 ppm</td>
<td>OSHA P0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>180 mg/m3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>STEL</td>
<td>150 ppm</td>
<td>OSHA P0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>270 mg/m3</td>
<td></td>
</tr>
</tbody>
</table>

Engineering measures:
Ensure adequate ventilation.

Personal protective equipment

Respiratory protection:
Use respiratory protection unless adequate local exhaust ventilation is provided or exposure assessment demonstrates that exposures are within recommended exposure guidelines.

Hand protection
Remarks:
- Wear suitable gloves.

Eye protection:
- Wear safety glasses with side shields (or goggles).
- Face-shield
- Always wear eye protection when the potential for inadvertent eye contact with the product cannot be excluded.

Protective measures:
- Remove respiratory and skin/eye protection only after vapors have been cleared from the area.
- Ensure that eye flushing systems and safety showers are located close to the working place.
- Use personal protective equipment as required.

Hygiene measures:
- Handle in accordance with good industrial hygiene and safety practice.

SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

Appearance: liquid
Color: colorless
Odor: pungent
Odor Threshold: 0.05 ppm
pH: not determined
Melting point/range: -189 °F / -123 °C
Boiling point/boiling range: 70 °F / 21 °C
Flash point: -38 °F / -39 °C
   Method: Tag closed cup
Evaporation rate: not determined
Vapor pressure: 532 mbar (41 °F / 5 °C)
Relative vapor density: 1.5
Relative density: 0.788 (68 °F / 20 °C)
Solubility(ies):
   Water solubility: completely soluble
Partition coefficient: n-octanol/water:
   Pow: 2.7
   log Pow: 0.43
Autoignition temperature: 300 °F / 149 °C
   Method: ASTM D2155
Decomposition temperature: Thermal stability not tested. Low stability hazard expected at normal operating temperatures.

Viscosity:
- Viscosity, dynamic: not determined
- Viscosity, kinematic: not determined

Explosive properties: No data available

Oxidizing properties: No data available

SECTION 10. STABILITY AND REACTIVITY

Reactivity: Stable

Chemical stability: Stable under normal conditions.

Possibility of hazardous reactions: Stable

Conditions to avoid: Heat, flames and sparks.

Incompatible materials: Strong oxidizing agents

Hazardous decomposition products: Carbon dioxide (CO2), Carbon monoxide

SECTION 11. TOXICOLOGICAL INFORMATION

Acute toxicity
Harmful if swallowed.

Product:
- Acute oral toxicity: Remarks: No data available
- Acute inhalation toxicity: Remarks: No data available
- Acute dermal toxicity: Remarks: No data available

Ingredients:
- acetaldehyde:
  - Acute oral toxicity: LD50 Oral (Rat): 1,930 mg/kg
    LD50 Oral (Rat): 661 mg/kg
  - Acute inhalation toxicity: LC50 (Rat): 13300 ppm
    Exposure time: 4 h
  - Acute dermal toxicity: LD50 Dermal (Rabbit): 3,540 mg/kg
Skin corrosion/irritation
Not classified based on available information.

**Product:**

**Remarks:**
No data available

**Ingredients:**

**Acetaldehyde:**

<table>
<thead>
<tr>
<th>Species</th>
<th>Rabbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure time</td>
<td>24 h</td>
</tr>
<tr>
<td>Result</td>
<td>slight</td>
</tr>
</tbody>
</table>

Serious eye damage/eye irritation
Causes serious eye irritation.

**Product:**

**Remarks:**
No data available

**Ingredients:**

**Acetaldehyde:**

<table>
<thead>
<tr>
<th>Species</th>
<th>Rabbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Respiratory or skin sensitization

Skin sensitization
Not classified based on available information.

Respiratory sensitization
Not classified based on available information.

**Product:**

**Remarks:**
No data available

**Ingredients:**

**Acetaldehyde:**

<table>
<thead>
<tr>
<th>Species</th>
<th>Guinea pig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td>negative</td>
</tr>
</tbody>
</table>

Germ cell mutagenicity
Not classified based on available information.

Carcinogenicity
Suspected of causing cancer.

IARC
Group 2B: Possibly carcinogenic to humans

**Acetaldehyde**

75-07-0
OSHA
No component of this product present at levels greater than or equal to 0.1% is on OSHA’s list of regulated carcinogens.

NTP
Reasonably anticipated to be a human carcinogen acetaldehyde 75-07-0

Reproductive toxicity
Not classified based on available information.

Product:
Effects on fertility : Remarks: No data available

STOT-single exposure
May cause respiratory irritation.

Product:
Remarks : No data available

STOT-repeated exposure
Not classified based on available information.

Product:
Remarks : No data available

Aspiration toxicity
Not classified based on available information.

Product:
No data available

No aspiration toxicity classification

Information on likely routes of exposure

Product:
Inhalation : Remarks: Iritating to respiratory system.
Skin contact : Remarks: None known.
Eye contact : Remarks: Causes serious eye irritation.
Ingestion : Remarks: Harmful if swallowed.

Further information

Product:
Remarks : None known.
SAFETY DATA SHEET

Eastman(TM) Acetaldehyde

SECTION 12. ECOLOGICAL INFORMATION

Ecotoxicity

Ingredients:

acetaldehyde:
Toxicity to fish: LC50 (Lepomis macrochirus (Bluegill sunfish)): 53 mg/l
Exposure time: 96 h
LC50 (golden orfe): 124 - 140 mg/l
Exposure time: 48 h

Toxicity to daphnia and other aquatic invertebrates: EC50 (daphnid): 57.4 mg/l
Exposure time: 48 h

Toxicity to algae: EC50 (Pseudokirchneriella subcapitata (algae)): > 100 mg/l
Exposure time: 72 h

Persistence and degradability

Ingredients:

acetaldehyde:
Biochemical Oxygen Demand (BOD): 127 - 130 mg/g
Incubation time: 5 d

Bioaccumulative potential
No data available

Mobility in soil
No data available

Other adverse effects
No data available

SECTION 13. DISPOSAL CONSIDERATIONS

Disposal methods
Waste from residues: Dispose of in accordance with local regulations.

SECTION 14. TRANSPORT INFORMATION

International Regulations

IATA-DGR
Not permitted for transport

IMDG-Code
UN number: UN 1089
Proper shipping name: ACETALDEHYDE
Transport in bulk according to Annex II of MARPOL 73/78 and the IBC Code
Not applicable for product as supplied.

Domestic regulation

49 CFR
UN/ID/NA number : UN 1089
Proper shipping name : Acetaldehyde

Class : 3
Packing group : I
Labels : Class 3 - Flammable Liquid
ERG Code : 129
Marine pollutant : no

Special precautions for user
The transport classification(s) provided herein are for informational purposes only, and solely based upon the properties of the unpackaged material as it is described within this Safety Data Sheet. Transportation classifications may vary by mode of transportation, package sizes, and variations in regional or country regulations.

SECTION 15. REGULATORY INFORMATION

EPCRA - Emergency Planning and Community Right-to-Know

CERCLA Reportable Quantity

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>CAS-No.</th>
<th>Component RQ (lbs)</th>
<th>Calculated product RQ (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acetaldehyde</td>
<td>75-07-0</td>
<td>1000</td>
<td>1000</td>
</tr>
</tbody>
</table>

SARA 304 Extremely Hazardous Substances Reportable Quantity
This material does not contain any components with a section 304 EHS RQ.

SARA 302 Extremely Hazardous Substances Threshold Planning Quantity
This material does not contain any components with a section 302 EHS TPQ.

SARA 311/312 Hazards : Flammable (gases, aerosols, liquids, or solids)
Acute toxicity (any route of exposure)
Serious eye damage or eye irritation
Specific target organ toxicity (single or repeated exposure)
Carcinogenicity

SARA 313 : The following components are subject to reporting levels established by SARA Title III, Section 313:
acetaldehyde 75-07-0
California Prop. 65

WARNING: This product can expose you to chemicals including acetaldehyde, which is/are known to the State of California to cause cancer. For more information go to www.P65Warnings.ca.gov.

The ingredients of this product are reported in the following inventories:

- **TSCA**: On TSCA Inventory
- **DSL**: All components of this product are on the Canadian DSL
- **AICS**: On the inventory, or in compliance with the inventory
- **ENCS**: On the inventory, or in compliance with the inventory
- **ISHL**: On the inventory, or in compliance with the inventory
- **KECI**: On the inventory, or in compliance with the inventory
- **PICCS**: On the inventory, or in compliance with the inventory
- **IECSC**: On the inventory, or in compliance with the inventory

**TSCA list**

No substances are subject to a Significant New Use Rule.

The following substance(s) is/are subject to TSCA 12(b) export notification requirements: acetaldehyde 75-07-0

---

**SECTION 16. OTHER INFORMATION**

**Further information**

<table>
<thead>
<tr>
<th>NFPA 704</th>
<th>HMIS® IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability</td>
<td>HEALTH</td>
</tr>
<tr>
<td>Health</td>
<td>*</td>
</tr>
<tr>
<td>Special hazard</td>
<td></td>
</tr>
</tbody>
</table>

HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks. The "*" represents a chronic hazard, while the "/" represents the absence of a chronic hazard.

**Full text of other abbreviations**

- **ACGIH**: USA. ACGIH Threshold Limit Values (TLV)
SAFETY DATA SHEET

Eastman(TM) Acetaldehyde

SAFETY DATA SHEET

Eastman(TM) Acetaldehyde

Version 2.2
Revision Date: 02/20/2019
SDS Number: 150000000122
Date of last issue: 11/26/2018
Date of first issue: 09/06/2016

OSHA P0: USA. OSHA - TABLE Z-1 Limits for Air Contaminants - 1910.1000
OSHA Z-1: USA. Occupational Exposure Limits (OSHA) - Table Z-1 Limits for Air Contaminants
ACGIH / C: Ceiling limit
OSHA P0 / TWA: 8-hour time weighted average
OSHA P0 / STEL: Short-term exposure limit
OSHA Z-1 / TWA: 8-hour time weighted average

AICS - Australian Inventory of Chemical Substances; ASTM - American Society for the Testing of Materials; bw - Body weight; CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act; CMR - Carcinogenic, Mutagen or Reproductive Toxicant; DIN - Standard of the German Institute for Standardisation; DOT - Department of Transportation; DSL - Domestic Substances List (Canada); ECx - Concentration associated with x% response; EHS - Extremely Hazardous Substance; ELx - Loading rate associated with x% response; EmS - Emergency Schedule; ENCS - Existing and New Chemical Substances (Japan); ERx - Concentration associated with x% growth rate response; ERG - Emergency Response Guide; GHS - Globally Harmonized System; GLP - Good Laboratory Practice; HMIS - Hazardous Materials Identification System; IARC - International Agency for Research on Cancer; IATA - International Air Transport Association; IBC - International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk; IC50 - Half maximal inhibitory concentration; ICAO - International Civil Aviation Organization; IECSC - Inventory of Existing Chemical Substances in China; IMDG - International Maritime Dangerous Goods; IMO - International Maritime Organization; ISHL - Industrial Safety and Health Law (Japan); ISO - International Organisation for Standardization; KECI - Korea Existing Chemicals Inventory; LC50 - Lethal Concentration to 50 % of a test population; LC50 - Lethal Dose to 50% of a test population (Median Lethal Dose); MARPOL - International Convention for the Prevention of Pollution from Ships; MSHA - Mine Safety and Health Administration; n.o.s. - Not Otherwise Specified; NFPA - National Fire Protection Association; NO(A)EL - No Observed (Adverse) Effect Concentration; NO(A)EC - No Observed (Adverse) Effect Level; NOELR - No Observable Effect Loading Rate; NTP - National Toxicology Program; NZIoC - New Zealand Inventory of Chemicals; OECD - Organization for Economic Co-operation and Development; OPPTS - Office of Chemical Safety and Pollution Prevention; PBT - Persistent, Bioaccumulative and Toxic substance; PICCS - Philippines Inventory of Chemicals and Chemical Substances; (Q)SAR - (Quantitative) Structure Activity Relationship; RCRA - Resource Conservation and Recovery Act; REACH - Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals; RQ - Reportable Quantity; SADT - Self-Accelerating Decomposition Temperature; SARA - Superfund Amendments and Reauthorization Act; SDS - Safety Data Sheet; TCSI - Taiwan Chemical Substance Inventory; TSCA - Toxic Substances Control Act (United States); UN - United Nations; UNRTDG - United Nations Recommendations on the Transport of Dangerous Goods; vPvB - Very Persistent and Very Bioaccumulative

Revision Date: 02/20/2019

The information provided in this Material Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

US / Z8
SAFETY DATA SHEET

Creation Date 13-Apr-2009 Revision Date 17-Jan-2018 Revision Number 6

1. Identification

Product Name Methyl Ethyl Ketone
CAS-No 78-93-3
Synonyms 2-Butanone; MEK; Ethyl methyl ketone
Recommended Use Laboratory chemicals.
Uses advised against Not for food, drug, pesticide or biocidal product use

Details of the supplier of the safety data sheet

Company Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

Classification This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammable liquids</td>
<td>Category 2</td>
</tr>
<tr>
<td>Serious Eye Damage/Eye Irritation</td>
<td>Category 2</td>
</tr>
<tr>
<td>Specific target organ toxicity (single exposure)</td>
<td>Category 3</td>
</tr>
<tr>
<td>Target Organs - Central nervous system (CNS).</td>
<td></td>
</tr>
<tr>
<td>Specific target organ toxicity - (repeated exposure)</td>
<td>Category 2</td>
</tr>
<tr>
<td>Target Organs - Kidney, Liver.</td>
<td></td>
</tr>
</tbody>
</table>

Label Elements

Signal Word Danger

Hazard Statements
Highly flammable liquid and vapor
Causes serious eye irritation
May cause drowsiness or dizziness
May cause damage to organs through prolonged or repeated exposure
Precautionary Statements

Prevention
Wash face, hands and any exposed skin thoroughly after handling
Do not breathe dust/fume/gas/mist/vapors/spray
Use only outdoors or in a well-ventilated area
Keep away from heat/sparks/open flames/hot surfaces. - No smoking
Keep container tightly closed
Ground/bond container and receiving equipment
Use explosion-proof electrical/ventilating/lighting/equipment
Use only non-sparking tools
Take precautionary measures against static discharge
Wear protective gloves/protective clothing/eye protection/face protection
Keep cool

Response
Get medical attention/advice if you feel unwell

Inhalation
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
Call a POISON CENTER or doctor/physician if you feel unwell

Skin
IF ON SKIN (or hair): Take off immediately all contaminated clothing. Rinse skin with water/shower

Eyes
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
If eye irritation persists: Get medical advice/attention

Fire
In case of fire: Use CO2, dry chemical, or foam for extinction

Storage
Store in a well-ventilated place. Keep container tightly closed
Store locked up

Disposal
Dispose of contents/container to an approved waste disposal plant

Hazards not otherwise classified (HNOC)
Repeated exposure may cause skin dryness or cracking

### 3. Composition/Information on Ingredients

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>78-93-3</td>
<td>&gt;95</td>
</tr>
</tbody>
</table>

### 4. First-aid measures

**Eye Contact**
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.

**Skin Contact**
Wash off immediately with plenty of water for at least 15 minutes. Get medical attention if symptoms occur.

**Inhalation**
Move to fresh air. Get medical attention if symptoms occur. If not breathing, give artificial respiration.
Ingestion
Do not induce vomiting. Obtain medical attention.

Most important symptoms and effects
Breathing difficulties. Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting: Inhalation of high vapor concentrations may cause symptoms like headache, dizziness, tiredness, nausea and vomiting

Notes to Physician
Treat symptomatically

5. Fire-fighting measures

Suitable Extinguishing Media
CO₂, dry chemical, dry sand, alcohol-resistant foam. Cool closed containers exposed to fire with water spray.

Unsuitable Extinguishing Media
Water may be ineffective

Flash Point
-7 °C / 19.4 °F

Method -
Closed cup

Autoignition Temperature
404 °C / 759.2 °F

Explosion Limits
Upper
11.4 vol %

Lower
1.4 vol %

Oxidizing Properties
Not oxidising

Sensitivity to Mechanical Impact
No information available

Sensitivity to Static Discharge
No information available

Specific Hazards Arising from the Chemical
Flammable. Risk of ignition. Vapors may form explosive mixtures with air. Vapors may travel to source of ignition and flash back. Containers may explode when heated. Thermal decomposition can lead to release of irritating gases and vapors. Keep product and empty container away from heat and sources of ignition.

Hazardous Combustion Products
Carbon monoxide (CO) Carbon dioxide (CO₂)

Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPA

<table>
<thead>
<tr>
<th>Health</th>
<th>Flammability</th>
<th>Instability</th>
<th>Physical hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

6. Accidental release measures

Personal Precautions
Use personal protective equipment. Remove all sources of ignition. Take precautionary measures against static discharges. Avoid contact with skin, eyes and clothing. Ensure adequate ventilation.

Environmental Precautions
Avoid release to the environment. See Section 12 for additional ecological information.

Methods for Containment and Clean Up
Remove all sources of ignition. Soak up with inert absorbent material. Keep in suitable, closed containers for disposal. Use spark-proof tools and explosion-proof equipment.

7. Handling and storage

Handling
Wear personal protective equipment. Ensure adequate ventilation. Use spark-proof tools and explosion-proof equipment. Avoid contact with skin, eyes and clothing. Avoid ingestion and inhalation. Keep away from open flames, hot surfaces and sources of ignition. Take precautionary measures against static discharges. Use only non-sparking tools. To avoid ignition of vapors by static electricity discharge, all metal parts of the equipment must be grounded.
Storage
Keep containers tightly closed in a dry, cool and well-ventilated place. Keep away from heat and sources of ignition. Flammables.

8. Exposure controls / personal protection

Exposure Guidelines

<table>
<thead>
<tr>
<th>Component</th>
<th>ACGIH TLV</th>
<th>OSHA PEL</th>
<th>NIOSH IDLH</th>
<th>Mexico OEL (TWA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>TWA: 200 ppm</td>
<td>(Vacated) TWA: 200 ppm</td>
<td>IDLH: 3000 ppm</td>
<td>TWA: 200 ppm</td>
</tr>
<tr>
<td></td>
<td>STEL: 300 ppm</td>
<td>(Vacated) STEL: 590 mg/m³</td>
<td>TWA: 200 ppm</td>
<td>TWA: 590 mg/m³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Vacated) STEL: 300 ppm</td>
<td>TWA: 590 mg/m³</td>
<td>STEL: 300 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 200 ppm</td>
<td>STEL: 885 mg/m³</td>
<td>STEL: 300 ppm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TWA: 885 mg/m³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend

ACGIH - American Conference of Governmental Industrial Hygienists
OSHA - Occupational Safety and Health Administration
NIOSH IDLH: The National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health

Engineering Measures
Ensure adequate ventilation, especially in confined areas. Use explosion-proof electrical/ventilating/lighting/equipment. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection
Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.

Skin and body protection
Wear appropriate protective gloves and clothing to prevent skin exposure.

Respiratory Protection
Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.

Hygiene Measures
Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical State</td>
<td>Liquid</td>
</tr>
<tr>
<td>Appearance</td>
<td>Colorless</td>
</tr>
<tr>
<td>Odor</td>
<td>Characteristic - sweet</td>
</tr>
<tr>
<td>Odor Threshold</td>
<td>No information available</td>
</tr>
<tr>
<td>pH</td>
<td>No information available</td>
</tr>
<tr>
<td>Melting Point/Range</td>
<td>-87 °C / -124.6 °F</td>
</tr>
<tr>
<td>Boiling Point/Range</td>
<td>80 °C / 176 °F</td>
</tr>
<tr>
<td>Flash Point</td>
<td>-7 °C / 19.4 °F</td>
</tr>
<tr>
<td>Method -</td>
<td>Closed cup</td>
</tr>
<tr>
<td>Evaporation Rate</td>
<td>3.7</td>
</tr>
<tr>
<td>Flammability (solid,gas)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Flammability or explosive limits</td>
<td>11.4 vol %</td>
</tr>
<tr>
<td>Upper</td>
<td>1.4 vol %</td>
</tr>
<tr>
<td>Vapor Pressure</td>
<td>105 mbar @ 20 °C</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>2.41</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.806</td>
</tr>
<tr>
<td>Solubility</td>
<td>Soluble in water</td>
</tr>
<tr>
<td>Partition coefficient; n-octanol/water</td>
<td>No data available</td>
</tr>
</tbody>
</table>
10. Stability and reactivity

Reactive Hazard None known, based on information available
Stability Hygroscopic.
Conditions to Avoid Incompatible products. Excess heat. Keep away from open flames, hot surfaces and sources of ignition. Exposure to moist air or water.
Incompatible Materials Strong oxidizing agents, Strong acids, Strong bases, Strong reducing agents, Ammonia, copper, Amines
Hazardous Decomposition Products Carbon monoxide (CO), Carbon dioxide (CO₂)
Hazardous Polymerization Hazardous polymerization does not occur.
Hazardous Reactions None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information

<table>
<thead>
<tr>
<th>Component</th>
<th>LD₅₀ Oral</th>
<th>LD₅₀ Dermal</th>
<th>LC₅₀ Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>LD₅₀ = 2483 mg/kg ( Rat )</td>
<td>LD₅₀ = 5000 mg/kg ( Rabbit )</td>
<td>LC₅₀ = 11700 ppm ( Rat ) 4 h</td>
</tr>
<tr>
<td></td>
<td>LD₅₀ = 2737 mg/kg ( Rat )</td>
<td>LD₅₀ = 6480 mg/kg ( Rabbit )</td>
<td></td>
</tr>
</tbody>
</table>

Toxicologically Synergistic Products

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation Irritating to eyes
Sensitization No information available
Carcinogenicity The table below indicates whether each agency has listed any ingredient as a carcinogen.

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>IARC</th>
<th>NTP</th>
<th>ACGIH</th>
<th>OSHA</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>78-93-3</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

Mutagenic Effects Not mutagenic in AMES Test
Reproductive Effects No information available.
Developmental Effects No information available.
Teratogenicity No information available.
STOT - single exposure Central nervous system (CNS)
STOT - repeated exposure Kidney Liver
Aspiration hazard No information available

Symptoms / effects, both acute and delayed Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting; Inhalation of high vapor concentrations may cause symptoms like headache, dizziness,
tiredness, nausea and vomiting

Endocrine Disruptor Information  No information available

Other Adverse Effects  The toxicological properties have not been fully investigated.

## 12. Ecological information

### Ecotoxicity

<table>
<thead>
<tr>
<th>Component</th>
<th>Freshwater Algae</th>
<th>Freshwater Fish</th>
<th>Microtox</th>
<th>Water Flea</th>
</tr>
</thead>
</table>
| Methyl ethyl ketone| Not listed       | Lepomis macrochirus: LC50=3.22 g/L 96 h | EC50 = 3403 mg/L 30 min  
EC50 = 3426 mg/L 5 min | EC50: 4625 - 6440 mg/L, 48h Static (Daphnia magna)  
EC50: > 520 mg/L, 48h (Daphnia magna) |

### Persistence and Degradability

Persistence is unlikely based on information available.

### Bioaccumulation/ Accumulation

No information available.

### Mobility

Will likely be mobile in the environment due to its volatility.

<table>
<thead>
<tr>
<th>Component</th>
<th>log Pow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>0.29</td>
</tr>
</tbody>
</table>

## 13. Disposal considerations

### Waste Disposal Methods

Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

### DOT

<table>
<thead>
<tr>
<th>Component</th>
<th>RCRA - U Series Wastes</th>
<th>RCRA - P Series Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>U159</td>
<td>-</td>
</tr>
</tbody>
</table>

## 14. Transport information

### IMDG/IMO

<table>
<thead>
<tr>
<th>Component</th>
<th>UN-No</th>
<th>Proper Shipping Name</th>
<th>Hazard Class</th>
<th>Packing Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>UN1193</td>
<td>Ethyl methyl ketone</td>
<td>3</td>
<td>II</td>
</tr>
</tbody>
</table>

## 15. Regulatory information

All of the components in the product are on the following Inventory lists:  X = listed
International Inventories

<table>
<thead>
<tr>
<th>Component</th>
<th>TSCA</th>
<th>DSL</th>
<th>NDSL</th>
<th>EINECS</th>
<th>ELINCS</th>
<th>NLP</th>
<th>PICCS</th>
<th>ENCS</th>
<th>AICS</th>
<th>IECSC</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>201-159-0</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Legend:

- X - Listed
- E - Indicates a substance that is the subject of a Section 5(e) Consent order under TSCA.
- F - Indicates a substance that is the subject of a Section 5(f) Rule under TSCA.
- N - Indicates a polymeric substance containing no free-radical initiator in its inventory name but is considered to cover the designated polymer made with any free-radical initiator regardless of the amount used.
- P - Indicates a commenced PMN substance
- R - Indicates a substance that is the subject of a Section 6 risk management rule under TSCA.
- S - Indicates a substance that is identified in a proposed or final Significant New Use Rule
- T - Indicates a substance that is the subject of a Section 4 test rule under TSCA.
- XU - Indicates a substance exempt from reporting under the Inventory Update Rule, i.e. Partial Updating of the TSCA Inventory Data Base Production and Site Reports (40 CFR 710(B)).
- Y1 - Indicates an exempt polymer that has a number-average molecular weight of 1,000 or greater.
- Y2 - Indicates an exempt polymer that is a polyester and is made only from reactants included in a specified list of low concern reactants that comprises one of the eligibility criteria for the exemption rule.

U.S. Federal Regulations

- TSCA 12(b) Not applicable
- SARA 313 Not applicable
- SARA 311/312 Hazard Categories See section 2 for more information
- CWA (Clean Water Act) Not applicable
- Clean Air Act Not applicable
- OSHA Occupational Safety and Health Administration Not applicable

CERCLA

This material, as supplied, contains one or more substances regulated as a hazardous substance under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302)

<table>
<thead>
<tr>
<th>Component</th>
<th>Hazardous Substances RQs</th>
<th>CERCLA EHS RQs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>5000 lb</td>
<td>-</td>
</tr>
</tbody>
</table>

California Proposition 65

This product does not contain any Proposition 65 chemicals

U.S. State Right-to-Know Regulations

<table>
<thead>
<tr>
<th>Component</th>
<th>Massachusetts</th>
<th>New Jersey</th>
<th>Pennsylvania</th>
<th>Illinois</th>
<th>Rhode Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl ethyl ketone</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

U.S. Department of Transportation

- Reportable Quantity (RQ): Y
- DOT Marine Pollutant: N
- DOT Severe Marine Pollutant: N

U.S. Department of Homeland Security

This product does not contain any DHS chemicals.

Other International Regulations

- Mexico - Grade: Serious risk, Grade 3
16. Other information

Prepared By          Regulatory Affairs
                     Thermo Fisher Scientific
                     Email: EMSDS.RA@thermofisher.com

Creation Date       13-Apr-2009
Revision Date       17-Jan-2018
Print Date          17-Jan-2018
Revision Summary    This document has been updated to comply with the US OSHA HazCom 2012 Standard
                     replacing the current legislation under 29 CFR 1910.1200 to align with the Globally
                     Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer
The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the
date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage,
transportation, disposal and release and is not to be considered a warranty or quality specification. The information
relates only to the specific material designated and may not be valid for such material used in combination with any other
materials or in any process, unless specified in the text.

End of SDS
## n-Butyraldehyde
CAS No 123-72-8

<table>
<thead>
<tr>
<th>MATERIAL SAFETY DATA SHEET</th>
<th>SDS/MSDS</th>
</tr>
</thead>
</table>

### SECTION 1: Identification of the substance/mixture and of the company/undertaking

#### 1.1 Product identifiers
- **Product name**: n-Butyraldehyde
- **CAS-No.**: 123-72-8

#### 1.2 Relevant identified uses of the substance or mixture and uses advised against
- **Identified uses**: Laboratory chemicals, Industrial & for professional use only.

#### 1.3 Details of the supplier of the safety data sheet
- **Company**: Central Drug House (P) Ltd
  7/28 Vardaan House
  New Delhi-10002
  INDIA
- **Telephone**: +91 11 49404040
- **Email**: care@cdhfinechemical.com

#### 1.4 Emergency telephone number
- **Emergency Phone #**: +91 11 49404040 (9:00am - 6:00 pm) [Office hours]

### SECTION 2: Hazards identification

#### 2.1 Classification of the substance or mixture
- **Classification according to Regulation (EC) No 1272/2008**
  - Flammable liquids (Category 2), H225
  - Eye irritation (Category 2), H319

  For the full text of the H-Statements mentioned in this Section, see Section 16.

#### 2.2 Label elements
- **Labelling according Regulation (EC) No 1272/2008**
- **Pictogram**

  ![Flammable + Eye Irritation Pictogram](image)

  - **Signal word**: Danger
  - **Hazard statement(s)**:
    - H225: Highly flammable liquid and vapour.
    - H319: Causes serious eye irritation.
  - **Precautionary statement(s)**:
    - P210: Keep away from heat/sparks/open flames/hot surfaces. No smoking.
P305 + P351 + P338
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing.

Supplemental Hazard Statements

2.3 Other hazards
This substance/mixture contains no components considered to be either persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher.

SECTION 3: Composition/information on ingredients

3.1 Substances

Synonyms: Butanal
Formula: C₄H₈O
Molecular weight: 72.11 g/mol
CAS-No.: 123-72-8
EC-No.: 204-646-6
Index-No.: 605-006-00-2

Hazardous ingredients according to Regulation (EC) No 1272/2008

<table>
<thead>
<tr>
<th>Component</th>
<th>Classification</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butyraldehyde</td>
<td>Flam. Liq. 2; Eye Irrit. 2; H225, H319</td>
<td>&lt;= 100 %</td>
</tr>
<tr>
<td>CAS-No.</td>
<td>123-72-8</td>
<td></td>
</tr>
<tr>
<td>EC-No.</td>
<td>204-646-6</td>
<td></td>
</tr>
<tr>
<td>Index-No.</td>
<td>605-006-00-2</td>
<td></td>
</tr>
</tbody>
</table>

For the full text of the H-Statements mentioned in this Section, see Section 16.

SECTION 4: First aid measures

4.1 Description of first aid measures

General advice
Consult a physician. Show this safety data sheet to the doctor in attendance.

If inhaled
If breathed in, move person into fresh air. If not breathing, give artificial respiration. Consult a physician.

In case of skin contact
Wash off with soap and plenty of water. Consult a physician.

In case of eye contact
Rinse thoroughly with plenty of water for at least 15 minutes and consult a physician.

If swallowed
Do NOT induce vomiting. Never give anything by mouth to an unconscious person. Rinse mouth with water. Consult a physician.

4.2 Most important symptoms and effects, both acute and delayed
The most important known symptoms and effects are described in the labelling (see section 2.2) and/or in section 11

4.3 Indication of any immediate medical attention and special treatment needed
No data available

SECTION 5: Firefighting measures

5.1 Extinguishing media

Suitable extinguishing media
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.
5.2 Special hazards arising from the substance or mixture
Carbon oxides

5.3 Advice for firefighters
Wear self-contained breathing apparatus for firefighting if necessary.

5.4 Further information
Use water spray to cool unopened containers.

SECTION 6: Accidental release measures

6.1 Personal precautions, protective equipment and emergency procedures
Use personal protective equipment. Avoid breathing vapours, mist or gas. Ensure adequate ventilation. Remove all sources of ignition. Evacuate personnel to safe areas. Beware of vapours accumulating to form explosive concentrations. Vapours can accumulate in low areas. For personal protection see section 8.

6.2 Environmental precautions
Prevent further leakage or spillage if safe to do so. Do not let product enter drains. Discharge into the environment must be avoided.

6.3 Methods and materials for containment and cleaning up
Contain spillage, and then collect with an electrically protected vacuum cleaner or by wet-brushing and place in container for disposal according to local regulations (see section 13).

6.4 Reference to other sections
For disposal see section 13.

SECTION 7: Handling and storage

7.1 Precautions for safe handling
Avoid contact with skin and eyes. Avoid inhalation of vapour or mist. Keep away from sources of ignition - No smoking. Take measures to prevent the build up of electrostatic charge. For precautions see section 2.2.

7.2 Conditions for safe storage, including any incompatibilities
Store in cool place. Keep container tightly closed in a dry and well-ventilated place. Containers which are opened must be carefully resealed and kept upright to prevent leakage.
Stench. Dry residue is explosive.
Storage class (TRGS 510): Flammable Liquids

7.3 Specific end use(s)
Apart from the uses mentioned in section 1.2 no other specific uses are stipulated

SECTION 8: Exposure controls/personal protection

8.1 Control parameters

8.2 Exposure controls
Appropriate engineering controls
Handle in accordance with good industrial hygiene and safety practice. Wash hands before breaks and at the end of workday.

Personal protective equipment
Eye/face protection
Face shield and safety glasses Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU).

Skin protection
Handle with gloves. Gloves must be inspected prior to use. Use proper glove removal technique (without touching glove’s outer surface) to avoid skin contact with this product. Dispose of contaminated gloves after use in accordance with applicable laws and good laboratory practices. Wash and dry hands.
Body Protection
Impervious clothing, Flame retardant antistatic protective clothing. The type of protective equipment must be selected according to the concentration and amount of the dangerous substance at the specific workplace.

Respiratory protection
Where risk assessment shows air-purifying respirators are appropriate use (US) or type ABEK (EN 14387) respirator cartridges as a backup to enginee protection, use a full-face supplied air respirator. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

Control of environmental exposure
Prevent further leakage or spillage if safe to do so. Do not let product enter drains. Discharge into the environment must be avoided.

SECTION 9: Physical and chemical properties

9.1 Information on basic physical and chemical properties

a) Appearance Form: clear, liquid
   Colour: colourless
b) Odour pungent
c) Odour Threshold No data available
d) pH 6.0 - 7.0 at 71 g/l at 20 °C
e) Melting point/freezing point Melting point/range: -96 °C - lit.
f) Initial boiling point and boiling range 75 °C - lit.
g) Flash point -5 °C - closed cup
h) Evaporation rate No data available
i) Flammability (solid, gas) No data available
j) Upper/lower flammability or explosive limits Upper explosion limit: 8 % (V)
   Lower explosion limit: 1.8 % (V)
k) Vapour pressure 90 mmHg at 20 °C
l) Vapour density 2.49 - (Air = 1.0)
m) Relative density 0.8 g/cm3 at 25 °C
n) Water solubility 50 g/l at 20 °C - OECD Test Guideline 105 - soluble
o) Partition coefficient: n-octanol/water log Pow: 0.79
p) Auto-ignition temperature 190 °C at 1013.0 hPa
q) Decomposition temperature No data available
r) Viscosity No data available
s) Explosive properties No data available
t) Oxidizing properties No data available

9.2 Other safety information
Surface tension 70 mN/m at 20 °C
Relative vapour density 2.49 - (Air = 1.0)
SECTION 10: Stability and reactivity

10.1 Reactivity
No data available

10.2 Chemical stability
Stable under recommended storage conditions.

10.3 Possibility of hazardous reactions
No data available

10.4 Conditions to avoid
Heat, flames and sparks. Extremes of temperature and direct sunlight.

10.5 Incompatible materials
Oxidizing agents, Strong bases, Strong reducing agents, Strong acids

10.6 Hazardous decomposition products
Hazardous decomposition products formed under fire conditions. - Carbon oxides
Other decomposition products - No data available
In the event of fire: see section 5

SECTION 11: Toxicological information

11.1 Information on toxicological effects

Acute toxicity
LD50 Oral - Rat - male and female - 5,890 mg/kg(Butyraldehyde)  
(OECD Test Guideline 401)
LC50 Inhalation - Rat - male and female - 4 h - > 5.46 mg/l(Butyraldehyde)  
(OECD Test Guideline 403)
LD50 Dermal - Rabbit - 3,560 mg/kg(Butyraldehyde)

Skin corrosion/irritation
Skin - Rabbit(Butyraldehyde)
Result: No skin irritation - 4 h  
(OECD Test Guideline 404)

Serious eye damage/eye irritation
Eyes - Rabbit(Butyraldehyde)
Result: Irritating to eyes. - 24 h  
(Directive 67/548/EEC, Annex V, B.5.)

Respiratory or skin sensitisation
Buehler Test - Guinea pig(Butyraldehyde)
Result: Does not cause skin sensitisation.  
(OECD Test Guideline 406)

Germ cell mutagenicity
No data available(Butyraldehyde)
Ames test(Butyraldehyde)
S. typhimurium
Result: negative  
(Butyraldehyde)
Drosophila melanogaster - male
Result: negative

Carcinogenicity
IARC: No component of this product present at levels greater than or equal to 0.1% is identified as probable, possible or confirmed human carcinogen by IARC.

Reproductive toxicity
No data available(Butyraldehyde)
Specific target organ toxicity - single exposure
No data available (Butyraldehyde)

Specific target organ toxicity - repeated exposure
No data available

Aspiration hazard
No data available (Butyraldehyde)

Additional Information
RTECS: ES2275000

To the best of our knowledge, the chemical, physical, and toxicological properties have not been thoroughly investigated (Butyraldehyde)

SECTION 12: Ecological information

12.1 Toxicity
Toxicity to fish
static test LC50 - Pimephales promelas (fathead minnow) - 25.8 mg/l - 96 h (Butyraldehyde)

Toxicity to daphnia and other aquatic invertebrates
static test EC50 - Daphnia magna (Water flea) - 195 mg/l - 24 h (Butyraldehyde)

Toxicity to bacteria
EC50 - Photobacterium phosphoreum - 99.1 mg/l - 25 min (Butyraldehyde)

12.2 Persistence and degradability
Biodegradability
aerobic - Exposure time 5 d (Butyraldehyde)
Result: 46 - 57% - Readily biodegradable (OECD Test Guideline 301C)

Ratio BOD/ThBOD 28 - 43% (Butyraldehyde)

12.3 Bioaccumulative potential
No bioaccumulation is to be expected (log Pow <= 4).

12.4 Mobility in soil
No data available (Butyraldehyde)

12.5 Results of PBT and vPvB assessment
This substance/mixture contains no components considered to be either persistent, bioaccumulative and toxic (PBT), or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher.

12.6 Other adverse effects
Harmful to aquatic life.

SECTION 13: Disposal considerations

13.1 Waste treatment methods
Product
Burn in a chemical incinerator equipped with an afterburner and scrubber b highly flammable. Offer surplus and non-recyclable solutions to a licensed disposal company.

Contaminated packaging
Dispose of as unused product.
SECTION 14: Transport information

14.1 UN number
ADR/RID: 1129  
IMDG: 1129  
IATA: 1129

14.2 UN proper shipping name
ADR/RID: BUTYRALDEHYDE  
IMDG: BUTYRALDEHYDE  
IATA: Butyraldehyde

14.3 Transport hazard class(es)
ADR/RID: 3  
IMDG: 3  
IATA: 3

14.4 Packaging group
ADR/RID: II  
IMDG: II  
IATA: II

14.5 Environmental hazards
ADR/RID: no  
IMDG Marine pollutant: no  
IATA: no

14.6 Special precautions for user
No data available

SECTION 15: Regulatory information

15.1 Safety, health and environmental regulations/legislation specific for the substance or mixture
This safety datasheet complies with the requirements of Regulation (EC) No. 1907/2006.

15.2 Chemical safety assessment
For this product a chemical safety assessment was not carried out

SECTION 16: Other information

Full text of H-Statements referred to under sections 2 and 3.

H225  Highly flammable liquid and vapour.
H319  Causes serious eye irritation.

Further information
The above information is believed to be correct but does not purport to be all inclusive and shall be used only as a guide. The information in this document is based on the present state of our knowledge and is applicable to the product with regard to appropriate safety precautions. It does not represent any guarantee of the properties of the product. Central Drug House (P) Ltd and its Affiliates shall not be held liable for any damage resulting from handling or from contact with the above product. See www.cdhfinechemical.com for additional terms and conditions of sale.
SAFETY DATA SHEET

1. Identification

Product Name 1-Butanol (Spectranaalyzed)
Cat No. A400; A400-4
CAS-No 71-36-3
Synonyms n-Butanol; n-Butyl alcohol, Butan-1-ol
Recommended Use Laboratory chemicals.
Uses advised against Not for food, drug, pesticide or biocidal product use

Details of the supplier of the safety data sheet

Company Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Emergency Telephone Number
CHEMTREC®, Inside the USA: 800-424-9300
CHEMTREC®, Outside the USA: 001-703-527-3887

2. Hazard(s) identification

Classification
This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammable liquids</td>
<td>Category 3</td>
</tr>
<tr>
<td>Acute oral toxicity</td>
<td>Category 4</td>
</tr>
<tr>
<td>Skin Corrosion/irritation</td>
<td>Category 2</td>
</tr>
<tr>
<td>Serious Eye Damage/Eye Irritation</td>
<td>Category 1</td>
</tr>
<tr>
<td>Specific target organ toxicity (single exposure)</td>
<td>Category 3</td>
</tr>
<tr>
<td>Target Organs - Respiratory system, Central nervous system (CNS).</td>
<td></td>
</tr>
</tbody>
</table>

Label Elements

Signal Word Danger

Hazard Statements
Flammable liquid and vapor
Harmful if swallowed
Causes skin irritation
Causes serious eye damage
May cause respiratory irritation
May cause drowsiness or dizziness
Precautionary Statements

Prevention
Wash face, hands and any exposed skin thoroughly after handling
Do not eat, drink or smoke when using this product
Wear protective gloves/protective clothing/eye protection/face protection
Do not breathe dust/fume/gas/mist/vapors/spray
Use only outdoors or in a well-ventilated area
Keep away from heat/sparks/open flames/hot surfaces. - No smoking
Keep container tightly closed
Ground/bond container and receiving equipment
Use explosion-proof electrical/ventilating/lighting/equipment
Use only non-sparking tools
Take precautionary measures against static discharge
Keep cool

Response
Get medical attention/advice if you feel unwell

Inhalation
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
Call a POISON CENTER or doctor/physician if you feel unwell

Skin
If skin irritation occurs: Get medical advice/attention
IF ON SKIN (or hair): Take off immediately all contaminated clothing. Rinse skin with water/shower
Wash contaminated clothing before reuse

Eyes
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
Immediately call a POISON CENTER or doctor/physician

Ingestion
IF SWALLOWED: Call a POISON CENTER or doctor/physician if you feel unwell
Rinse mouth

Fire
In case of fire: Use CO2, dry chemical, or foam for extinction

Storage
Store in a well-ventilated place. Keep container tightly closed
Store locked up

Disposal
Dispose of contents/container to an approved waste disposal plant

Hazard not otherwise classified (HNOC)
None identified

3. Composition/Information on Ingredients

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>71-36-3</td>
<td>99</td>
</tr>
</tbody>
</table>

4. First-aid measures

General Advice
If symptoms persist, call a physician.

Eye Contact
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get
1-Butanol (Spectranalyzed)

**Handling**

**Skin Contact**

Wash off immediately with plenty of water for at least 15 minutes. If skin irritation persists, call a physician.

**Inhalation**

Move to fresh air. If not breathing, give artificial respiration. Get medical attention if symptoms occur.

**Ingestion**

Clean mouth with water and drink afterwards plenty of water.

**Most important symptoms and effects**

Breathing difficulties. Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting

**Notes to Physician**

Treat symptomatically

---

### 5. Fire-fighting measures

<table>
<thead>
<tr>
<th>Suitable Extinguishing Media</th>
<th>Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsuitable Extinguishing Media</td>
<td>No information available</td>
</tr>
<tr>
<td><strong>Flash Point</strong></td>
<td>35 °C / 95 °F</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>Closed cup</td>
</tr>
<tr>
<td><strong>Autoignition Temperature</strong></td>
<td>340 °C / 644 °F</td>
</tr>
</tbody>
</table>

### Specific Hazards Arising from the Chemical

Flammable. Risk of ignition. Vapors may form explosive mixtures with air. Vapors may travel to source of ignition and flash back. Containers may explode when heated. Thermal decomposition can lead to release of irritating gases and vapors. Keep product and empty container away from heat and sources of ignition.

### Hazardous Combustion Products

Carbon monoxide (CO) Carbon dioxide (CO₂)

### Protective Equipment and Precautions for Firefighters

As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

### NFPA

<table>
<thead>
<tr>
<th>Health</th>
<th>Flammability</th>
<th>Instability</th>
<th>Physical hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

---

### 6. Accidental release measures

| Personal Precautions | Use personal protective equipment. Ensure adequate ventilation. |
| Environmental Precautions | Should not be released into the environment. |

**Methods for Containment and Clean Up**

Soak up with inert absorbent material. Keep in suitable, closed containers for disposal.

---

### 7. Handling and storage

| Handling | Wear personal protective equipment. Ensure adequate ventilation. Do not get in eyes, on skin, or on clothing. Avoid ingestion and inhalation. |
| Storage  | Keep containers tightly closed in a dry, cool and well-ventilated place. Keep away from heat and sources of ignition. Flammables area. |
8. Exposure controls / personal protection

Exposure Guidelines

<table>
<thead>
<tr>
<th>Component</th>
<th>ACGIH TLV</th>
<th>OSHA PEL</th>
<th>NIOSH IDLH</th>
<th>Mexico OEL (TWA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>TWA: 20 ppm</td>
<td>Skin (Vacated) Ceiling: 50 ppm (Vacated) Ceiling: 150 mg/m³ TWA: 100 ppm TWA: 200 mg/m³</td>
<td>IDLH: 1400 ppm Ceiling: 50 ppm Ceiling: 150 mg/m³</td>
<td>Ceiling: 50 ppm Ceiling: 150 mg/m³</td>
</tr>
</tbody>
</table>

Legend

ACGIH - American Conference of Governmental Industrial Hygienists
OSHA - Occupational Safety and Health Administration
NIOSH IDLH: The National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health

Engineering Measures

Ensure adequate ventilation, especially in confined areas. Use explosion-proof electrical/ventilating/lighting/equipment. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection
Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA's eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.

Skin and body protection
Long sleeved clothing.

Respiratory Protection
Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.

Hygiene Measures
Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical State</td>
<td>Liquid</td>
</tr>
<tr>
<td>Appearance</td>
<td>Colorless</td>
</tr>
<tr>
<td>Odor</td>
<td>Alcohol-like</td>
</tr>
<tr>
<td>Odor Threshold</td>
<td>No information available</td>
</tr>
<tr>
<td>pH</td>
<td>No information available</td>
</tr>
<tr>
<td>Melting Point/Range</td>
<td>-89 °C / -128.2 °F</td>
</tr>
<tr>
<td>Boiling Point/Range</td>
<td>117.6 °C / 243.7 °F</td>
</tr>
<tr>
<td>Flash Point</td>
<td>35 °C / 95 °F</td>
</tr>
<tr>
<td>Method -</td>
<td>Closed cup</td>
</tr>
<tr>
<td>Evaporation Rate</td>
<td>0.46</td>
</tr>
<tr>
<td>Flammability (solid,gas)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Flammability or explosive limits</td>
<td></td>
</tr>
<tr>
<td>Upper</td>
<td>11.2 vol %</td>
</tr>
<tr>
<td>Lower</td>
<td>1.4 vol %</td>
</tr>
<tr>
<td>Vapor Pressure</td>
<td>6.7 mbar @ 20 °C</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>2.6</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.810</td>
</tr>
<tr>
<td>Solubility</td>
<td>Slightly soluble in water</td>
</tr>
<tr>
<td>Partition coefficient; n-octanol/water</td>
<td></td>
</tr>
<tr>
<td>Autoignition Temperature</td>
<td>340 °C / 644 °F</td>
</tr>
<tr>
<td>Decomposition Temperature</td>
<td>No information available</td>
</tr>
<tr>
<td>Viscosity</td>
<td>2.95 mPa.s (20 °C)</td>
</tr>
</tbody>
</table>
1-Butanol (Spectranalyzed)

Molecular Formula C4 H10 O
Molecular Weight 74.12
Refractive index 1.390 - 1.400

10. Stability and reactivity

Reactive Hazard None known, based on information available
Stability Stable under normal conditions.
Conditions to Avoid Keep away from open flames, hot surfaces and sources of ignition. Incompatible products.
Incompatible Materials Strong oxidizing agents, Reducing agents, Acid chlorides, copper, Copper alloys, Acid anhydrides
Hazardous Decomposition Products Carbon monoxide (CO), Carbon dioxide (CO2)
Hazardous Polymerization Hazardous polymerization does not occur.
Hazardous Reactions None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information
Component Information

<table>
<thead>
<tr>
<th>Component</th>
<th>LD50 Oral</th>
<th>LD50 Dermal</th>
<th>LC50 Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>LD50 = 700 mg/kg (Rat)</td>
<td>LD50 = 3402 mg/kg (Rabbit)</td>
<td>LC50 &gt; 8000 ppm (Rat) 4 h</td>
</tr>
</tbody>
</table>
LD50 = 790 mg/kg (Rat) | LD50 = 3400 mg/kg (Rabbit) |

Toxicologically Synergistic Products

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation Severe eye irritant; Irritating to respiratory system and skin
Sensitization No information available
Carcinogenicity The table below indicates whether each agency has listed any ingredient as a carcinogen.

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>IARC</th>
<th>NTP</th>
<th>ACGIH</th>
<th>OSHA</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>71-36-3</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

Mutagenic Effects No information available
Reproductive Effects No information available.
Developmental Effects No information available.
Teratogenicity No information available.
STOT - single exposure Respiratory system Central nervous system (CNS)
STOT - repeated exposure None known
Aspiration hazard No information available

Symptoms / effects, both acute and delayed Symptoms of overexposure may be headache, dizziness, tiredness, nausea and vomiting

Endocrine Disruptor Information No information available
Other Adverse Effects  The toxicological properties have not been fully investigated.

### 12. Ecological information

**Ecotoxicity**

Do not flush into surface water or sanitary sewer system.

<table>
<thead>
<tr>
<th>Component</th>
<th>Freshwater Algae</th>
<th>Freshwater Fish</th>
<th>Microtox</th>
<th>Water Flea</th>
</tr>
</thead>
</table>
| n-Butyl alcohol | EC50: > 500 mg/L, 72h  
Desmodesmus subspicatus)  
EC50: > 500 mg/L, 96h  
(Desmodesmus subspicatus) | LC50: 100000 - 500000  
µg/L, 96h static (Lepomis macrochirus)  
LC50: = 1740 mg/L, 96h flow-through (Pimephales promelas)  
LC50: = 1910000 µg/L, 96h static (Pimephales promelas)  
LC50: = 1730 - 1910 mg/L, 96h static (Pimephales promelas) | EC50 = 2041.4 mg/L 5 min  
EC50 = 2186 mg/L 30 min  
EC50 = 3980 mg/L 24 h  
EC50 = 4400 mg/L 17 h | EC50: = 1983 mg/L, 48h  
(Daphnia magna)  
EC50: 1897 - 2072 mg/L, 48h Static (Daphnia magna) |

**Persistence and Degradability**

Soluble in water Persistence is unlikely based on information available.

**Bioaccumulation/ Accumulation**

No information available.

**Mobility**

Will likely be mobile in the environment due to its water solubility.

<table>
<thead>
<tr>
<th>Component</th>
<th>log Pow</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>0.785</td>
</tr>
</tbody>
</table>

### 13. Disposal considerations

**Waste Disposal Methods**

Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

<table>
<thead>
<tr>
<th>Component</th>
<th>RCRA - U Series Wastes</th>
<th>RCRA - P Series Wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>U031</td>
<td>-</td>
</tr>
</tbody>
</table>

### 14. Transport information

**DOT**

- UN-No: UN1120
- Proper Shipping Name: BUTANOLS
- Hazard Class: 3
- Packing Group: III

**TDG**

- UN-No: UN1120
- Proper Shipping Name: BUTANOLS
- Hazard Class: 3
- Packing Group: III

**IATA**

- UN-No: UN1120
- Proper Shipping Name: BUTANOLS
- Hazard Class: 3
- Packing Group: III

**IMDG/IMO**

- UN-No: UN1120
- Proper Shipping Name: BUTANOLS
- Hazard Class: 3
- Packing Group: III

### 15. Regulatory information
All of the components in the product are on the following Inventory lists:  X = listed

International Inventories

<table>
<thead>
<tr>
<th>Component</th>
<th>TSCA</th>
<th>DSL</th>
<th>NDSL</th>
<th>ELINCS</th>
<th>NLP</th>
<th>PICCS</th>
<th>ENCS</th>
<th>AICS</th>
<th>IECSC</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>200-751-6</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Legend:

X - Listed
E - Indicates a substance that is the subject of a Section 5(e) Consent order under TSCA.
F - Indicates a substance that is the subject of a Section 5(f) Rule under TSCA.
N - Indicates a polymeric substance containing no free-radical initiator in its inventory name but is considered to cover the designated polymer made with any free-radical initiator regardless of the amount used.
P - Indicates a commenced PMN substance
R - Indicates a substance that is the subject of a Section 6 risk management rule under TSCA.
S - Indicates a substance that is identified in a proposed or final Significant New Use Rule.
T - Indicates a substance that is the subject of a Section 4 test rule under TSCA.
XU - Indicates a substance exempt from reporting under the Inventory Update Rule, i.e. Partial Updating of the TSCA Inventory Data Base Production and Site Reports (40 CFR 710(B)).
Y1 - Indicates an exempt polymer that has a number-average molecular weight of 1,000 or greater.
Y2 - Indicates an exempt polymer that is a polyester and is made only from reactants included in a specified list of low concern reactants that comprises one of the eligibility criteria for the exemption rule.

U.S. Federal Regulations

TSCA 12(b)  Not applicable

SARA 313

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
<th>SARA 313 - Threshold Values %</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>71-36-3</td>
<td>99</td>
<td>1.0</td>
</tr>
</tbody>
</table>

SARA 311/312 Hazard Categories  See section 2 for more information

CWA (Clean Water Act)  Not applicable

Clean Air Act  Not applicable

OSHA  Occupational Safety and Health Administration  Not applicable

CERCLA  This material, as supplied, contains one or more substances regulated as a hazardous substance under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302)

<table>
<thead>
<tr>
<th>Component</th>
<th>Hazardous Substances RQs</th>
<th>CERCLA EHS RQs</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>5000 lb</td>
<td>-</td>
</tr>
</tbody>
</table>

California Proposition 65  This product does not contain any Proposition 65 chemicals

U.S. State Right-to-Know Regulations

<table>
<thead>
<tr>
<th>Component</th>
<th>Massachusetts</th>
<th>New Jersey</th>
<th>Pennsylvania</th>
<th>Illinois</th>
<th>Rhode Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-Butyl alcohol</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>

U.S. Department of Transportation

Reportable Quantity (RQ):  Y
DOT Marine Pollutant  N
DOT Severe Marine Pollutant  N

U.S. Department of Homeland Security  This product does not contain any DHS chemicals.
Other International Regulations

Mexico - Grade  Serious risk, Grade 3

16. Other information

Prepared By  Regulatory Affairs
             Thermo Fisher Scientific
             Email: EMSDS.RA@thermofisher.com

Creation Date  21-Jan-2009
Revision Date  18-Jan-2018
Print Date  18-Jan-2018
Revision Summary  This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

Disclaimer

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

End of SDS
1. PRODUCT AND COMPANY IDENTIFICATION

1.1 Product identifiers

Product name: 2-Butanol

Product Number: W510254
Brand: Aldrich
Index-No.: 603-127-00-5

CAS-No.: 78-92-2

1.2 Relevant identified uses of the substance or mixture and uses advised against

Identified uses: Laboratory chemicals, Synthesis of substances

1.3 Details of the supplier of the safety data sheet

Company: Sigma-Aldrich
3050 Spruce Street
SAINT LOUIS MO  63103
USA

Telephone: +1 800-325-5832
Fax: +1 800-325-5052

1.4 Emergency telephone number

Emergency Phone #: +1-703-527-3887 (CHEMTREC)

2. HAZARDS IDENTIFICATION

2.1 Classification of the substance or mixture

GHS Classification in accordance with 29 CFR 1910 (OSHA HCS)
Flammable liquids (Category 3), H226
Eye irritation (Category 2A), H319
Specific target organ toxicity - single exposure (Category 3), Respiratory system, Central nervous system, H335, H336

For the full text of the H-Statements mentioned in this Section, see Section 16.

2.2 GHS Label elements, including precautionary statements

Pictogram

Signal word Warning

Hazard statement(s)
H226 Flammable liquid and vapour.
H319 Causes serious eye irritation.
H335 May cause respiratory irritation.
H336 May cause drowsiness or dizziness.

Precautionary statement(s)
P210 Keep away from heat/sparks/open flames/hot surfaces. No smoking.
P233 Keep container tightly closed.
P240 Ground/bond container and receiving equipment.
P241 Use explosion-proof electrical/ventilating/lighting/equipment.
P242 Use only non-sparking tools.
P243 Take precautionary measures against static discharge.
2.3 Hazards not otherwise classified (HNOC) or not covered by GHS
May form explosive peroxides.

3. COMPOSITION/INFORMATION ON INGREDIENTS

3.1 Substances

<table>
<thead>
<tr>
<th>Synonyms</th>
<th>sec-Butyl alcohol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>C4H10O</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>74.12 g/mol</td>
</tr>
<tr>
<td>CAS-No.</td>
<td>78-92-2</td>
</tr>
<tr>
<td>EC-No.</td>
<td>201-158-5</td>
</tr>
<tr>
<td>Index-No.</td>
<td>603-127-00-5</td>
</tr>
</tbody>
</table>

Hazardous components

<table>
<thead>
<tr>
<th>Component</th>
<th>Classification</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butan-2-ol</td>
<td>Flam. Liq. 3; Eye Irrit. 2A;</td>
<td>90 - 100 %</td>
</tr>
<tr>
<td></td>
<td>STOT SE 3; H226, H319,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H335, H336</td>
<td></td>
</tr>
</tbody>
</table>

For the full text of the H-Statements mentioned in this Section, see Section 16.

4. FIRST AID MEASURES

4.1 Description of first aid measures

General advice
Consult a physician. Show this safety data sheet to the doctor in attendance. Move out of dangerous area.

If inhaled
If breathed in, move person into fresh air. If not breathing, give artificial respiration. Consult a physician.

In case of skin contact
Wash off with soap and plenty of water. Consult a physician.

In case of eye contact
Rinse thoroughly with plenty of water for at least 15 minutes and consult a physician.

If swallowed
Do NOT induce vomiting. Never give anything by mouth to an unconscious person. Rinse mouth with water. Consult a physician.
4.2 Most important symptoms and effects, both acute and delayed
The most important known symptoms and effects are described in the labelling (see section 2.2) and/or in section 11

4.3 Indication of any immediate medical attention and special treatment needed
No data available

5. FIREFIGHTING MEASURES
5.1 Extinguishing media
Suitable extinguishing media
Use water spray, alcohol-resistant foam, dry chemical or carbon dioxide.

5.2 Special hazards arising from the substance or mixture
No data available

5.3 Advice for firefighters
Wear self-contained breathing apparatus for firefighting if necessary.

5.4 Further information
Use water spray to cool unopened containers.

6. ACCIDENTAL RELEASE MEASURES
6.1 Personal precautions, protective equipment and emergency procedures
Use personal protective equipment. Avoid breathing vapours, mist or gas. Ensure adequate ventilation. Remove all sources of ignition. Evacuate personnel to safe areas. Beware of vapours accumulating to form explosive concentrations. Vapours can accumulate in low areas. For personal protection see section 8.

6.2 Environmental precautions
Prevent further leakage or spillage if safe to do so. Do not let product enter drains.

6.3 Methods and materials for containment and cleaning up
Contain spillage, and then collect with an electrically protected vacuum cleaner or by wet-brushing and place in container for disposal according to local regulations (see section 13).

6.4 Reference to other sections
For disposal see section 13.

7. HANDLING AND STORAGE
7.1 Precautions for safe handling
Avoid contact with skin and eyes. Avoid inhalation of vapour or mist. Keep away from sources of ignition - No smoking. Take measures to prevent the build up of electrostatic charge. For precautions see section 2.2.

7.2 Conditions for safe storage, including any incompatibilities
Keep container tightly closed in a dry and well-ventilated place. Containers which are opened must be carefully resealed and kept upright to prevent leakage. Storage class (TRGS 510): 3: Flammable liquids

7.3 Specific end use(s)
Apart from the uses mentioned in section 1.2 no other specific uses are stipulated

8. EXPOSURE CONTROLS/PERSONAL PROTECTION
8.1 Control parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No.</th>
<th>Value</th>
<th>Control parameters</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butan-2-ol</td>
<td>78-92-2</td>
<td>TWA</td>
<td>100 ppm</td>
<td>USA. ACGIH Threshold Limit Values (TLV)</td>
</tr>
<tr>
<td>Remarks</td>
<td></td>
<td></td>
<td>Central Nervous System impairment Upper Respiratory Tract irritation</td>
<td></td>
</tr>
</tbody>
</table>
8.2 Exposure controls

**Appropriate engineering controls**
Handle in accordance with good industrial hygiene and safety practice. Wash hands before breaks and at the end of workday.

**Personal protective equipment**

**Eye/face protection**
Face shield and safety glasses. Use equipment for eye protection tested and approved under appropriate government standards such as NIOSH (US) or EN 166(EU).

**Skin protection**
Handle with gloves. Gloves must be inspected prior to use. Use proper glove removal technique (without touching glove’s outer surface) to avoid skin contact with this product. Dispose of contaminated gloves after use in accordance with applicable laws and good laboratory practices. Wash and dry hands.

**Full contact**
Material: Nitrile rubber
Minimum layer thickness: 0.4 mm
Break through time: 480 min
Material tested: Camatril® (KCL 730 / Aldrich Z677442, Size M)

**Splash contact**
Material: Nature latex/chloroprene
Minimum layer thickness: 0.6 mm
Break through time: 30 min
Material tested: Lapren® (KCL 706 / Aldrich Z677558, Size M)

data source: KCL GmbH, D-36124 Eichenzell, phone +49 (0)6659 87300, e-mail sales@kcl.de, test method: EN374

If used in solution, or mixed with other substances, and under conditions which differ from EN 374, contact the supplier of the CE approved gloves. This recommendation is advisory only and must be evaluated by an industrial hygienist and safety officer familiar with the specific situation of anticipated use by our customers. It should not be construed as offering an approval for any specific use scenario.

**Body Protection**
Impervious clothing, Flame retardant antistatic protective clothing. The type of protective equipment must be selected according to the concentration and amount of the dangerous substance at the specific workplace.

**Respiratory protection**
Where risk assessment shows air-purifying respirators are appropriate use a full-face respirator with multipurpose combination (US) or type ABEK (EN 14387) respirator cartridges as a backup to engineering controls. If the respirator is the sole means of protection, use a full-face supplied air respirator. Use respirators and components tested and approved under appropriate government standards such as NIOSH (US) or CEN (EU).

**Control of environmental exposure**
Prevent further leakage or spillage if safe to do so. Do not let product enter drains.

### 9. PHYSICAL AND CHEMICAL PROPERTIES

#### 9.1 Information on basic physical and chemical properties

<table>
<thead>
<tr>
<th></th>
<th>TWA</th>
<th>100 ppm</th>
<th>USA. NIOSH Recommended Exposure Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>305 mg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ST</td>
<td>150 ppm</td>
<td>USA. NIOSH Recommended Exposure Limits</td>
</tr>
<tr>
<td></td>
<td></td>
<td>455 mg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>USA. Occupational Exposure Limits (OSHA) - Table Z-1 Limits for Air Contaminants</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TWA</td>
<td>150 ppm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>450 mg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PEL</td>
<td>100 ppm</td>
<td>California permissible exposure limits for chemical contaminants (Title 8, Article 107)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>305 mg/m³</td>
<td></td>
</tr>
</tbody>
</table>

The value in mg/m³ is approximate.
c) Odour Threshold  No data available

d) pH  No data available

e) Melting point/freezing point  Melting point/range: -115 °C (-175 °F) - lit.

f) Initial boiling point and boiling range  98 °C (208 °F) - lit.

g) Flash point  27 °C (81 °F) - closed cup

h) Evaporation rate  No data available

i) Flammability (solid, gas)  No data available

j) Upper/lower flammability or explosive limits  Upper explosion limit: 9.8 %(V)

k) Vapour pressure  15.3 hPa (11.5 mmHg) at 20 °C (68 °F)
   24.4 hPa (18.3 mmHg) at 25 °C (77 °F)

l) Vapour density  2.56 - (Air = 1.0)

m) Relative density  0.808 g/cm3 at 25 °C (77 °F)

n) Water solubility  soluble

o) Partition coefficient: n-octanol/water  log Pow: 0.146

p) Auto-ignition temperature  No data available

q) Decomposition temperature  No data available

r) Viscosity  No data available

s) Explosive properties  No data available

t) Oxidizing properties  No data available

9.2 Other safety information

Surface tension  23 mN/m at 20 °C (68 °F)

Relative vapour density  2.56 - (Air = 1.0)

10. STABILITY AND REACTIVITY

10.1 Reactivity  No data available

10.2 Chemical stability  Stable under recommended storage conditions.

10.3 Possibility of hazardous reactions  Vapours may form explosive mixture with air.

10.4 Conditions to avoid

Heat, flames and sparks.

10.5 Incompatible materials

acids, Acid chlorides, Acid anhydrides, Oxidizing agents, Halogens, Peroxides

10.6 Hazardous decomposition products

Hazardous decomposition products formed under fire conditions. - Carbon oxides
Other decomposition products - No data available
In the event of fire: see section 5

Aldrich - W510254  Page 5 of 8
11. TOXICOLOGICAL INFORMATION

11.1 Information on toxicological effects

Acute toxicity
LD50 Oral - Rat - male and female - 2,193 mg/kg
(OECD Test Guideline 423)
LD50 Dermal - Rat - male and female - > 2,000 mg/kg
(OECD Test Guideline 402)
No data available

Skin corrosion/irritation
Skin - Rabbit
Result: No skin irritation - 4 h
(OECD Test Guideline 404)

Serious eye damage/eye irritation
No data available

Respiratory or skin sensitisation
Maximisation Test - Guinea pig
Result: Does not cause skin sensitisation.
(OECD Test Guideline 406)

Germ cell mutagenicity
Ames test
S. typhimurium
Result: negative

Carcinogenicity
IARC: No component of this product present at levels greater than or equal to 0.1% is identified as probable, possible or confirmed human carcinogen by IARC.
NTP: No component of this product present at levels greater than or equal to 0.1% is identified as a known or anticipated carcinogen by NTP.
OSHA: No component of this product present at levels greater than or equal to 0.1% is on OSHA’s list of regulated carcinogens.

Reproductive toxicity
Reproductive toxicity - Rat - Inhalation
Effects on Fertility: Post-implantation mortality (e.g., dead and/or resorbed implants per total number of implants). Effects on Embryo or Fetus: Fetal death. Specific Developmental Abnormalities: Musculoskeletal system.

Developmental Toxicity - Rat - Inhalation
Effects on Embryo or Fetus: Fetotoxicity (except death, e.g., stunted fetus).

Specific target organ toxicity - single exposure
No data available

Specific target organ toxicity - repeated exposure
No data available

Aspiration hazard
No data available

Additional Information
RTECS: EO1750000
Nausea, Dizziness, Headache, To the best of our knowledge, the chemical, physical, and toxicological properties have not been thoroughly investigated.

12. ECOLOGICAL INFORMATION

12.1 Toxicity
Toxicity to fish
LC50 - Pimephales promelas (fathead minnow) - 3,670 mg/l - 96 h

Aldrich - W510254
12.2 Persistence and degradability
Biodegradability: aerobic - Exposure time 5 d
Result: 86 % - Readily biodegradable.

12.3 Bioaccumulative potential
No data available

12.4 Mobility in soil
No data available

12.5 Results of PBT and vPvB assessment
PBT/vPvB assessment not available as chemical safety assessment not required/not conducted

12.6 Other adverse effects

13. DISPOSAL CONSIDERATIONS

13.1 Waste treatment methods

Product
Burn in a chemical incinerator equipped with an afterburner and scrubber but exert extra care in igniting as this material is highly flammable. Offer surplus and non-recyclable solutions to a licensed disposal company. Contact a licensed professional waste disposal service to dispose of this material.

Contaminated packaging
Dispose of as unused product.

14. TRANSPORT INFORMATION

DOT (US)
UN number: 1120  Class: 3  Packing group: III
Proper shipping name: Butanols
Reportable Quantity (RQ):
Poison Inhalation Hazard: No

IMDG
UN number: 1120  Class: 3  Packing group: III  EMS-No: F-E, S-D
Proper shipping name: BUTANOLS

IATA
UN number: 1120  Class: 3  Packing group: III
Proper shipping name: Butanols

15. REGULATORY INFORMATION

SARA 302 Components
No chemicals in this material are subject to the reporting requirements of SARA Title III, Section 302.

SARA 313 Components
The following components are subject to reporting levels established by SARA Title III, Section 313:

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No.</th>
<th>Revision Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butan-2-ol</td>
<td>78-92-2</td>
<td>2007-07-01</td>
</tr>
</tbody>
</table>

SARA 311/312 Hazards
Fire Hazard, Acute Health Hazard

Massachusetts Right To Know Components

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No.</th>
<th>Revision Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butan-2-ol</td>
<td>78-92-2</td>
<td>2007-07-01</td>
</tr>
</tbody>
</table>

Pennsylvania Right To Know Components
16. OTHER INFORMATION

Full text of H-Statements referred to under sections 2 and 3.

Eye Irrit.  Eye irritation
Flam. Liq.  Flammable liquids
H226  Flammable liquid and vapour.
H319  Causes serious eye irritation.
H335  May cause respiratory irritation.
H336  May cause drowsiness or dizziness.
STOT SE  Specific target organ toxicity - single exposure

HMIS Rating
Health hazard:  2
Chronic Health Hazard:
Flammability:  3
Physical Hazard  0

NFPA Rating
Health hazard:  2
Fire Hazard:  3
Reactivity Hazard:  0

Further information
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Preparation Information
Sigma-Aldrich Corporation
Product Safety – Americas Region
1-800-521-8956

Version: 5.8  Revision Date: 04/13/2018  Print Date: 11/10/2018
1. Identification

Product Name: Raney Nickel®, activated catalyst, 50% slurry in water

Cat No.: AC395920000; AC395921000; AC395925000

Synonyms: Chemicals.

Recommended Use: Laboratory chemicals.

Uses advised against: Not for food, drug, pesticide or biocidal product use

Details of the supplier of the safety data sheet

Company
Fisher Scientific
One Reagent Lane
Fair Lawn, NJ 07410
Tel: (201) 796-7100

Acros Organics
One Reagent Lane
Fair Lawn, NJ 07410

Emergency Telephone Number
For information US call: 001-800-ACROS-01 / Europe call: +32 14 57 52 11
Emergency Number US: 001-201-796-7100 / Europe: +32 14 57 52 99
CHEMTREC Tel. No. US: 001-800-424-9300 / Europe: 001-703-527-3887

2. Hazard(s) identification

Classification
This chemical is considered hazardous by the 2012 OSHA Hazard Communication Standard (29 CFR 1910.1200)

Substances/mixtures which, in contact with water, emit
flammable gases
Skin Corrosion/irritation
Serious Eye Damage/Eye Irritation
Skin Sensitization
Carcinogenicity
Specific target organ toxicity (single exposure)
Specific target organ toxicity - (repeated exposure)
Target Organs - Respiratory system, Central nervous system (CNS)
Target Organs - Skin.

Category 2
Category 2
Category 2
Category 1
Category 1B
Category 3
Category 1

Label Elements

Signal Word: Danger

Hazard Statements
In contact with water releases flammable gas
Causes skin irritation
Causes eye irritation
May cause an allergic skin reaction
May cause cancer
May cause respiratory irritation. May cause drowsiness and dizziness. Causes damage to organs through prolonged or repeated exposure.

Precautionary Statements
Prevention
Obtain special instructions before use
Do not handle until all safety precautions have been read and understood
Wear protective gloves/protective clothing/eye protection/face protection
Handle under inert gas. Protect from moisture
Wash face, hands and any exposed skin thoroughly after handling
Contaminated work clothing should not be allowed out of the workplace
Use only outdoors or in a well-ventilated area
Do not breathe dust/fume/gas/mist/vapors/spray
Do not eat, drink or smoke when using this product
Response
IF exposed or concerned: Get medical attention/advice
Inhalation
IF INHALED: Remove victim to fresh air and keep at rest in a position comfortable for breathing
Skin
Take off contaminated clothing and wash before reuse
IF ON SKIN: Wash with plenty of soap and water
If skin irritation or rash occurs: Get medical advice/attention
Eyes
IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing
If eye irritation persists: Get medical advice/attention
Fire
Evacuate area
Use CO2, dry chemical, or foam
Storage
Store locked up
Store in a dry place
Store in a well-ventilated place. Keep container tightly closed
Disposal
Dispose of contents/container to an approved waste disposal plant
Hazard not otherwise classified (HNOC).
Toxic to aquatic life with long lasting effects

3. Composition/Information on Ingredients

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>7732-18-5</td>
<td>47-53</td>
</tr>
<tr>
<td>Nickel</td>
<td>7440-02-0</td>
<td>46-49</td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>7429-90-5</td>
<td>1-4</td>
</tr>
</tbody>
</table>

4. First-aid measures

Eye Contact
Rinse immediately with plenty of water, also under the eyelids, for at least 15 minutes. Get medical attention.
Raney Nickel®, activated catalyst, 50% slurry in water

Skin Contact
Obtain medical attention. Wash off immediately with plenty of water for at least 15 minutes.

Inhalation
Move to fresh air. If breathing is difficult, give oxygen. Obtain medical attention.

Ingestion
Do not induce vomiting. Obtain medical attention.

Most important symptoms and effects
May cause allergic skin reaction. Symptoms of allergic reaction may include rash, itching, swelling, trouble breathing, tingling of the hands and feet, dizziness, lightheadedness, chest pain, muscle pain or flushing.

Notes to Physician
Treat symptomatically

5. Fire-fighting measures

Suitable Extinguishing Media
Water spray. Carbon dioxide (CO₂). Dry chemical. Use water spray to cool unopened containers. Chemical foam.

Unsuitable Extinguishing Media
No information available

Flash Point
No information available

Method -
No information available

Autoignition Temperature
No information available

Explosion Limits
Upper
No data available

Lower
No data available

Sensitivity to Mechanical Impact
No information available

Sensitivity to Static Discharge
No information available

Specific Hazards Arising from the Chemical
Self-heating; exposure to air may cause substance to self-heat without an energy supply. This material poses an explosion hazard when dry.

Hazardous Combustion Products
Burning produces obnoxious and toxic fumes

Protective Equipment and Precautions for Firefighters
As in any fire, wear self-contained breathing apparatus pressure-demand, MSHA/NIOSH (approved or equivalent) and full protective gear.

NFPA

<table>
<thead>
<tr>
<th>Health</th>
<th>Flammability</th>
<th>Instability</th>
<th>Physical hazards</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>0</td>
<td>W</td>
</tr>
</tbody>
</table>

6. Accidental release measures

Personal Precautions
Ensure adequate ventilation. Use personal protective equipment.

Environmental Precautions
Do not flush into surface water or sanitary sewer system. See Section 12 for additional ecological information.

Methods for Containment and Clean Up
Soak up with inert absorbent material (e.g. sand, silica gel, acid binder, universal binder, sawdust). Keep in suitable, closed containers for disposal. Remove all sources of ignition. Use spark-proof tools and explosion-proof equipment. Do not flush into surface water or sanitary sewer system.

7. Handling and storage

Handling
Do not breathe vapors or spray mist. Do not get in eyes, on skin, or on clothing. Take precautionary measures against static discharges. Use only in area provided with appropriate exhaust ventilation. Use explosion-proof equipment. Use only non-sparking tools. Minimize dust generation and accumulation. Wear personal protective equipment.

Storage
Keep in a dry, cool and well-ventilated place. Keep container tightly closed. Keep away from heat and sources of ignition. Flammables area. Material can explode if dry. Keep at
Raney Nickel®, activated catalyst, 50% slurry in water

8. Exposure controls / personal protection

<table>
<thead>
<tr>
<th>Component</th>
<th>ACGIH TLV</th>
<th>OSHA PEL</th>
<th>NIOSH IDLH</th>
<th>Mexico OEL (TWA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>TWA: 1.5 mg/m³</td>
<td>(Vacated) TWA: 1 mg/m³</td>
<td>IDLH: 10 mg/m³</td>
<td>TWA: 1 mg/m³</td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>TWA: 1 mg/m³</td>
<td>(Vacated) TWA: 15 mg/m³</td>
<td>TWA: 10 mg/m³</td>
<td>TWA: 10 mg/m³</td>
</tr>
</tbody>
</table>

Legend
ACGIH - American Conference of Governmental Industrial Hygienists
OSHA - Occupational Safety and Health Administration
NIOSH IDLH: The National Institute for Occupational Safety and Health Immediately Dangerous to Life or Health

Engineering Measures
Use explosion-proof electrical/ventilating/lighting/equipment. Ensure that eyewash stations and safety showers are close to the workstation location.

Personal Protective Equipment

Eye/face Protection
Wear appropriate protective eyeglasses or chemical safety goggles as described by OSHA’s eye and face protection regulations in 29 CFR 1910.133 or European Standard EN166.

Skin and body protection
Wear appropriate protective gloves and clothing to prevent skin exposure.

Respiratory Protection
Follow the OSHA respirator regulations found in 29 CFR 1910.134 or European Standard EN 149. Use a NIOSH/MSHA or European Standard EN 149 approved respirator if exposure limits are exceeded or if irritation or other symptoms are experienced.

Hygiene Measures
Handle in accordance with good industrial hygiene and safety practice.

9. Physical and chemical properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical State</td>
<td>Slurry Liquid</td>
</tr>
<tr>
<td>Appearance</td>
<td>Dark grey</td>
</tr>
<tr>
<td>Odor</td>
<td>Odorless</td>
</tr>
<tr>
<td>Odor Threshold</td>
<td>No information available</td>
</tr>
<tr>
<td>pH</td>
<td>10-11  1500 g/L aq.sol</td>
</tr>
<tr>
<td>Melting Point/Range</td>
<td>No data available</td>
</tr>
<tr>
<td>Boiling Point/Range</td>
<td>No information available</td>
</tr>
<tr>
<td>Flash Point</td>
<td>No information available</td>
</tr>
<tr>
<td>Evaporation Rate</td>
<td>No information available</td>
</tr>
<tr>
<td>Flammability (solid,gas)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Flammability or explosive limits</td>
<td>No data available</td>
</tr>
<tr>
<td>Upper</td>
<td>No data available</td>
</tr>
<tr>
<td>Lower</td>
<td>No data available</td>
</tr>
<tr>
<td>Vapor Pressure</td>
<td>23.5 mbar @ 20 °C</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>No information available</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>No information available</td>
</tr>
<tr>
<td>Solubility</td>
<td>No information available</td>
</tr>
<tr>
<td>Partition coefficient; n-octanol/water</td>
<td>No data available</td>
</tr>
<tr>
<td>Autoignition Temperature</td>
<td>No information available</td>
</tr>
<tr>
<td>Decomposition Temperature</td>
<td>&gt; 100°C</td>
</tr>
<tr>
<td>Viscosity</td>
<td>No information available</td>
</tr>
<tr>
<td>Molecular Formula</td>
<td>Ni</td>
</tr>
</tbody>
</table>
Molecular Weight 58.69

10. Stability and reactivity

Reactive Hazard Yes
Stability Stable. Do not allow evaporation to dryness. This material poses an explosion hazard when dry.
Conditions to Avoid Heat, flames and sparks. Keep away from open flames, hot surfaces and sources of ignition. Exposure to air. Incompatible products.
Hazardous Decomposition Products Burning produces obnoxious and toxic fumes
Hazardous Polymerization Hazardous polymerization does not occur.
Hazardous Reactions None under normal processing.

11. Toxicological information

Acute Toxicity

Product Information
Oral LD50 Based on ATE data, the classification criteria are not met. ATE > 2000 mg/kg.
Dermal LD50 Based on ATE data, the classification criteria are not met. ATE > 2000 mg/kg.
Vapor LC50 Based on ATE data, the classification criteria are not met. ATE > 20 mg/l.

Component Information

<table>
<thead>
<tr>
<th>Component</th>
<th>LD50 Oral</th>
<th>LD50 Dermal</th>
<th>LC50 Inhalation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>-</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Nickel</td>
<td>LD50 &gt; 9000 mg/kg ( Rat )</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

Toxicologically Synergistic Products
No information available

Delayed and immediate effects as well as chronic effects from short and long-term exposure

Irritation Irritating to eyes, respiratory system and skin Vapors may cause drowsiness and dizziness

Sensitization May cause sensitization by skin contact

Carcinogenicity The table below indicates whether each agency has listed any ingredient as a carcinogen.

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>IARC</th>
<th>NTP</th>
<th>ACGIH</th>
<th>OSHA</th>
<th>Mexico</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>7732-18-5</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
<tr>
<td>Nickel</td>
<td>7440-02-0</td>
<td>Group 2B</td>
<td>Reasonably Anticipated</td>
<td>Not listed</td>
<td>X</td>
<td>Not listed</td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>7429-90-5</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
<td>Not listed</td>
</tr>
</tbody>
</table>

Mutagenic Effects No information available.

Reproductive Effects No information available.

Developmental Effects No information available.

Teratogenicity No information available.

STOT - single exposure Respiratory system Central nervous system (CNS)
STOT - repeated exposure Skin

Aspiration hazard No information available
Symptoms / effects, both acute and delayed
Symptoms of allergic reaction may include rash, itching, swelling, trouble breathing, tingling of the hands and feet, dizziness, lightheadedness, chest pain, muscle pain or flushing

Endocrine Disruptor Information
No information available

Other Adverse Effects
The toxicological properties have not been fully investigated. See actual entry in RTECS for complete information.

12. Ecological information

Ecotoxicity
Do not flush into surface water or sanitary sewer system. Do not allow material to contaminate ground water system. Do not empty into drains. The product contains following substances which are hazardous for the environment. Toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment. Very toxic to aquatic organisms, may cause long-term adverse effects in the aquatic environment.

<table>
<thead>
<tr>
<th>Component</th>
<th>Freshwater Algae</th>
<th>Freshwater Fish</th>
<th>Microtox</th>
<th>Water Flea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>EC50 = 0.1 mg/L 72h EC50 = 0.18 mg/L 72h</td>
<td>LC50: = 10.4 mg/L, 96h static (Cyprinus carpio) LC50: = 1.3 mg/L, 96h semi-static (Cyprinus carpio) LC50: &gt; 100 mg/L, 96h (Brachydanio rerio)</td>
<td>Not listed</td>
<td>EC50 = 510 µg/L 96h</td>
</tr>
</tbody>
</table>

Persistence and Degradability
Insoluble in water

Bioaccumulation/ Accumulation
No information available.

Mobility
Is not likely mobile in the environment due its low water solubility.

13. Disposal considerations

Waste Disposal Methods
Chemical waste generators must determine whether a discarded chemical is classified as a hazardous waste. Chemical waste generators must also consult local, regional, and national hazardous waste regulations to ensure complete and accurate classification.

14. Transport information

DOT
- UN-No: UN1378
- Proper Shipping Name: METAL CATALYST, WETTED
- Hazard Class: 4.2
- Packing Group: II

TDG
- UN-No: UN1378
- Proper Shipping Name: METAL CATALYST, WETTED
- Hazard Class: 4.2
- Packing Group: II

IATA
- UN-No: 1378
- Proper Shipping Name: METAL CATALYST, WETTED
- Hazard Class: 4.2
- Packing Group: II

IMDG/IMO
- UN-No: 1378
- Proper Shipping Name: METAL CATALYST, WETTED
- Hazard Class: 4.2
- Packing Group: II

15. Regulatory information
International Inventories

<table>
<thead>
<tr>
<th>Component</th>
<th>TSCA</th>
<th>DSL</th>
<th>NDSL</th>
<th>EINECS</th>
<th>ELINCS</th>
<th>NLP</th>
<th>PICCS</th>
<th>ENCS</th>
<th>AICS</th>
<th>IECSC</th>
<th>KECL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>231-791-2</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>231-111-4</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>231-072-3</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
X - Listed
E - Indicates a substance that is the subject of a Section 5(e) Consent order under TSCA.
F - Indicates a substance that is the subject of a Section 5(f) Rule under TSCA.
N - Indicates a polymeric substance containing no free-radical initiator in its inventory name but is considered to cover the designated polymer made with any free-radical initiator regardless of the amount used.
P - Indicates a commenced PMN substance
R - Indicates a substance that is the subject of a Section 6 risk management rule under TSCA.
S - Indicates a substance that is identified in a proposed or final Significant New Use Rule
T - Indicates a substance that is the subject of a Section 4 test rule under TSCA.
XU - Indicates a substance exempt from reporting under the Inventory Update Rule, i.e. Partial Updating of the TSCA Inventory Data Base

U.S. Federal Regulations

TSCA 12(b) Not applicable

SARA 313

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>Weight %</th>
<th>SARA 313 - Threshold Values %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>7440-02-0</td>
<td>46-49</td>
<td>0.1</td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>7429-60-5</td>
<td>1-4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

SARA 311/312 Hazard Categories See section 2 for more information

CWA (Clean Water Act)

<table>
<thead>
<tr>
<th>Component</th>
<th>CWA - Hazardous Substances</th>
<th>CWA - Reportable Quantities</th>
<th>CWA - Toxic Pollutants</th>
<th>CWA - Priority Pollutants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Clean Air Act

<table>
<thead>
<tr>
<th>Component</th>
<th>HAPS Data</th>
<th>Class 1 Ozone Depletors</th>
<th>Class 2 Ozone Depletors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

OSHA Occupational Safety and Health Administration
Not applicable

CERCLA This material, as supplied, contains one or more substances regulated as a hazardous substance under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) (40 CFR 302)

<table>
<thead>
<tr>
<th>Component</th>
<th>Hazardous Substances RQs</th>
<th>CERCLA EHS RQs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>100 lb</td>
<td>-</td>
</tr>
</tbody>
</table>

California Proposition 65 This product contains the following proposition 65 chemicals

<table>
<thead>
<tr>
<th>Component</th>
<th>CAS-No</th>
<th>California Prop. 65</th>
<th>Prop 65 NSRL</th>
<th>Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>7440-02-0</td>
<td>Carcinogen</td>
<td>-</td>
<td>Carcinogen</td>
</tr>
</tbody>
</table>

U.S. State Right-to-Know Regulations

<table>
<thead>
<tr>
<th>Component</th>
<th>Massachusetts</th>
<th>New Jersey</th>
<th>Pennsylvania</th>
<th>Illinois</th>
<th>Rhode Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nickel</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aluminium powder</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>

**U.S. Department of Transportation**

Reportable Quantity (RQ): N
DOT Marine Pollutant: N
DOT Severe Marine Pollutant: N

**U.S. Department of Homeland Security**

This product contains the following DHS chemicals:

**Other International Regulations**

Mexco - Grade: No information available

---

### 16. Other information

**Prepared By**
Regulatory Affairs
Thermo Fisher Scientific
Email: EMSDS.RA@thermofisher.com

**Creation Date**
24-Nov-2010

**Revision Date**
15-Feb-2018

**Print Date**
15-Feb-2018

**Revision Summary**
This document has been updated to comply with the US OSHA HazCom 2012 Standard replacing the current legislation under 29 CFR 1910.1200 to align with the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).

**Disclaimer**

The information provided in this Safety Data Sheet is correct to the best of our knowledge, information and belief at the date of its publication. The information given is designed only as a guidance for safe handling, use, processing, storage, transportation, disposal and release and is not to be considered a warranty or quality specification. The information relates only to the specific material designated and may not be valid for such material used in combination with any other materials or in any process, unless specified in the text.

---

End of SDS
28.5 Ethyl Acetate Product Specifications

Celanese Chemicals

Sales Specification

1 of 1

**Ethyl Acetate, Urethane Grade**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethyl Acetate, wt.%(^1)</td>
<td>min.</td>
</tr>
<tr>
<td>Ethanol, wt.%</td>
<td>max.</td>
</tr>
<tr>
<td>Water, wt.%</td>
<td>max.</td>
</tr>
<tr>
<td>Color, Pt-Co Units</td>
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**References:**
1 By Difference – 100.0% minus (acid plus water plus impurities as determined by Gas Chromatography).

2 Product conforms to limit, but test is not routinely performed.

Test methods used for each specification analysis are available. Contact your Customer Service Representative to request copies.

Product Number: HCCG-070 UG  Revised: February 1996
Reviewed: April 2004  Supersedes: June 1988

This information is based on our present state of knowledge and is intended to provide general notes on our products and their uses. It should therefore not be construed as guaranteeing specific properties of the products described or their suitability for a particular application. Any existing industrial property rights must be observed. The quality of our products is guaranteed under our General Conditions of Sale.

Celanese Chemicals (North America)
1601 West LEU Freeway
Dallas, TX 75234
1-972-443-4000

Celanese Chemicals (Europe GmbH)
Frankfurter Straße 111
61476 Kronberg im Taunus
Deutschland / Germany
Tel: +49 (0) 69 305 16000

SS-070 UG  8/05  9073

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28.6 Project Statement

Ethanol to Ethyl Acetate

(Recommended by Bruce M. Vrana, DuPont and UPenn)

Ethyl acetate is used in a variety of applications, including as a solvent, because of its low toxicity. Key applications are nail polish remover, paints, adhesives, cleaning circuit boards, etc. Global sales exceed $4 billion per year and are growing faster than global GDP. Although the ethyl part of the molecule can come from either fermentation or synthetic ethanol (making it at least sometimes green), the acetate part of the molecule comes almost exclusively from synthetic acetic acid, made from methanol and carbon monoxide (decidedly not green, given the energy intensity and acute toxicity of CO).

Greenyug, LLC, a small, privately-held startup company based in Santa Barbara, has developed and is commercializing a new process that uses (fermentation) ethanol as the sole feedstock. Although the process will be much more sustainable than conventional ethyl acetate, coming 100% from renewable resources, Greenyug also claims that it will be cost competitive with or even more economical than petrochemical ethyl acetate, depending on the relative price of oil and ethanol.

Wild claims from startup companies, especially in the biotech arena, are commonplace, and usually do not translate into commercial success. Often, they seem like a ploy to get attention (and money) from venture capital firms or existing players in the industry. As a conventional manufacturer of ethyl acetate, your company has dismissed such claims in the past. However, the fact that in 2018 Greenyug is in the midst of actually building and starting up a commercial scale facility at ADMs corn processing plant in Columbus, NE caught your senior management off guard.

Although the ethanol feedstock comes from a fermentation plant, Greenyug is not doing any biotech. They have patent applications using heterogeneous catalysis to convert ethanol directly to ethyl acetate. Furthermore, their applications indicate they have reactive distillation technology to make ethyl acetate in a simple, low cost process. Reactive
distillation has recently received attention from the AIChE as part of its RAPID process intensification effort. And Greenyug has demonstrated the technology at a pilot plant in Pune, India. Unfortunately for you, all of that makes their claims a bit more credible.

A 9/5/18 local news report of the ribbon-cutting ceremony (last reference, including video) caused your CEO to take immediate action and commission your team to rapidly put together a process design for the Greenyug plant and to estimate their capital and operating cost. The key question is what green premium, if any, Greenyug will need to get on top of the market price of ethyl acetate to achieve a 15% IRR on their investment. And how does this premium vary with the prices of ethanol and oil? Under what circumstances can they compete economically with you (putting your company and your job at risk)?

Assume that the trade journals are correct and that Greenyug (through its subsidiary Prairie Catalytic LLC) is building a 50 kt plant. Assume that ADM will supply steam and other utilities at market prices. But otherwise, Greenyug (Prairie Catalytic) will be an independent company, responsible for its own investment, maintenance, operations, technical support, etc.

The overall main chemical reaction is: \[ 2\text{C}_2\text{H}_5\text{OH} \rightarrow \text{H}_3\text{COOC}_2\text{H}_5 + 2\text{H}_2 \]

This begs the question of what to do with the hydrogen coproduct. The patent applications indicate that it can be used to hydrogenate liquid coproducts such as butyraldehyde and 2-butanone (MEK). It seems likely that this will be needed to meet the typical purity spec of 99.8% min for ethyl acetate, which Greenyug must meet to sell into all markets. But there will still be an excess of hydrogen. Assume that excess hydrogen can be used on the site complex at a value of $1/lb (2019 dollars). If this is a crucial part of your economics, estimate a fair price to sell hydrogen to ADM as rigorously as possible and include it in your sensitivity analysis. You will also need to decide what to do with the other byproducts after they are separated from the main ethyl acetate product.

Obviously, your company and thus your group cannot have any contact with Greenyug at this time, since they are a potential competitor. Thus, you must base your design only
on what can be gleaned from public information, such as the references and any other published information you can find. You may not contact anyone affiliated with Greenyug, including academic partners at UCSB and elsewhere.

You will need to make many assumptions to complete your design, since the data you have is far from complete. State them explicitly in your report, so that management may understand the uncertainty in your design and economic projections in deciding whether Greenyug is a threat. Test your economics to reasonable ranges of your assumptions. If there are any possible show-stoppers (i.e., possible fatal flaws, if one assumption is incorrect that would make the design either technically infeasible or uneconomical), these need to be clearly communicated and understood before your management can decide on an action plan.

The plant design should be as environmentally friendly as possible, at a minimum meeting Federal and state emissions regulations. Recover and recycle process materials to the maximum economic extent. Also, energy consumption should be minimized, to the extent economically justified. The plant design must also be controllable and safe to operate. Be sure to consider how the plant will be started up in your design.

References
U. S. Patent Application US 2013/0197266 A1 (Gadewar et al., assigned to Greenyug)
28.7 ASPEN Process Simulation

28.7.1 Process Flowsheet

![Overall ASPEN Flowsheet](image-url)
28.7.2 Input File

; Input Summary created by Aspen Plus Rel. 36.0 at 13:40:38 Sun Apr 14, 2019
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  / 'APV100 INORGANIC' / 'APESV100 AP-EOS' / &
  'NISTV100 NIST-TRC' / NOASPENPCD

PROP-SOURCES 'APV100 PURE36' / 'APV100 AQUEOUS' / &
  'APV100 SOLIDS' / 'APV100 INORGANIC' / 'APESV100 AP-EOS' &
  / 'NISTV100 NIST-TRC'

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  ETHYLACE C4H8O2-3 /
  ACETA-01 C2H4O-1 /
  METHY-01 C4H8O-3 /
  N-BUT-01 C4H8O-1 /
  N-BUT-02 C4H10O-1 /
  2-BUT-01 C4H10O-2

HENRY-COMPS HC-1 HYDROGEN

SOLVE
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CHEMISTRY C-1
  PARAM
REAC-COMPS ETHANOL / ACETA-01 / HYDROGEN / ETHYLACE

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BLOCK R-100 IN=11 OUT=12
BLOCK C-102 IN=14 OUT=15 16 17
BLOCK E-103 IN=12 CH2OIN OUT=13 14 CH2OUT
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PROPERTIES NRTL HENRY-COMPS=HC-1
PROPERTIES UNIQUAC

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<tr>
<td>N-Butanol</td>
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<td>97.4</td>
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<td>Ethanol</td>
<td>0.85</td>
<td>97.4</td>
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40.00000000 69.91000000 0.0  
BPVAL 2-BUT-01 N-BUT-02 2.632300000 -644.8218000 0.0 0.0  &  
40.00000000 69.91000000 0.0  
BPVAL ETHANOL ACETA-01 -7.963400000 2209.547900 0.0 0.0  &  
10.00000000 77.70000000 0.0  
BPVAL ACETA-01 ETHANOL 1.226700000 -113.5067000 0.0 0.0  &  
10.00000000 77.70000000 0.0  
BPVAL N-BUT-02 ACETA-01 0.0 -83.82230000 0.0 0.0  &  
22.00000000 65.60000000 0.0  
BPVAL ACETA-01 N-BUT-02 95.45970000 0.0 0.0  &  
22.00000000 65.60000000 0.0  
BPVAL ETHANOL WATER 2.004600000 -728.9705000 0.0 0.0  &  
24.99000000 100.0000000 0.0  
BPVAL WATER ETHANOL 2.493600000 756.9477000 0.0 0.0  &  
24.99000000 100.0000000 0.0  
BPVAL ETHYLACE WATER 2.721400000 -1212.889200 0.0 0.0  &  
70.40000000 0.0  
BPVAL WATER ETHYLACE 2.053200000 531.0333000 0.0 0.0  &  
70.40000000 0.0  
BPVAL ACETA-01 WATER 12.276200000 -4345.301300 0.0 0.0  &  
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BPVAL WATER ACETA-01 4.639600000 1516.808600 0.0 0.0  &  
10.00000000 55.80000000 0.0  
BPVAL METHY-01 WATER 0.0 -311.2552000 0.0 0.0 73.30000000  &  
100.0000000 0.0  
BPVAL WATER METHY-01 0.0 -71.01930000 0.0 0.0 73.30000000  &  
100.0000000 0.0  
BPVAL N-BUT-01 WATER 0.0 -440.7517000 0.0 0.0 50.00000000  &  
93.10000000 0.0  
BPVAL WATER N-BUT-01 0.0 -26.12870000 0.0 0.0 50.00000000  &  
93.10000000 0.0  
BPVAL N-BUT-02 WATER 3.764400000 -1446.611300 0.0 0.0  &  
19.17000000 117.6000000 0.0  
BPVAL WATER N-BUT-02 -4.993400000 1569.050900 0.0 0.0  &  
19.17000000 117.6000000 0.0  
BPVAL 2-BUT-01 WATER -1.236100000 369.1626000 0.0 0.0  &  
25.00000000 100.0000000 0.0  
BPVAL WATER 2-BUT-01 .04820000000 -213.2224000 0.0 0.0  &  
25.00000000 100.0000000 0.0  

PROP-SET PS-1 TBUB SUBSTREAM=MIXED  
PROP-SET PS-2 KVL SUBSTREAM=MIXED
STREAM 1
   SUBSTREAM MIXED TEMP=35. PRES=1.
   MASS-FLOW ETHANOL 54.59 <ktonne/oper-year>

STREAM 2
   SUBSTREAM MIXED TEMP=35. PRES=20.
   MASS-FLOW ETHANOL 54.59 <ktonne/year>

STREAM 6
   SUBSTREAM MIXED TEMP=43. PRES=20. &
   MASS-FLOW=2.87 <ktonne/year>
   MOLE-FRAC HYDROGEN 0.42 / WATER 0.1 / ETHANOL 0.02 / &
   ETHYLACE 0.46

STREAM 16
   SUBSTREAM MIXED TEMP=98. PRES=2.

STREAM CH2OIN
   SUBSTREAM MIXED TEMP=90. <F> PRES=1. MASS-FLOW=46400.
   MOLE-FRAC WATER 1.

STREAM STEAMIN
   SUBSTREAM MIXED PRES=150. <psig> VFRAC=1. MASS-FLOW=320.
   MASS-FRAC WATER 1.

BLOCK MIXER MIXER
   PARAM PRES=4.

BLOCK SPILT FSPLIT
   FRAC 4 0.9

BLOCK S-100 SEP
   PARAM
   FRAC STREAM=WATER SUBSTREAM=MIXED COMPS=HYDROGEN WATER &
   ETHANOL ETHYLACE ACETA-01 METHY-01 N-BUT-01 N-BUT-02 &
   2-BUT-01 FRACS=0. 1. 0. 0. 0. 0. 0. 0.

BLOCK E-102 HEATX
   PARAM T-COLD=150. CALC-TYPE=DESIGN U-OPTION=PHASE &
   F-OPTION=CONSTANT CALC-METHOD=SHORTCUT
   FEEDS HOT=STEAMIN COLD=10
   OUTLETS-HOT STEAMOUT
   OUTLETS-COLD 11
   HOT-SIDE DP-OPTION=CONSTANT DPPARMOPT=NO
COLD-SIDE DP-OPTION=CONSTANT DPPARMOPT=NO
TQ-PARAM CURVE=YES

BLOCK E-103 HEATX
PARAM T-HOT=50. CALC-TYPE=DESIGN PRES-HOT=0. U-OPTION=PHASE & F-OPTION=CONSTANT CALC-METHOD=SHORTCUT
FEEDS HOT=12 COLD=CH2OIN
OUTLETS-HOT 13 V / 14 L
OUTLETS-COLD CH2OUT
HOT-SIDE DP-OPTION=CONSTANT DPPARMOPT=NO
COLD-SIDE DP-OPTION=CONSTANT DPPARMOPT=NO
TQ-PARAM CURVE=YES

BLOCK C-100 RADFRAC
PARAM NSTAGE=5 ALGORITHM=STANDARD INIT-OPTION=STANDARD & MAXOL=200 DAMPING=NONE
COL-CONFIG CONDENSER=NONE REBOILER=NONE
FEEDS 2 1 / 6 5 ON-STAGE
PRODUCTS 5 5 L / 3 1 V
P-SPEC 1 20.
COL-SPECS

BLOCK C-101 RADFRAC
SUBOBJECTS INTERNALS = CS-1 CS-2
PARAM NSTAGE=20 ALGORITHM=NONIDEAL INIT-OPTION=STANDARD & HYDRAULIC=NO MAXOL=200 TOLOL=0.001 NPHASE=2 DAMPING=NONE
PARAM2 STATIC-DP=YES
COL-CONFIG CONDENSER=PARTIAL-V CA-CONFIG=INT-1
FEEDS 5 12 ON-STAGE
PRODUCTS 6 1 V / 7 20 L
P-SPEC 1 20.
COL-SPECS DP-STAGE=0.1 <psi> MASS-B=51.7655 <ktonne/year> & MOLE-RR=1.6
REAC-STAGES 12 12 ETHYLACE
BLOCK-OPTION FREE-WATER=NO
REPORT NOHYDRAULIC
INTERNALS CS-1 STAGE1=2 STAGE2=11 P-UPDATE=NO
TRAY-SIZE 1 2 11 SIEVE
INTERNALS CS-2 STAGE1=12 STAGE2=19 P-UPDATE=NO
TRAY-SIZE 2 12 19 SIEVE

BLOCK C-102 RADFRAC
SUBOBJECTS INTERNALS = CS-1 CS-2
PARAM NSTAGE=20 ALGORITHM=NONIDEAL INIT-OPTION=STANDARD &
HYDRAULIC=NO MAXOL=200 TOLOL=0.001 DAMPING=NONE
PARAM2 STATIC-DP=YES
COL-CONFIG CONDENSER=PARTIAL-V-L CA-CONFIG=INT-1
FEEDS 14 10 ON-STAGE-LIQ
PRODUCTS 16 1 L / 17 20 L / 15 1 V
P-SPEC 1 2.
COL-SPECS MASS-RDV=0.00012958 MASS-D=50. <ktonne/year> &
   MOLE-RR=10.
SC-REFLUX
T-EST 1 98.
REPORT NOHYDRAULIC
INTERNALS CS-1 STAGE1=2 STAGE2=9 P-UPDATE=NO
TRAY-SIZE 1 2 9 SIEVE
INTERNALS CS-2 STAGE1=10 STAGE2=19 P-UPDATE=NO
TRAY-SIZE 2 10 19 SIEVE

BLOCK R-100 RPLUG
   PARAM TYPE=ADIABATIC LENGTH=5. DIAM=1.
   REACTIONS RXN-IDS=HYDROGEN

BLOCK P-100 PUMP
   PARAM PRES=20.

DESIGN-SPEC PURITY
   DEFINE PURITY MASS-FRAC STREAM=7 SUBSTREAM=MIXED &
      COMPONENT=ETHYLACE
   SPEC "PURITY" TO "0.985"
   TOL-SPEC "0.002"
   VARY BLOCK-VAR BLOCK=C-101 VARIABLE=MOLE-RR &
      SENTENCE=COL-SPECS
   LIMITS "0.5" "2"

DESIGN-SPEC PURITY2
   DEFINE PURITY2 MASS-FRAC STREAM=16 SUBSTREAM=MIXED &
      COMPONENT=ETHYLACE
   SPEC "PURITY2" TO "0.998"
   TOL-SPEC "0.0001"
   VARY BLOCK-VAR BLOCK=C-102 VARIABLE=MOLE-RR &
      SENTENCE=COL-SPECS
   LIMITS "1" "100"

EO-CONV-OPTI

SENSITIVITY CONDENSE
DEFINE TEMP STREAM=VAR STREAM=16 SUBSTREAM=MIXED & VARIABLE=TEMP UOM="F"
DEFINE MASSFRAC MASS-FRAC STREAM=16 SUBSTREAM=MIXED & COMPONENT=ETHYLACE
TABULATE 1 "TEMP"
TABULATE 2 "MASSFRAC"
VARY BLOCK=VAR BLOCK=C-102 VARIABLE=MASS-RDV & SENTENCE=COL-SPECS
RANGE OPT-LIST=RANGE LOWER="0.00005" UPPER="0.0003" & NPOINT="1000"

SENSITIVITY HX1-SENS
DEFINE AREA BLOCK=VAR BLOCK=E-102 VARIABLE=CALC-AREA & SENTENCE=RESULTS UOM="sqft"
TABULATE 1 "AREA"
VARY STREAM=VAR STREAM=STEAMIN SUBSTREAM=MIXED & VARIABLE=MASS-FLOW UOM="kg/hr"
RANGE OPT-LIST=RANGE LOWER="320" UPPER="600" INCR="1"

SENSITIVITY HX2-SENS
DEFINE AREA BLOCK=VAR BLOCK=E-103 VARIABLE=CALC-AREA & SENTENCE=RESULTS UOM="sqft"
DEFINE TEMP STREAM=VAR STREAM=CH2OOUT SUBSTREAM=MIXED & VARIABLE=TEMP UOM="C"
TABULATE 2 "AREA"
TABULATE 1 "TEMP"
VARY STREAM=VAR STREAM=CH2OIN SUBSTREAM=MIXED & VARIABLE=MASS-FLOW UOM="kg/hr"
RANGE OPT-LIST=RANGE LOWER="10000" UPPER="100000" INCR="100"

CONV-OPTIONS
PARAM TEAR-METHOD=WEGSTEIN TOL=0.01 COMB-METHOD=BROYDEN
WEGSTEIN MAXIT=9999

TEAR
TEAR 6 0.0001

STREAM-REPOR MOLEFLOW

PROPERTY-REP PCES NOPARAM-PLUS

REACTIONS ETHYLACE REAC-DIST
REAC-DATA 1 EQUIL
REAC-DATA 2 EQUIL
REAC-DATA 3 CONV  
K-STOIC 1 A=16.5 B=-9136.4  
K-STOIC 2 A=-4.79 B=4386.  
STOIC 1 ETHANOL -1. / HYDROGEN 1. / ACETA-01 1.  
STOIC 2 ACETA-01 -1. / ETHANOL -1. / HYDROGEN 1. / & ETHYLACE 1.  
STOIC 3 ACETA-01 -2. / HYDROGEN -1. / WATER 1. / & METHY-01 0.5 / N-BUT-01 0.5  
CONV 3 CONV A=0.2 KEY-CID=ACETA-01  

REACTIONS HYDROGEN POWERLAW  
REAC-DATA 1 PHASE=V CBASIS=PARTIALPRES  
REAC-DATA 2 PHASE=V CBASIS=PARTIALPRES  
RATE-CON 1 PRE-EXP=220. ACT-ENERGY=7730.  
RATE-CON 2 PRE-EXP=220. ACT-ENERGY=7730.  
STOIC 1 MIXED METHY-01 -1. / HYDROGEN -1. / 2-BUT-01 1.  
STOIC 2 MIXED HYDROGEN -1. / N-BUT-01 -1. / N-BUT-02 1.  
POWLAW-EXP 1 MIXED METHY-01 1. / MIXED HYDROGEN -0.5  
POWLAW-EXP 2 MIXED HYDROGEN -0.5 / MIXED N-BUT-01 1.  

PROP-TABLE PURE-1 PROPS  
IN-UNITS MET PRESSURE=bar TEMPERATURE=F DELTA-T=C PDROP=bar & INVERSE-PRES='1/bar' SHORT-LENGTH=mm  
ANALYSIS ANAL-TYPE=PURE PURE-PROP='PL' PURE-PHASES= L  
MOLE-FLOW ETHYLACE 1  
PROPERTIES NRTL HENRY-COMPS=HC-1 FREE-WATER=STEAM-TA & SOLU-WATER=3 TRUE-COMPS=YES  
VARY TEMP  
RANGE VARVALUE=RANGE LOWER=0 UPPER=300. NPOINT=200  
VARY PRES  
RANGE LIST=1.013250000  
PARAM  

PROP-TABLE MIX-1 FLASHCURVE  
IN-UNITS MET PRESSURE=bar TEMPERATURE=F DELTA-T=C PDROP=bar & INVERSE-PRES='1/bar' SHORT-LENGTH=mm  
MOLE-FLOW WATER 0.5 / N-BUT-02 0.25 / 2-BUT-01 0.25  
VARY PRES  
RANGE VARVALUE=LIST LIST=2.25  
VARY TEMP  
RANGE VARVALUE=RANGE LOWER=0 UPPER=250. NPOINT=100  
PARAM  
TABULATE PROPERTIES=PS-1
PROP-TABLE MIX-2 FLASHCURVE
IN-UNITS MET PRESSURE=bar TEMPERATURE=F DELTA-T=C PDROP=bar &
INVERSE-PRES='1/bar' SHORT-LENGTH=mm
MOLE-FLOW HYDROGEN 0.66 / WATER 0.005 / ETHYLACE 0.325 / &
N-BUT-02 0.0025 / 2-BUT-01 0.0025
VARY PRES
RANGE VARVALUE=LIST LIST=2.125
VARY TEMP
RANGE VARVALUE=RANGE LOWER=190. UPPER=210. NPOINT=10
PARAM
TABULATE PROPERTIES=PS-2

DISABLE
SENSITIVITY CONDENSE
DESIGN-SPEC PURITY PURITY2
;
;
;
;
;
28.7.3 Block Reports

BLOCK: C-100  MODEL: RADFRAC
--

INLETS - 2  STAGE 1
6  STAGE 5
OUTLETS - 3  STAGE 1
5  STAGE 5
PROPERTY OPTION SET:  NRTL  RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:  HC-1

*** MASS AND ENERGY BALANCE ***

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<th>IN</th>
<th>OUT</th>
<th>RELATIVE DIFF.</th>
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<td>MOLE(KMOL/HR)</td>
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<td>MASS(KG/HR)</td>
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<td>ENTHALPY(CAL/SEC)</td>
<td>-0.290902E+07</td>
<td>-0.290902E+07</td>
<td>0.891480E-07</td>
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*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E  0.00000  KG/HR
PRODUCT STREAMS CO2E  0.00000  KG/HR
NET STREAMS CO2E PRODUCTION  0.00000  KG/HR
UTILITIES CO2E PRODUCTION  0.00000  KG/HR
TOTAL CO2E PRODUCTION  0.00000  KG/HR

**********************
****  INPUT DATA  ****
**********************

**** INPUT PARAMETERS ****

NUMBER OF STAGES  5
ALGORITHM OPTION  STANDARD
ABSORBER OPTION  NO
INITIALIZATION OPTION  STANDARD
HYDRAULIC PARAMETER CALCULATIONS  NO
INSIDE LOOP CONVERGENCE METHOD  BROYDEN
DESIGN SPECIFICATION METHOD  NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS  200
MAXIMUM NO. OF INSIDE LOOP ITERATIONS  10
MAXIMUM NUMBER OF FLASH ITERATIONS  30
FLASH TOLERANCE  0.00010000
OUTSIDE LOOP CONVERGENCE TOLERANCE  0.00010000

**** COL-SPECS ****
MOLAR VAPOR DIST / TOTAL DIST                            1.00000
CONDENSER DUTY (W/O SUBCOOL)   CAL/SEC                   0.0
REBOILER DUTY                  CAL/SEC                   0.0

**** PROFILES ****

P-SPEC    STAGE    1  PRES, BAR                      20.0000

*******************

**** RESULTS ****

*******************

*** COMPONENT SPLIT FRACTIONS ***

OUTLET STREAMS

--------------

COMPONENT:
HYDROGEN  .99289       .71106E-02
WATER      .87420E-08   1.0000
ETHANOL    .86985E-02   .99130
ETHYLACE   .96532E-06   1.0000
ACETALDEHYDE .37903E-06 .99996
 METHYLACETATE .28853E-06 1.0000
  N-BUTYLACETATE .11874E-06 1.0000

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE          C                        39.5848
BOTTOM STAGE TEMPERATURE       C                        87.6679
TOP STAGE LIQUID FLOW          KMOL/HR                    136.211
BOTTOM STAGE LIQUID FLOW       KMOL/HR                    157.270
TOP STAGE VAPOR FLOW           KMOL/HR                    134.164
BOILUP VAPOR FLOW              KMOL/HR                    146.605
CONDENSER DUTY (W/O SUBCOOL)   CAL/SEC                   0.0
REBOILER DUTY                  CAL/SEC                   0.0

**** MAXIMUM FINAL RELATIVE ERRORS ****

DEW POINT     0.96802E-06  STAGE= 3
BUBBLE POINT  0.98321E-04  STAGE= 3
COMPONENT MASS BALANCE          0.36697E-05  STAGE= 2  COMP=HYDROGEN
ENERGY BALANCE         0.12380E-04  STAGE= 2
**NOTE** REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

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<tr>
<th>STAGE</th>
<th>TEMPERATURE</th>
<th>PRESSURE</th>
<th>LIQUID ENTHALPY</th>
<th>VAPOR ENTHALPY</th>
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**** MASS-Y-PROFILE ****
STAGE HYDROGEN WATER ETHANOL ETHYLACE ACETA-01
1 0.83185 0.40730E-08 0.16813 0.24403E-05 0.24262E-04
2 0.78461 0.41013E-06 0.21475 0.68539E-04 0.57479E-03
4 0.47486 0.86770E-03 0.46382 0.15915E-01 0.44525E-01
5 0.30441 0.12568E-01 0.47645 0.11005 0.96375E-01

**** MASS-Y-PROFILE ****
STAGE METHY-01 N-BUT-01
1 0.92831E-09 0.95623E-10
2 0.33605E-07 0.44057E-08
4 0.12992E-04 0.25705E-05
5 0.11375E-03 0.25791E-04

BLOCK: C-101 MODEL: RADFRAC
-----------------------------------
INLETS - 5 STAGE 12
OUTLETS - 6 STAGE 1
7 STAGE 20
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1

*** MASS AND ENERGY BALANCE ***
IN OUT GENERATION RELATIVE DIFF.
TOTAL BALANCE
MOLE(KMOL/HR ) 157.270 224.271 67.0001 -0.521458E-05
MASS(KG/HR ) 7349.22 7349.29 -0.937569E-05
ENTHALPY(CAL/SEC ) -0.289446E+07 -0.238788E+07 -0.175017

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 0.00000 KG/HR
PRODUCT STREAMS CO2E 0.00000 KG/HR
NET STREAMS CO2E PRODUCTION 0.00000 KG/HR
UTILITIES CO2E PRODUCTION 0.00000 KG/HR
TOTAL CO2E PRODUCTION 0.00000 KG/HR

******************************
**** INPUT DATA ****
******************************

**** INPUT PARAMETERS ****
NUMBER OF STAGES                                        20
ALGORITHM OPTION                                      NONIDEAL
INITIALIZATION OPTION                                 STANDARD
HYDRAULIC PARAMETER CALCULATIONS                      NO
INSIDE LOOP CONVERGENCE METHOD                        NEWTON
DESIGN SPECIFICATION METHOD                           NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                 200
MAXIMUM NO. OF INSIDE LOOP ITERATIONS                  10
MAXIMUM NUMBER OF FLASH ITERATIONS                     30
FLASH TOLERANCE                                        0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE                     0.00100000

****   COL-SPECS   ****

MOLAR VAPOR DIST / TOTAL DIST                          1.00000
MOLAR REFLUX RATIO                                      1.60000
MASS BOTTOMS RATE                                      KG/HR  5,905.26

**** REAC-STAGES SPECIFICATIONS ****

STAGE TO STAGE                              REACTIONS/CHEMISTRY ID
12        12                        ETHYLACE

***** REACTION PARAGRAPH ETHYLACE*****

**** REACTION PARAMETERS ****

RXN NO. TYPE   PHASE  CONC.       TEMP APP TO EQUIL  CONVERSION
              BASIS  C                      
1      EQUILIBRIUM  LIQUID  MOLE-GAMMA  0.0000
2      EQUILIBRIUM  LIQUID  MOLE-GAMMA  0.0000
3      CONVERSION                SIMULTANEOUS

** STOICHIOMETRIC COEFFICIENTS **

RXN NO.   HYDROGEN   WATER   ETHANOL   ETHYLACE     ACETA-01
1       1.000       0.000   -1.000      0.000      1.000
2       1.000       0.000   -1.000      1.000     -1.000
3      -1.000       1.000      0.000      0.000    -2.000

RXN NO.   METHY-01   N-BUT-01
1       0.000       0.000
2       0.000       0.000
3      0.50000      0.50000
** COEFFICIENTS OF EQUILIBRIUM CONSTANT EXPRESSION **

RXN NO.   A     B     C     D
1   16.500  -9136.4  0.0000  0.0000
2   -4.7900  4386.0  0.0000  0.0000

** COEFFICIENTS OF CONVERSION EXPRESSION **

RXN NO. COMPONENT ID   A     B     C     D
3   ACETA-01  0.20000  0.0000  0.0000  0.0000

**** PROFILES ****

P-SPEC STAGE 1 PRES, BAR 20.0000

*******************

**** RESULTS ****

*******************

*** COMPONENT SPLIT FRACTIONS ***

OUTLET STREAMS

--------------

6    7

COMPONENT:

HYDROGEN  1.0000  0.0000
WATER     .89167  .10833
ETHANOL   .97876  .21237E-01
ETHYLACE  .12290  .87710
ACETA-01  .99998  .16777E-04
METHY-01  .27631E-01  .97237
N-BUT-01  .70624E-02  .99294

*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE     C  97.1078
BOTTOM STAGE TEMPERATURE  C  207.194
TOP STAGE LIQUID FLOW     KMOL/HR  250.009
BOTTOM STAGE LIQUID FLOW  KMOL/HR  68.0140
TOP STAGE VAPOR FLOW      KMOL/HR  156.256
BOILUP VAPOR FLOW         KMOL/HR  912.593
MOLAR REFLUX RATIO        1.60000
MOLAR BOILUP RATIO        13.4177
CONDENSER DUTY (W/O SUBCOOL)  CAL/SEC  -673,482.
REBOILER DUTY             CAL/SEC  1,180,090.
*** MAXIMUM FINAL RELATIVE ERRORS ***

DEW POINT  0.16623E-04  STAGE= 16
BUBBLE POINT  0.30014E-04  STAGE= 16
COMPONENT MASS BALANCE  0.18807E-07  STAGE= 20  COMP=WATER
ENERGY BALANCE  0.62004E-05  STAGE= 20

*** PROFILES ***

**NOTE** REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

**ENTHALPY**

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**STAGE FLOW RATE FEED RATE PRODUCT RATE**

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1 250.0 156.3 156.2569
2 323.5 406.3
11 331.1 485.6
12 635.5 487.3 157.2696
13 716.7 567.4
18 959.2 856.3
19 980.6 891.2
20 68.01 912.6 68.0139

*** MASS FLOW PROFILES ***

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**** K-VALUES ****

**** RATES OF GENERATION ****

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**** K-VALUES ****

**** RATES OF GENERATION ****

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**** MASS-Y-PROFILE ****
*** DEFINITIONS ***

MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
QR = QV*SQRT(RHOV/(RHOL-RHOV))
F FACTOR = QV*SQRT(RHOV)
WHERE:
SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE
SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE
ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
MV IS THE MASS FLOW OF VAPOR TO THE STAGE
RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE
QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE

TEMPERATURE
C
STAGE LIQUID FROM VAPOR TO
  1  97.108  163.16
  2  163.16  167.74
 11  168.54  168.70
 12  168.70  185.42
 13  185.42  187.86
 18  204.92  206.38
 19  206.38  207.19
 20  207.19  207.19

MASS FLOW VOLUME FLOW MOLECULAR WEIGHT
KG/HR L/MIN
STAGE LIQUID FROM VAPOR TO LIQUID FROM VAPOR TO LIQUID FROM VAPOR TO
<table>
<thead>
<tr>
<th>Stage</th>
<th>Density (GM/CC)</th>
<th>Viscosity (CP)</th>
<th>Surface Tension (DYNE/CM)</th>
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DENSITY  VISCOSITY  SURFACE TENSION
GM/CC  CP  DYNE/CM
STAGE LIQUID FROM VAPOR TO LIQUID FROM VAPOR TO LIQUID FROM
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<tr>
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<th>Flow Param</th>
<th>QR</th>
<th>Reduced F-Factor</th>
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MARANGONI INDEX  FLOW PARAM  QR  REDUCED F-FACTOR
STAGE  DYNE/CM  L/MIN  (GM-L)**.5/MIN
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************************************
***** TRAY SIZING CALCULATIONS *****
************************************

******************************
*** SECTION 1 ***
******************************

STARTING STAGE NUMBER  2
ENDING STAGE NUMBER  11
FLOODING CALCULATION METHOD  GLITSCH6
DESIGN PARAMETERS
-------------------
PEAK CAPACITY FACTOR                                      1.00000
SYSTEM FOAMING FACTOR                                     1.00000
FLOODING FACTOR                                           0.80000
MINIMUM COLUMN DIAMETER METER                             0.30480
MINIMUM DC AREA/COLUMN AREA                                0.100000
HOLE AREA/ACTIVE AREA                                      0.100000

TRAY SPECIFICATIONS
-------------------
TRAY TYPE                                                 SIEVE
NUMBER OF PASSES                                         1
TRAY SPACING METER                                        0.60960

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER                                11
COLUMN DIAMETER METER                                      0.80845
DC AREA/COLUMN AREA                                        0.100000
DOWNCOMER VELOCITY M/SEC                                  0.11101
FLOW PATH LENGTH METER                                    0.55544
SIDE DOWNCOMER WIDTH METER                                0.12650
SIDE WEIR LENGTH METER                                    0.58743
CENTER DOWNCOMER WIDTH METER                              0.0
CENTER WEIR LENGTH METER                                   MISSING
OFF-CENTER DOWNCOMER WIDTH METER                          0.0
OFF-CENTER SHORT WEIR LENGTH METER                        0.0
OFF-CENTER LONG WEIR LENGTH METER                         0.0
TRAY CENTER TO OCDC CENTER METER                           0.0

**** SIZING PROFILES ****

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### HEIGHT DC REL TR LIQ REL FRA APPR TO STAGE OVER WEIR FROTH DENS FROTH DENS SYS LIMIT METER

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### DESIGN PARAMETERS

- **Peak Capacity Factor**: 1.0000
- **System Foaming Factor**: 1.0000
FLOODING FACTOR  0.80000
MINIMUM COLUMN DIAMETER  METER  0.30480
MINIMUM DC AREA/COLUMN AREA  0.100000
HOLE AREA/ACTIVE AREA  0.100000

TRAY SPECIFICATIONS

---
TRAY TYPE  SIEVE
NUMBER OF PASSES  1
TRAY SPACING  METER  0.60960

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER  19
COLUMN DIAMETER  METER  1.83112
DC AREA/COLUMN AREA  0.12541
DOWNCOMER VELOCITY  M/SEC  0.11782
FLOW PATH LENGTH  METER  1.16070
SIDE DOWNCOMER WIDTH  METER  0.33521
SIDE WEIR LENGTH  METER  1.41626
CENTER DOWNCOMER WIDTH  METER  0.0
CENTER WEIR LENGTH  METER  MISSING
OFF-CENTER DOWNCOMER WIDTH  METER  0.0
OFF-CENTER SHORT WEIR LENGTH  METER  MISSING
OFF-CENTER LONG WEIR LENGTH  METER  MISSING
TRAY CENTER TO OCDC CENTER  METER  0.0

**** SIZING PROFILES ****

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**** ADDITIONAL SIZING PROFILES ****

FLOODING  DC BACKUP/
STAGE FACTOR  PRES. DROP  DC BACKUP (TSPC+WHT)
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BLOCK: C-102  MODEL: RADFRAC

-----------------------------
INLETS - 14 STAGE 10
OUTLETS - 15 STAGE 1
  16 STAGE 1
  17 STAGE 20
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1

*** MASS AND ENERGY BALANCE ***

IN         OUT        RELATIVE DIFF.
TOTAL BALANCE
MOLE(KMOL/HR ) 65.9665 65.9665 0.00000
MASS(KG/HR )  5784.83 5784.83 -0.199470E-08
ENTHALPY(CAL/SEC) -0.206704E+07 -0.207431E+07 0.350385E-02

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E 0.00000 KG/HR
PRODUCT STREAMS CO2E 0.00000 KG/HR
NET STREAMS CO2E PRODUCTION 0.00000 KG/HR
UTILITIES CO2E PRODUCTION 0.00000 KG/HR
TOTAL CO2E PRODUCTION 0.00000 KG/HR
***********************
****  INPUT DATA  ****
***********************

****  INPUT PARAMETERS  ****

NUMBER OF STAGES                                        20
ALGORITHM OPTION                                      NONIDEAL
ABSORBER OPTION                                      NO
INITIALIZATION OPTION                                 STANDARD
HYDRAULIC PARAMETER CALCULATIONS                      NO
INSIDE LOOP CONVERGENCE METHOD                        BROYDEN
DESIGN SPECIFICATION METHOD                           NESTED
MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                 200
MAXIMUM NO. OF INSIDE LOOP ITERATIONS                   10
MAXIMUM NUMBER OF FLASH ITERATIONS                      30
FLASH TOLERANCE                                      0.000100000
OUTSIDE LOOP CONVERGENCE TOLERANCE                       0.00100000

****  COL-SPECS  ****

MOLAR REFLUX RATIO                                      10.0000
MASS VAPOR DIST / TOTAL DIST                              0.00012958
MASS DISTILLATE RATE                                     5,703.86

****  PROFILES  ****

P-SPEC STAGE  1  PRES, BAR    2.00000
TEMP-EST STAGE  1  TEMP, C     98.0000

***********************
****  RESULTS  ****
***********************

***  COMPONENT SPLIT FRACTIONS  ***

OUTLET STREAMS

------------------------------------------------
15   16   17
COMPONENT:
HYDROGEN   .54790   .45210   0.0000
WATER       .29235E-03  .99971  .62161E-07
ETHANOL     .24163E-03  .99976  .35165E-06

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*** SUMMARY OF KEY RESULTS ***

TOP STAGE TEMPERATURE C  38.9962
BOTTOM STAGE TEMPERATURE C  128.444
TOP STAGE LIQUID FLOW KMOL/HR  648.985
BOTTOM STAGE LIQUID FLOW KMOL/HR  1.06801
TOP STAGE VAPOR FLOW KMOL/HR  0.060399
BOILUP VAPOR FLOW KMOL/HR  841.130
MOLAR REFLUX RATIO  10.0000
MOLAR BOILUP RATIO  787.569
CONDENSER DUTY (W/O SUBCOOL) CAL/SEC  -1,995,670.
REBOILER DUTY  CAL/SEC  1,988,610.

**** MAXIMUM FINAL RELATIVE ERRORS ****

DEW POINT  0.22234E-02  STAGE= 1
BUBBLE POINT  0.30890E-01  STAGE= 1
COMPONENT MASS BALANCE  0.47654E-06  STAGE= 10  COMP=HYDROGEN
ENERGY BALANCE  0.14746E-02  STAGE= 1

**** PROFILES ****

**NOTE** REPORTED VALUES FOR STAGE LIQUID AND VAPOR RATES ARE THE FLOWS FROM THE STAGE INCLUDING ANY SIDE PRODUCT.

ENTHALPY
STAGE TEMPERATURE PRESSURE CAL/MOL HEAT DUTY
C  BAR  LIQUID  VAPOR  CAL/SEC

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**** MASS FLOW PROFILES ****

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**** MOLE-X-PROFILE ****

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**MOLE-Y-PROFILE**

**STAGE**

**HYDROGEN**

**WATER**

**ETHANOL**

**ETHYLACE**

**ACETA-01**

1.0.88104 0.33618E-10 0.45470E-09 0.11844 0.12518E-05
2.0.75169E-03 0.10708E-09 0.17524E-02 0.99642 0.13044E-05
9.0.10118E-03 0.12013E-10 0.20029E-03 0.99072 0.10777E-06
10.0.10124E-03 0.11940E-10 0.19914E-03 0.98759 0.10783E-06
11.0.11848E-06 0.50272E-11 0.86569E-04 0.98329 0.21173E-07
12.0.13904E-09 0.21186E-11 0.37817E-04 0.97683 0.41591E-08
19.0.51060E-30 0.49832E-14 0.18454E-06 0.56697 0.43640E-13
20.0.54828E-33 0.16337E-14 0.87418E-07 0.30269 0.62394E-14

**K-VALUES**

**STAGE**

**HYDROGEN**

**WATER**

**ETHANOL**

**ETHYLACE**

**ACETA-01**

1.1347.0 0.31361 0.25859 0.11859 0.96443
2.861.32 2.3791 2.3269 0.99869 5.0973
9.857.09 2.3792 2.3117 1.0038 5.1032
10.855.46 2.3777 2.3031 1.0053 5.0985
11.853.16 2.3756 2.2920 1.0076 5.0967
12.849.93 2.3721 2.2756 1.0107 5.0927
19.932.90 3.0532 2.1119 1.8743 7.0038
20.969.74 4.0415 2.3344 2.4973 8.7357

**K-VALUES**

**STAGE**

**HYDROGEN**

**WATER**

**ETHANOL**

**ETHYLACE**

**ACETA-01**

1.0.24490E-01 0.56818E-01
2.0.47184 0.70641
9.0.45687 0.70446
10.0.45080 0.70248
11.0.44201 0.70111
12.0.42975 0.69892
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**** MASS-Y-PROFILE ****

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**** MASS-Y-PROFILE ****

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19  0.93040E-01  0.29815
20  0.26683       0.39281

*****************************************************************************
***** HYDRAULIC PARAMETERS *****
*****************************************************************************

*** DEFINITIONS ***

MARANGONI INDEX = SIGMA - SIGMATO
FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
QR = QV*SQRT(RHOV/((RHOL-RHOV))
F FACTOR = QV*SQRT(RHOV)

WHERE:
SIGMA IS THE SURFACE TENSION OF LIQUID FROM THE STAGE
SIGMATO IS THE SURFACE TENSION OF LIQUID TO THE STAGE
ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
MV IS THE MASS FLOW OF VAPOR TO THE STAGE
RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE
QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE

TEMPERATURE
C
STAGE LIQUID FROM VAPOR TO
1  38.996     99.350
2  99.350     99.398
9  99.526     99.579
10 99.579     99.653
11 99.653     99.754
12 99.754     99.904
19 115.94     128.44
20 128.44     128.44

MASS FLOW VOLUME FLOW MOLECULAR WEIGHT
KG/HR L/MIN
STAGE LIQUID FROM VAPOR TO LIQUID FROM VAPOR TO LIQUID FROM VAPOR TO
1  62787.     62788.   1190.6  0.18425E+06 87.959   87.953
2  78974.     84678.   1648.3  0.24826E+06 88.053   88.042
9  78734.     84438.   1645.4  0.24802E+06 87.922   87.920
10 86258.     86177.   1803.6  0.25332E+06 87.857   87.870
11 86085.     86004.   1801.3  0.25314E+06 87.768   87.781
12 85826.     85745.   1797.8  0.25286E+06 87.637   87.650
19 65988.     65907.   1511.9  0.23404E+06 78.352   78.356

351
DENSITY  VISCOITY  SURFACE TENSION
GM/CC    CP       DYNE/CM
STAGE LIQUID FROM VAPOR TO  LIQUID FROM  VAPOR TO  LIQUID FROM
1  0.87896      0.56797E-02  0.36857      0.95485E-02  21.157
2  0.79855      0.56848E-02  0.20556      0.95467E-02  14.045
9  0.79750      0.56741E-02  0.20661      0.95473E-02  14.035
10 0.79708      0.56698E-02  0.20712      0.95475E-02  14.034
11 0.79650      0.56625E-02  0.20778      0.95481E-02  14.031
12 0.79566      0.56518E-02  0.20876      0.95492E-02  14.028
19 0.72742      0.46934E-02  0.26276      0.99306E-02  13.829
20 0.70013      0.56518E-02  0.20712      0.95492E-02  14.028

MARANGONI INDEX   FLOW PARAM  QR   REDUCED F-FACTOR
STAGE  DYNE/CM L/MIN (GM-L)**.5/MIN
1  0.80385E-01  14859.  0.43910E+06
2  -7.1120       0.78690E-01  21021.  0.59192E+06
9  -65137E-03    0.78652E-01  20995.  0.59080E+06
10 -36636E-02    0.84419E-01  21441.  0.60319E+06
11 -39892E-02    0.84395E-01  21420.  0.60237E+06
12 -34278E-02    0.84360E-01  21387.  0.60113E+06
19 -.15010       0.80423E-01  18860.  0.50704E+06
20 -.35861       0.0000      0.0000

******************************
***** TRAY SIZING CALCULATIONS *****
******************************

*** SECTION  1 ***

STARTING STAGE NUMBER 2
ENDING STAGE NUMBER 9
FLOODING CALCULATION METHOD GLITSCH6

DESIGN PARAMETERS

------------------------
PEAK CAPACITY FACTOR  1.00000
SYSTEM FOAMING FACTOR  1.00000
FLOODING FACTOR  0.80000
MINIMUM COLUMN DIAMETER METER  0.30480
MINIMUM DC AREA/COLUMN AREA  0.100000
HOLE AREA/ACTIVE AREA  0.100000
TRAY SPECIFICATIONS
-------------------
TRAY TYPE          SIEVE
NUMBER OF PASSES  1
TRAY SPACING       METER  0.60960

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER  3
COLUMN DIAMETER          METER  2.44142
DC AREA/COLUMN AREA      0.100000
DOWNCOMER VELOCITY       M/SEC  0.058705
FLOW PATH LENGTH         METER  1.67738
SIDE DOWNCOMER WIDTH     METER  0.38202
SIDE WEIR LENGTH         METER  1.77397
CENTER DOWNCOMER WIDTH   METER  0.0
CENTER WEIR LENGTH       METER  MISSING
OFF-CENTER DOWNCOMER WIDTH METER  0.0
OFF-CENTER SHORT WEIR LENGTH METER  MISSING
OFF-CENTER LONG WEIR LENGTH METER  MISSING
TRAY CENTER TO OCDC CENTER METER  0.0

***** SIZING PROFILES *****

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***** ADDITIONAL SIZING PROFILES *****

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**HEIGHT   DC REL   TR LIQ. REL   FRA APPR TO:**

STAGE OVER WEIR    FROTH DENS    FROTH DENS    SYS LIMIT
METER

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*** SECTION 2 ***

***************

STARTING STAGE NUMBER 10
ENDING STAGE NUMBER 19
FLOODING CALCULATION METHOD GLITSCH6

DESIGN PARAMETERS

-------------
PEAK CAPACITY FACTOR 1.00000
SYSTEM FOAMING FACTOR 1.00000
FLOODING FACTOR 0.80000
MINIMUM COLUMN DIAMETER METER 0.30480
MINIMUM DC AREA/COLUMN AREA 0.100000
HOLE AREA/ACTIVE AREA 0.100000

TRAY SPECIFICATIONS

-------------
TRAY TYPE SIEVE
NUMBER OF PASSES 1
TRAY SPACING METER 0.60960

***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

STAGE WITH MAXIMUM DIAMETER 10
COLUMN DIAMETER METER 2.48218
DC AREA/COLUMN AREA                                       0.100000
DOWNCOMER VELOCITY              M/SEC         0.062120
FLOW PATH LENGTH               METER         1.70538
SIDE DOWNCOMER WIDTH            METER         0.38840
SIDE WEIR LENGTH                METER         1.80358
CENTER DOWNCOMER WIDTH          METER         0.0
CENTER WEIR LENGTH              METER         MISSING
OFF-CENTER DOWNCOMER WIDTH      METER         0.0
OFF-CENTER SHORT WEIR LENGTH    METER         MISSING
OFF-CENTER LONG WEIR LENGTH     METER         MISSING
TRAY CENTER TO OCDC CENTER      METER         0.0

**** SIZING PROFILES ****

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<thead>
<tr>
<th>STAGE</th>
<th>DIAMETER</th>
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<th>ACTIVE AREA</th>
<th>SIDE DC AREA</th>
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**** ADDITIONAL SIZING PROFILES ****

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HEIGHT   DC REL   TR LIQ REL   FRA APPR TO
STAGE OVER WEIR   FROTH DENS  FROTH DENS  SYS LIMIT
METER
10  0.1591  0.6075  0.1821       53.93
11  0.1588  0.6075  0.1823       53.86
12  0.1584  0.6075  0.1824       53.77
13  0.1578  0.6075  0.1827       53.62
14  0.1569  0.6075  0.1831       53.40
15  0.1553  0.6074  0.1838       53.02
16  0.1526  0.6074  0.1851       52.35
17  0.1468  0.6072  0.1878       50.95
18  0.1358  0.6069  0.1939       48.25
19  0.1275  0.6062  0.1997       46.36

BLOCK:  E-102  MODEL:  HEATX
---------------------------------------------
HOT SIDE:
---------
INLET STREAM:             STEAMIN
OUTLET STREAM:            STEAMOUT
PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:        HC-1
COLD SIDE:
---------
INLET STREAM:             10
OUTLET STREAM:            11
PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:        HC-1

***  MASS AND ENERGY BALANCE  ***
IN              OUT        RELATIVE DIFF.
TOTAL BALANCE
MOLE(KMOL/HR )            98.1805         98.1805         0.00000
MASS(KG/HR   )          6239.25         6239.25         0.00000
ENTHALPY(CAL/SEC ) -0.221674E+07   -0.221674E+07     0.00000

***  CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E             0.00000      KG/HR
PRODUCT STREAMS CO2E          0.00000      KG/HR
NET STREAMS CO2E PRODUCTION  0.00000      KG/HR
UTILITIES CO2E PRODUCTION    0.00000      KG/HR
TOTAL CO2E PRODUCTION         0.00000      KG/HR

***  INPUT DATA  ***
FLASH SPECS FOR HOT SIDE:
TWO PHASE FLASH
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.00010000

FLASH SPECS FOR COLD SIDE:
TWO PHASE FLASH
MAXIMUM NO. ITERATIONS 30
CONVERGENCE TOLERANCE 0.00010000

FLOW DIRECTION AND SPECIFICATION:
COUNTERCURRENT HEAT EXCHANGER
SPECIFIED COLD OUTLET TEMP
SPECIFIED VALUE C 150.0000
LMTD CORRECTION FACTOR 1.0000

PRESSURE SPECIFICATION:
HOT SIDE PRESSURE DROP BAR 0.0000
COLD SIDE PRESSURE DROP BAR 0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:
HOT LIQUID COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT LIQUID COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT LIQUID COLD VAPOR CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD VAPOR CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD VAPOR CAL/SEC-SQCM-K 0.0203

*** OVERALL RESULTS ***

STREAMS:
------------------------------------------------------------------------
|               |    |               |
| STEAMIN ----->| HOT | -----> STEAMOUT |
| T= 1.8558D+02 |    | T= 1.1828D+02 |
| P= 1.1355D+01 |    | P= 1.1355D+01 |
| V= 1.0000D+00 |    | V= 0.0000D+00 |
|               |    |               |
| 11 <------| COLD | <---- 10 |
| T= 1.5000D+02 |    | T= 1.1671D+02 |
| P= 4.0000D+00 |    | P= 4.0000D+00 |
DUTY AND AREA:
CALCULATED HEAT DUTY     CAL/SEC     49626.5247
CALCULATED (REQUIRED) AREA SQM 5.6507
ACTUAL EXCHANGER AREA      SQM 5.6507
PER CENT OVER-DESIGN       0.0000

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY) CAL/SEC-SQCM-K 0.0203
UA (DIRTY) CAL/SEC-K 1147.1987

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR 1.0000
LMTD (CORRECTED) C 43.2589
NUMBER OF SHELLS IN SERIES 1

PRESSURE DROP:
HOTSIDE, TOTAL BAR 0.0000
COLDSIDE, TOTAL BAR 0.0000

*** ZONE RESULTS ***

TEMPERATURE LEAVING EACH ZONE:

HOT
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<th>COND</th>
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ZONE HEAT TRANSFER AND AREA:

ZONE HEAT DUTY AREA LMTD AVERAGE U UA
CAL/SEC SQM C CAL/SEC-SQCM-K CAL/SEC-K
1 20325.372 2.0152 49.6805 0.0203 409.1218

V= 1.0000D+00 | V= 8.1811D-01

---

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HEATX COLD-TQCU E-102  TQCURV INLET

-------------------------------
PRESSURE PROFILE:  CONSTANT2
PRESSURE DROP:  0.0  BAR
PROPERTY OPTION SET:  NRTL  RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:  HC-1

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BLOCK: E-103  MODEL: HEATX
----------------------
HOT SIDE:
----------
INLET STREAM:             12
OUTLET VAPOR STREAM:   13
OUTLET LIQUID STREAM:   14
PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:        HC-1
COLD SIDE:
----------
INLET STREAM: CH2OIN
OUTLET STREAM: CH2OOUT
PROPERTY OPTION SET:   NRTL      RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1

***  MASS AND ENERGY BALANCE  ***
IN              OUT        RELATIVE DIFF.
TOTAL BALANCE
MOLE(KMOL/HR )            2655.00         2655.00         0.00000
MASS(KG/HR )            52319.5         52319.5         0.00000
ENTHALPY(CAL/SEC )    -0.506343E+08  -0.506343E+08    0.397291E-14

***  CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E             0.00000      KG/HR
PRODUCT STREAMS CO2E          0.00000      KG/HR
NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
UTILITIES CO2E PRODUCTION     0.00000      KG/HR
TOTAL CO2E PRODUCTION         0.00000      KG/HR

***  INPUT DATA  ***

FLASH SPECS FOR HOT SIDE:
TWO PHASE   FLASH
MAXIMUM NO. ITERATIONS   30
CONVERGENCE TOLERANCE    0.000100000

FLASH SPECS FOR COLD SIDE:
TWO PHASE   FLASH
MAXIMUM NO. ITERATIONS   30
CONVERGENCE TOLERANCE    0.000100000

FLOW DIRECTION AND SPECIFICATION:
COUNTERCURRENT HEAT EXCHANGER

SPECIFIED HOT OUTLET TEMP

SPECIFIED VALUE C 50.0000

LMTD CORRECTION FACTOR 1.00000

PRESSURE SPECIFICATION:

HOT SIDE PRESSURE DROP BAR 0.0000
COLD SIDE PRESSURE DROP BAR 0.0000

HEAT TRANSFER COEFFICIENT SPECIFICATION:

HOT LIQUID COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD LIQUID CAL/SEC-SQCM-K 0.0203
HOT LIQUID COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD 2-PHASE CAL/SEC-SQCM-K 0.0203
HOT LIQUID COLD VAPOR CAL/SEC-SQCM-K 0.0203
HOT 2-PHASE COLD VAPOR CAL/SEC-SQCM-K 0.0203
HOT VAPOR COLD VAPOR CAL/SEC-SQCM-K 0.0203

*** OVERALL RESULTS ***

STREAMS:

--------------------------------------
|                                    |
|                                    |
| 12 -----| HOT |-----| 13 |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
|                                    |
| 14 |-----| COLD |-----| CH2OIN |
|                                    |

DUTY AND AREA:

CALCULATED HEAT DUTY CAL/SEC 214424.7275
CALCULATED (REQUIRED) AREA SQM 25.4508
ACTUAL EXCHANGER AREA SQM 25.4508
PER CENT OVER-DESIGN 0.0000

HEAT TRANSFER COEFFICIENT:
AVERAGE COEFFICIENT (DIRTY)   CAL/SEC-SQCM-K   0.0203
UA (DIRTY)               CAL/SEC-K               5167.0025

LOG-MEAN TEMPERATURE DIFFERENCE:
LMTD CORRECTION FACTOR       1.0000
LMTD (CORRECTED)       C       41.4989
NUMBER OF SHELLS IN SERIES   1

PRESSURE DROP:
HOTSIDE, TOTAL   BAR       0.0000
COLDSPIDE, TOTAL   BAR      0.0000

*** ZONE RESULTS ***

TEMPERATURE LEAVING EACH ZONE:

HOT

HOT IN  |     VAP     |  COND  |     HOT OUT
------- |-----------|--------|-----------
156.5   | 119.4     | 50.0   |

COLDOUT |     LIQ     |     LIQ     | COLDIN
<------ |-----------|-----------|<-------
48.9    | 47.0      | 32.2     |

ZONE HEAT TRANSFER AND AREA:

ZONE   HEAT DUTY   AREA   LMTD   AVERAGE U   UA
      CAL/SEC   SQM     C   CAL/SEC-SQCM-K   CAL/SEC-K
1   24066.509   1.3346  88.8220  0.0203     270.9522
2   190358.218  24.1162 38.8800  0.0203     4896.0503

HEATX COLD-TQCU E-103   TQCURV INLET

PRESSURE PROFILE:       CONSTANT2
PRESSURE DROP:       0.0   BAR
PROPERTY OPTION SET:   NRTL   RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:       HC-1

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HEATX HOT-TQCUR E-103  TQCURV INLET

PRESSURE PROFILE: CONSTANT2
PRESSURE DROP: 0.0 BAR
PROPERTY OPTION SET: NRTL  RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1
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BLOCK: MIXER  MODEL: MIXER

---------
INLET STREAMS: 9 8
OUTLET STREAM: 10
PROPERTY OPTION SET: NRTL  RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1

365
*** MASS AND ENERGY BALANCE ***

TOTAL BALANCE
MOLE (KMOL/HR)  80.4178  80.4178  0.00000
MASS (KG/HR)    5919.25  5919.25  0.00000
ENTHALPY (CAL/SEC)  -0.193822E+07  -0.193822E+07  0.00000

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E  0.00000  KG/HR
PRODUCT STREAMS CO2E  0.00000  KG/HR
NET STREAMS CO2E PRODUCTION  0.00000  KG/HR
UTILITIES CO2E PRODUCTION  0.00000  KG/HR
TOTAL CO2E PRODUCTION  0.00000  KG/HR

*** INPUT DATA ***

TWO PHASE FLASH
MAXIMUM NO. ITERATIONS  30
CONVERGENCE TOLERANCE  0.000100000
OUTLET PRESSURE  4.00000

BLOCK: P-100  MODEL: PUMP

-------------
INLET STREAM:  1
OUTLET STREAM:  2
PROPERTY OPTION SET:  NRTL  RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:  HC-1

*** MASS AND ENERGY BALANCE ***

TOTAL BALANCE
MOLE (KMOL/HR)  135.177  135.177  0.00000
MASS (KG/HR)    6227.47  6227.47  0.00000
ENTHALPY (CAL/SEC)  -0.247786E+07  -0.247527E+07  -0.104471E-02

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E  0.00000  KG/HR
PRODUCT STREAMS CO2E  0.00000  KG/HR
NET STREAMS CO2E PRODUCTION  0.00000  KG/HR
UTILITIES CO2E PRODUCTION  0.00000  KG/HR
TOTAL CO2E PRODUCTION  0.00000  KG/HR

*** INPUT DATA ***

OUTLET PRESSURE  20.0000
DRIVER EFFICIENCY  1.00000
FLASH SPECIFICATIONS:
LIQUID PHASE CALCULATION
NO FLASH PERFORMED
MAXIMUM NUMBER OF ITERATIONS 30
TOLERANCE 0.000100000

*** RESULTS ***
VOLUMETRIC FLOW RATE L/MIN 131.906
PRESSURE CHANGE BAR 19.0000
NPSH AVAILABLE M-KGF/KG 11.1668
FLUID POWER KW 4.17701
BRAKE POWER KW 10.8382
ELECTRICITY KW 10.8382
PUMP EFFICIENCY USED 0.38540
NET WORK REQUIRED KW 10.8382
HEAD DEVELOPED M-KGF/KG 246.227

BLOCK: R-100  MODEL: RPLUG

--------------------------------
INLET STREAM: 11
OUTLET STREAM: 12
PROPERTY OPTION SET: NRTL RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID: HC-1

*** MASS AND ENERGY BALANCE ***

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*** CO2 EQUIVALENT SUMMARY ***

FEED STREAMS CO2E 0.00000 KG/HR
PRODUCT STREAMS CO2E 0.00000 KG/HR
NET STREAMS CO2E PRODUCTION 0.00000 KG/HR
UTILITIES CO2E PRODUCTION 0.00000 KG/HR
TOTAL CO2E PRODUCTION 0.00000 KG/HR

*** INPUT DATA ***

REACTOR TYPE:
ADIABATIC
VAPOR FLUID PHASE
REACTOR TUBE LENGTH  METER  5.0000
REACTOR DIAMETER  METER  1.0000
REACTOR RISE  METER  0.0000
NUMBER OF REACTOR TUBES  1
REACTOR VOLUME  L  3927.0
PRESSURE DROP OPTION: SPECIFIED
HOLDUP OPTION: NO-SLIP
ERROR TOLERANCE  0.10000E-03
INTEGRATION METHOD  GEAR
CORRECTOR METHOD  NEWTON
INITIAL STEP SIZE FACTOR  0.10000E-01
CORRECTOR TOLERANCE FACTOR  0.10000
MAXIMUM NUMBER OF STEPS  1000

REACTION PARAGRAPH  ID: HYDROGEN  TYPE: POWERLAW

GLOBAL BASES:
  KBASIS  MOLE-GAMMA
  CBASIS  MOLARITY
  SBASIS  GLOBAL

STOICHIOMETRY:

REACTION NUMBER: 1
SUBSTREAM: MIXED
  HYDROGEN  -1.0000  METHY-01  -1.0000  2-BUT-01  1.0000

REACTION NUMBER: 2
SUBSTREAM: MIXED
  HYDROGEN  -1.0000  N-BUT-01  -1.0000  N-BUT-02  1.0000

REACTION DATA ENTRIES:

REACTION NO  TYPE  PHASE  DELT  BASIS
  C

  1  KINETIC  V  0.0000  PARTIALPRES
  2  KINETIC  V  0.0000  PARTIALPRES

RATE PARAMETERS:

REACTION NO  PREEXP. FACTOR  ACT. ENERGY  TEMP. EXPONENT  REF. TEMP  CAL/MOL
  C

  1
  2
POWERLAW EXPONENTS:

REACTION NUMBER:  1
SUBSTREAM: MIXED
HYDROGEN  -0.5000  METHY-01  1.0000

REACTION NUMBER:  2
SUBSTREAM: MIXED
HYDROGEN  -0.5000  N-BUT-01  1.0000

*** RESULTS ***

REACTOR DUTY  CAL/SEC  0.0000
RESIDENCE TIME  HR  0.55377E-02
REACTOR MINIMUM TEMPERATURE  C  150.00
REACTOR MAXIMUM TEMPERATURE  C  156.50

*** RESULTS PROFILE (PROCESS STREAM) ***

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**TOTAL MOLE FRACTION PROFILE (PROCESS STREAM)**

LENGTH (METER)

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1.5000 0.0000 0.0000 0.0000 0.0000
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2.5000 0.0000 0.0000 0.0000 0.0000
3.0000 0.0000 0.0000 0.0000 0.0000
3.5000 0.0000 0.0000 0.0000 0.0000
4.0000 0.0000 0.0000 0.0000 0.0000
4.5000 0.0000 0.0000 0.0000 0.0000
5.0000 0.0000 0.0000 0.0000 0.0000
5.5000 0.0000 0.0000 0.0000 0.0000

**ACETA-01 METHYL-01 N-BUTYL-01 N-BUTYL-02**

LENGTH (METER)

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2.5000 0.12129E-05 0.0000 0.0000 0.63930E-02
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**2-BUTYL-01**

LENGTH (METER)

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### Total Mass Fraction Profile (Process Stream)

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<tr>
<td>5.0000</td>
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Block: S-100 Model: SEP

Inlet Stream: 7
Outlet Streams: 8 Water
Property Option Set: NRTL Renon (NRTL) / Ideal Gas
Henry-Comps ID: HC-1

*** Mass and Energy Balance ***

<table>
<thead>
<tr>
<th></th>
<th>IN</th>
<th>OUT</th>
<th>Relative Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole (kmol/hr)</td>
<td>68.0140</td>
<td>68.0140</td>
<td>417881E-15</td>
</tr>
<tr>
<td>Mass (kg/hr)</td>
<td>5905.26</td>
<td>5905.26</td>
<td>154014E-15</td>
</tr>
<tr>
<td>Enthalpy (cal/sec)</td>
<td>-195414E+07</td>
<td>-195490E+07</td>
<td>388402E-03</td>
</tr>
</tbody>
</table>

*** CO2 Equivalent Summary ***
Feed Streams CO2E 0.00000 kg/hr
Product Streams CO2E 0.00000 kg/hr
Net Streams CO2E Production 0.00000 kg/hr
Utilities CO2E Production 0.00000 kg/hr
Total CO2E Production 0.00000 kg/hr

*** Input Data ***

Flash Specs for Stream 8
Two Phase TP Flash
Pressure Drop Bar 0.0
Maximum No. Iterations 30
Convergence Tolerance 0.000100000

Flash Specs for Stream Water
Two Phase TP Flash
PRESSURE DROP         BAR                                 0.0
MAXIMUM NO. ITERATIONS                         30
CONVERGENCE TOLERANCE                                     0.000100000

FRACTION OF FEED
SUBSTREAM= MIXED
STREAM= WATER     CPT= HYDROGEN     FRACTION=          0.0
          WATER     1.00000
          ETHANOL     0.0
          ETHYLACE    0.0
          ACETA-01    0.0
          METHY-01    0.0
          N-BUT-01    0.0
          N-BUT-02    0.0
          2-BUT-01    0.0

***  RESULTS  ***

HEAT DUTY             CAL/SEC    -759.29

COMPONENT = WATER
STREAM     SUBSTREAM    SPLIT FRACTION
WATER      MIXED                 1.00000

COMPONENT = ETHANOL
STREAM     SUBSTREAM    SPLIT FRACTION
8          MIXED                 1.00000

COMPONENT = ETHYLACE
STREAM     SUBSTREAM    SPLIT FRACTION
8          MIXED                 1.00000

COMPONENT = ACETA-01
STREAM     SUBSTREAM    SPLIT FRACTION
8          MIXED                 1.00000

COMPONENT = METHY-01
STREAM     SUBSTREAM    SPLIT FRACTION
8          MIXED                 1.00000

COMPONENT = N-BUT-01
STREAM     SUBSTREAM    SPLIT FRACTION
8          MIXED                 1.00000


BLOCK: SPILT   MODEL: FSPLIT

-------------------------------
INLET STREAM:          3
OUTLET STREAMS:        9  4
PROPERTY OPTION SET:   NRTL   RENON (NRTL) / IDEAL GAS
HENRY-COMPS ID:        HC-1

*** MASS AND ENERGY BALANCE ***

IN           OUT        RELATIVE DIFF.
TOTAL BALANCE
MOLE(KMOL/HR )            134.164         134.164         0.00000
MASS(KG/HR   )            322.280         322.280         -0.176379E-15
ENTHALPY(CAL/SEC )   -14551.7         -14551.7         0.00000

*** CO2 EQUIVALENT SUMMARY ***
FEED STREAMS CO2E             0.00000      KG/HR
PRODUCT STREAMS CO2E          0.00000      KG/HR
NET STREAMS CO2E PRODUCTION   0.00000      KG/HR
UTILITIES CO2E PRODUCTION     0.00000      KG/HR
TOTAL CO2E PRODUCTION         0.00000      KG/HR

*** INPUT DATA ***
FRACTION OF FLOW              STRM=4        FRAC=  0.90000

*** RESULTS ***
STREAM= 9  SPLIT=  0.100000  KEY= 0  STREAM-ORDER= 2
4                    0.90000                    0                        1

374
### 28.7.4 Stream Results

<table>
<thead>
<tr>
<th>STREAM ID</th>
<th>1 10 11 12 13</th>
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<tbody>
<tr>
<td>FROM:</td>
<td>---- MIXER E-102 R-100 E-103</td>
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<tr>
<td>TO:</td>
<td>P-100 E-102 R-100 E-103 ----</td>
</tr>
<tr>
<td>SUBSTREAM:</td>
<td>MIXED</td>
</tr>
<tr>
<td>PHASE:</td>
<td>LIQUID MIXED VAPOR VAPOR VAPOR</td>
</tr>
<tr>
<td>COMPONENTS:</td>
<td>KMOL/HR</td>
</tr>
<tr>
<td>HYDROGEN</td>
<td>0.0 13.2988 13.2988 12.2835 12.1864</td>
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<tr>
<td>WATER</td>
<td>0.0 7.2863-09 7.2863-09 7.2863-09 3.4097-10</td>
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<tr>
<td>ETHANOL</td>
<td>135.1769 0.1184 0.1184 0.1184 4.7010-03</td>
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<tr>
<td>ETHYLACETATE</td>
<td>0.0 65.9884 65.9884 65.9884 1.2408</td>
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<td>METHYLACETATE</td>
<td>0.0 9.6312-05 9.6312-05 9.6312-05 1.1662-05</td>
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<td>N-BUTANE</td>
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<td>TOTAL FLOW:</td>
<td>KMOL/HR 135.1769 80.4178 80.4178 79.4057 13.4392</td>
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<td>KG/HR</td>
<td>6227.4698 5919.2451 5919.2451 5919.4735 134.6441</td>
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<td>L/MIN</td>
<td>131.9056 8913.3630 1.1789+04 1.1819+04 1504.5009</td>
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<td>STATE VARIABLES:</td>
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<td>TEMP °C</td>
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<td>PRES BAR</td>
<td>1.0000 4.0000 4.0000 4.0000 4.0000</td>
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<td>VFRAC</td>
<td>0.0 0.8181 1.0000 1.0000 1.0000</td>
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<td>LFRAC</td>
<td>1.0000 0.1819 0.0 0.0 0.0</td>
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<td>SFRAC</td>
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<td>GM/CC</td>
<td>0.7869 1.1068-02 8.3686-03 8.3474-03 1.4916-03</td>
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<td>AVG MW</td>
<td>46.0690 73.6062 73.6062 74.5472 10.0188</td>
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| STREAM ID | 14 15 16 17 2 |
| FROM: | E-103 C-102 C-102 C-102 P-100 |
TO : C-102 ---- ---- ---- C-100

SUBSTREAM: MIXED
PHASE: LIQUID VAPOR LIQUID LIQUID LIQUID

COMPONENTS: KMOL/HR

<table>
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<tr>
<th>Component</th>
<th>KMOL/HR</th>
<th>KMOL/HR</th>
<th>KMOL/HR</th>
<th>KMOL/HR</th>
<th>KMOL/HR</th>
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<td>WATER</td>
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<td>2.0305-12</td>
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<td>ETHANOL</td>
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<td>2.7463-05</td>
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<td>ETHYLACETE</td>
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<td>N-BUT-01</td>
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TOTAL FLOW:

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<th>L/MIN</th>
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STATE VARIABLES:

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<th>LFRAC</th>
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ENTHALPY:

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ENTROPY:

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<td>-1.4505</td>
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<td>75.8174</td>
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3 4 5 6 7

--------
STREAM ID 3 4 5 6 7
FROM : C-100 SPILT C-100 C-101 C-101
TO : SPILT ---- C-101 C-100 S-100

CONV. MAX. REL. ERR: 0.0 0.0 0.0 -7.3607-05 0.0
SUBSTREAM: MIXED
PHASE: VAPOR VAPOR LIQUID VAPOR LIQUID
COMPONENTS: KMOL/HR
HYDROGEN 132.9879 119.6891 0.9524 133.9403 3.1966-14
WATER 7.2863-08 6.5577-08 8.3348 8.3348 1.0126
ETHANOL 1.1761 1.0585 134.0351 3.4324-02 7.4477-04
ETHYLACE 8.9261-02 8.0335-06 9.2468 9.2468 65.9884
ACETALDEHYDE 1.7749-04 1.5974-06 4.6826 4.6827 7.8563-05
METHYLFORMALDEHYDE 4.1491-04 3.7342-06 1.5974-04 1.5974-06 65.9884
N-BUTYLATE 4.2738-10 3.8465-10 3.5994-03 3.5994-03 0.5061
N-BUTYLACETATE 0.0 0.0 0.0 0.0
2-BUTYLACETATE 0.0 0.0 0.0 0.0
TOTAL FLOW:
KMOL/HR 134.1642 120.7478 157.2696 156.2569 68.0140
KG/HR 322.2797 290.0517 7349.2188 1444.0287 5905.2590
L/MIN 2907.0937 2616.3843 168.0849 4008.7315 164.3826
STATE VARIABLES:
TEMP C 39.5848 39.5848 87.6679 97.1078 207.1942
PRES BAR 20.0000 20.0000 20.0000 20.0000 20.1310
VFRAC 1.0000 1.0000 0.0 1.0000 0.0
LFRAC 0.0 0.0 1.0000 0.0 1.0000
SFRAC 0.0 0.0 0.0 0.0 0.0
ENTHALPY:
CAL/MOL -390.4614 -390.4614 -6.6256+04 -9992.9776 -1.0343+05
CAL/GM -162.5481 -162.5481 -1.5860 -1.0679 -1.0589
CAL/SEC -1.4552+04 -1.3096+04 -2.8945+06 -4.3374+05 -1.9541+06
ENTROPY:
CAL/MOL-K -5.9618 -5.9618 -74.1117 -9.8692 -91.9422
CAL/GM-K -2.4819 -2.4819 -1.5860 -1.0679 -1.0589
DENSITY:
MOL/CC 7.6918-04 7.6918-04 1.5594-02 6.4965-04 6.8959-03
GM/CC 1.8477-03 1.8477-03 0.7287 6.0037-03 0.5987
AVG MW 2.4021 2.4021 46.7301 9.2414 86.8242

8 9 CH2OIN CH2OOUT STEAMIN
---------------------------------
STREAM ID 8 9 CH2OIN CH2OOUT STEAMIN
FROM: S-100 SPILT ---- E-103 ----
TO: MIXER MIXER E-103 ---- E-102
SUBSTREAM: MIXED
PHASE: LIQUID VAPOR LIQUID LIQUID VAPOR
COMPONENTS: KMOL/HR
HYDROGEN 0.0 13.2988 0.0 0.0 0.0
WATER  0.0  7.2863-09 2575.5914 2575.5914  17.7627
ETHANOL  7.4477-04  0.1176  0.0  0.0  0.0
ETHYLACE  65.9884  8.9261-07  0.0  0.0  0.0
ACETA-01  7.8563-05  1.7749-05  0.0  0.0  0.0
METHY-01  0.5061  4.1491-10  0.0  0.0  0.0
N-BUT-01  0.5061  4.2738-11  0.0  0.0  0.0
N-BUT-02  0.0  0.0  0.0  0.0  0.0
2-BUT-01  0.0  0.0  0.0  0.0  0.0

TOTAL FLOW:
KMOL/HR  67.0014  13.4164  2575.5914  2575.5914  17.7627
KG/HR  5887.0171  32.2280  4.6400E+04  4.6400E+04  320.0000
L/MIN  164.0166  290.7094  783.5485  796.7406  994.3450

STATE VARIABLES:
TEMP C  207.1942  39.5848  32.2222  48.8731  185.5767
PRES BAR  20.1310  20.0000  1.0000  1.0000  11.3554
VFRAC  0.0  1.0000  0.0  0.0  1.0000
LFRAC  1.0000  0.0  1.0000  1.0000  0.0
SFRAC  0.0  0.0  0.0  0.0  0.0

ENTHALPY:
CAL/MOL  -1.0406E+05  -390.4614E+04  -6.8134E+04  -5.6449E+04
CAL/GM  -1184.3608E-03  -162.5481E+00  -3781.9979E+00  -3765.3615E+00  -3133.3975E+00
CAL/SEC  -1.9368E+06  -1455.1655E+00  -4.8746E+07  -4.8531E+07  -2.7852E+05

ENTROPY:
CAL/GM-K  -1.0596  -2.4819  -2.1394  -2.0865  -0.6608

DENSITY:
MOL/CC  6.8084-03  7.6918-04  5.4785-02  5.3878-02  2.9773-04
GM/CC  0.5982  1.8477-03  0.9870  0.9706  5.3637-03
AVG MW  87.8641  2.4021  18.0153  18.0153  18.0153

STEAMOUT WATER
------------------
STREAM ID    STEAMOUT WATER
FROM :        E-102  S-100
TO :          ----  ----

SUBSTREAM: MIXED
PHASE:       LIQUID  LIQUID
COMPONENTS: KMOL/HR
HYDROGEN  0.0  0.0
WATER  17.7627  1.0126
ETHANOL  0.0  0.0
ETHYLACE  0.0  0.0
ACETA-01  0.0  0.0
TOTAL FLOW:
KMOL/HR     17.7627  1.0126
KG/HR      320.0000  18.2419
L/MIN      5.9348  0.3832

STATE VARIABLES:
TEMP   C     118.2789  207.1942
PRES   BAR  11.3554   20.1310
VFRAC     0.0  0.0
LFRAC   1.0000  1.0000
SFRAC    0.0  0.0

ENTHALPY:
CAL/MOL -6.6507e+04 -6.4484e+04
CAL/GM -3691.6959 -3579.4042
CAL/SEC -3.2815e+05 -1.8138e+04

ENTROPY:
CAL/MOL-K -33.9158 -29.5373
CAL/GM-K -1.8826 -1.6396

DENSITY:
MOL/CC 4.9883-02 4.4037-02
GM/CC 0.8987 0.7933
AVG MW 18.0153 18.0153

1

STREAM ID 1
FROM : ----
TO : P-100

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
HYDROGEN 0.0
WATER 0.0
ETHANOL 135.1769
ETHYLACE 0.0
ACETA-01 0.0
METHY-01 0.0
N-BUT-01 0.0
N-BUT-02 0.0
2-BUT-01 0.0
TOTAL FLOW:
  KMOL/HR  135.1769
  KG/HR  6227.4698
  L/MIN  132.3632

STATE VARIABLES:
  TEMP  C  35.0000
  PRES  BAR  1.0000
  VFRAC  0.0
  LFRAC  1.0000
  SFRAC  0.0

ENTHALPY:
  CAL/MOL  -6.5990+04
  CAL/GM  -1432.4121
  CAL/SEC  -2.4779+06

ENTROPY:
  CAL/MOL-K  -81.8300
  CAL/GM-K  -1.7762

DENSITY:
  MOL/CC  1.7080-02
  GM/CC  0.7869
  AVG MW  46.0690

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
  HYDROGEN  0.0
  WATER  0.0
  ETHANOL  135.1769
  ETHYLACE  0.0
  ACETA-01  0.0
  METHY-01  0.0
  N-BUT-01  0.0
  N-BUT-02  0.0
  2-BUT-01  0.0

TOTAL FLOW:
  KMOL/HR  135.1769
  KG/HR  6227.4698
  L/MIN  132.3632
STATE VARIABLES:
TEMP C 37.3071
PRES BAR 20.0000
VFRAC 0.0
LFRAC 1.0000
SFRAC 0.0

ENTHALPY:
CAL/MOL -6.5921+04
CAL/GM -1430.9157
CAL/SEC -2.4753+06

ENTROPY:
CAL/MOL-K -81.6091
CAL/GM-K -1.7715

DENSITY:
MOL/CC 1.7021-02
GM/CC 0.7841
AVG MW 46.0690

3
STREAM ID 3
FROM: C-100
TO: SPILT

SUBSTREAM: MIXED
PHASE: VAPOR
COMPONENTS: KMOL/HR
HYDROGEN 132.9879
WATER 7.2863-08
ETHANOL 1.1761
ETHYLACE 8.9261-06
ACETA-01 1.7749-04
METHY-01 4.1491-09
N-BUT-01 4.2738-10
N-BUT-02 0.0
2-BUT-01 0.0

TOTAL FLOW:
KMOL/HR 134.1642
KG/HR 322.2797
L/MIN 2907.0937

STATE VARIABLES:
TEMP C 39.5848
PRES BAR 20.0000
VFRAC 1.0000
LFRAC       0.0
SFRAC       0.0

ENTHALPY:
  CAL/MOL    -390.4614
  CAL/GM     -162.5481
  CAL/SEC    -1.4552e+04

ENTROPY:
  CAL/MOL-K  -5.9618
  CAL/GM-K   -2.4819

DENSITY:
  MOL/CC     7.6918e-04
  GM/CC      1.8477e-03
  AVG MW     2.4021

STREAM ID               4
FROM :                  SPILT
TO   :
----

SUBSTREAM: MIXED
PHASE:                  VAPOR
COMPONENTS: KMOL/HR
  HYDROGEN     119.6891
  WATER        6.5577e-08
  ETHANOL      1.0585
  ETHYLACE     8.0335e-06
  ACETA-01     1.5974e-04
  METHY-01     3.7342e-09
  N-BUT-01     3.8465e-10
  N-BUT-02     0.0
  2-BUT-01     0.0

TOTAL FLOW:
  KMOL/HR     120.7478
  KG/HR       290.0517
  L/MIN       2616.3843

STATE VARIABLES:
  TEMP C       39.5848
  PRES BAR     20.0000
  VFRAC        1.0000
  LFRAC        0.0
  SFRAC        0.0

ENTHALPY:
  CAL/MOL     -390.4614
CAL/GM -162.5481
CAL/SEC -1.3096+04

ENTROPY:
CAL/MOL-K -5.9618
CAL/GM-K -2.4819

DENSITY:
MOL/CC 7.6918-04
GM/CC 1.8477-03
AVG MW 2.4021

5

STREAM ID 5
FROM: C-100
TO: C-101

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
HYDROGEN 0.9524
WATER 8.3348
ETHANOL 134.0351
ETHYLACE 9.2468
ACETA-01 4.6826
METHY-01 1.4380-02
N-BUT-01 3.5994-03
N-BUT-02 0.0
2-BUT-01 0.0

TOTAL FLOW:
KMOL/HR 157.2696
KG/HR 7349.2188
L/MIN 168.0849

STATE VARIABLES:
TEMP C 87.6679
PRES BAR 20.0000
VFRAC 0.0
LFRAC 1.0000
SFRAC 0.0

ENTHALPY:
CAL/MOL -6.6256+04
CAL/GM -1417.8475
CAL/SEC -2.8945+06

ENTROPY:
CAL/MOL-K -74.1117
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<th>Component</th>
<th>KMOL/HR</th>
<th>KG/HR</th>
<th>L/MIN</th>
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<td>8.3348</td>
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<td>2-BUT-01</td>
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**STATE VARIABLES:**
- **TEMP:** C = 97.1078
- **PRES:** BAR = 20.0000
- **VFRAC:** 1.0000
- **LFRAC:** 0.0
- **SFRAC:** 0.0

**ENTHALPY:**
- **CAL/MOL-K:** -9992.9776
- **CAL/GM-K:** -1081.3303
- **CAL/SEC:** -4.3374E+05

**ENTROPY:**
- **CAL/MOL-K:** -9.8692
- **CAL/GM-K:** -1.0679

**DENSITY:**
- **CAL/GM-K:** -1.5860
- **DENSITY:**
  - **MOL/CC:** 1.5594E-02
  - **GM/CC:** 0.7287
  - **AVG MW:** 46.7301

**STREAM ID:** 6
**FROM:** C-101
**TO:** C-100

**CONV. MAX. REL. ERR:** -7.3607E-05
**SUBSTREAM:** MIXED
**PHASE:** VAPOR
**COMPONENTS:** KMOL/HR

**TOTAL FLOW:**
- **KMOL/HR:** 156.2569
- **KG/HR:** 1444.0287
- **L/MIN:** 4008.7315
MOL/CC  6.4965-04
GM/CC   6.0037-03
AVG MW   9.2414

7

STREAM ID    7
FROM :       C-101
TO :         S-100

SUBSTREAM: MIXED
PHASE:       LIQUID
COMPONENTS:  KMOL/HR
HYDROGEN     3.1966-14
WATER        1.0126
ETHANOL      7.4477-04
ETHYLACE     65.9884
ACETA-01     7.8563-05
METHY-01     0.5061
N-BUT-01     0.5061
N-BUT-02     0.0
2-BUT-01     0.0

TOTAL FLOW:
KMOL/HR     68.0140
KG/HR       5905.2590
L/MIN       164.3826

STATE VARIABLES:
TEMP C       207.1942
PRES BAR     20.1310
VFRAC         0.0
LFRAC 1.0000
SFRAC         0.0

ENTHALPY:
CAL/MOL      -1.0343+05
CAL/GM       -1191.2964
CAL/SEC      -1.9541+06

ENTROPY:
CAL/MOL-K    -91.9422
CAL/GM-K     -1.0589

DENSITY:
MOL/CC       6.8959-03
GM/CC        0.5987
AVG MW       86.8242
8

STREAM ID 8
FROM: S-100
TO: MIXER

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
HYDROGEN 0.0
WATER 0.0
ETHANOL 7.4477-04
ETHYLACE 65.9884
ACETA-01 7.8563-05
METHY-01 0.5061
N-BUT-01 0.5061
N-BUT-02 0.0
2-BUT-01 0.0

TOTAL FLOW:
KMOL/HR 67.0014
KG/HR 5887.0171
L/MIN 164.0166

STATE VARIABLES:
TEMP C 207.1942
PRES BAR 20.1310
VFRAC 0.0
LFRAC 1.0000
SFRAC 0.0

ENTHALPY:
CAL/MOL -1.0406+05
CAL/GM -1184.3608
CAL/SEC -1.9368+06

ENTROPY:
CAL/MOL-K -93.1030
CAL/GM-K -1.0596

DENSITY:
MOL/CC 6.8084-03
GM/CC 0.5982
AVG MW 87.8641

9

STREAM ID 9
FROM: SPILT
TO : MIXER

SUBSTREAM: MIXED
PHASE: VAPOR
COMPONENTS: KMOL/HR
HYDROGEN  13.2988
WATER  7.2863-09
ETHANOL  0.1176
ETHYLAC   8.9261-07
ACETA-01  1.7749-05
METHY-01  4.1491-10
N-BUT-01  4.2738-11
N-BUT-02  0.0
2-BUT-01  0.0
TOTAL FLOW:
KMOL/HR  13.4164
KG/HR  32.2280
L/MIN  290.7094
STATE VARIABLES:
TEMP C  39.5848
PRES BAR  20.0000
VFRAC  1.0000
LFRAC  0.0
SFRAC  0.0
ENTHALPY:
CAL/MOL  -390.4614
CAL/GM  -162.5481
CAL/SEC  -1455.1655
ENTROPY:
CAL/MOL-K  -5.9618
CAL/GM-K  -2.4819
DENSITY:
MOL/CC  7.6918-04
GM/CC  1.8477-03
AVG MW  2.4021

10
--
STREAM ID  10
FROM : MIXER
TO : E-102

SUBSTREAM: MIXED
PHASE: MIXED
### COMPONENTS: KMOL/HR
- **HYDROGEN**: 13.2988
- **WATER**: 7.2863
- **ETHANOL**: 0.1184
- **ETHYLACETATE**: 65.9884
- **METHYLACETATE**: 9.6312
- **N-BUTYLACETATE**: 0.5061
- **N-BUTYLALCOHOL**: 0.0
- **2-BUTYLALCOHOL**: 0.0

### TOTAL FLOW:
- **KMOL/HR**: 80.4178
- **KG/HR**: 5919.2451
- **L/MIN**: 8913.3630

### STATE VARIABLES:
- **TEMP C**: 116.7085
- **PRES BAR**: 4.0000
- **VFRAC**: 0.8181
- **LFRAC**: 0.1819
- **SFRAC**: 0.0

### ENTHALPY:
- **CAL/MOL**: -8.6767\times10^4
- **CAL/GM**: -1178.7974
- **CAL/SEC**: -1.9382\times10^6

### ENTROPY:
- **CAL/MOL-K**: -75.5924
- **CAL/GM-K**: -1.0270

### DENSITY:
- **MOL/CC**: 1.5037\times10^{-4}
- **GM/CC**: 1.1068\times10^{-2}
- **AVG MW**: 73.6062

---

**11**

**STREAM ID**: 11
**FROM**: E-102
**TO**: R-100

**SUBSTREAM**: MIXED
**PHASE**: VAPOR

### COMPONENTS: KMOL/HR
- **HYDROGEN**: 13.2988
- **WATER**: 7.2863
- **ETHANOL**: 0.1184
ETHYLACE    65.9884
ACETA-01    9.6312-05
METHY-01    0.5061
N-BUT-01    0.5061
N-BUT-02    0.0
2-BUT-01    0.0

TOTAL FLOW:
KMOL/HR     80.4178
KG/HR       5919.2451
L/MIN       1.1789E+04

STATE VARIABLES:
TEMP   C      150.0000
PRES   BAR   4.0000
VFRAC   1.0000
LFRAC    0.0
SFRAC    0.0

ENTHALPY:
CAL/MOL    -8.4545E+04
CAL/GM     -1148.6153
CAL/SEC    -1.8886E+06

ENTROPY:
CAL/MOL-K  -70.0031
CAL/GM-K   -0.9510

DENSITY:
MOL/CC     1.1369-04
GM/CC      8.3686-03
AVG MW      73.6062

12
--
STREAM ID    12
FROM:        R-100
TO:          E-103

SUBSTREAM: MIXED
PHASE:       VAPOR
COMPONENTS: KMOL/HR
HYDROGEN     12.2835
WATER        7.2863-09
ETHANOL      0.1184
ETHYLACE     65.9884
ACETA-01     9.6312-05
METHY-01     9.6312-05
N-BUT-01     0.0
N-BUT-02   0.5076  
2-BUT-01   0.5076  
TOTAL FLOW:  
KMOL/HR    79.4057  
KG/HR      5919.4735  
L/MIN      1.1819x10+4  
STATE VARIABLES:  
TEMP      C     156.5000  
PRES      BAR   4.0000  
VFRAC                     1.0000  
LFRAC                     0.0  
SFRAC                     0.0  
ENTHALPY:  
CAL/MOL              -8.5623x10+4  
CAL/GM               -1148.5710  
CAL/SEC              -1.8886x10+6  
ENTROPY:  
CAL/MOL-K            -70.8108  
CAL/GM-K             -0.9499  
DENSITY:  
MOL/CC              1.1197x10-04  
GM/CC               8.3474x10-03  
AVG MW            74.5472  

13  
--  
STREAM ID    13  
FROM :         E-103  
TO :            ----  
SUBSTREAM: MIXED  
PHASE:         VAPORE  
COMPONENTS: KMOL/HR  
HYDROGEN        12.1864  
WATER            3.4097-10  
ETHANOL         4.7010-03  
ETHYLACE        1.2408  
ACETA-01        1.1662-05  
METHY-01        0.0  
N-BUT-01        0.0  
N-BUT-02        2.3435-03  
2-BUT-01        4.9668-03  
TOTAL FLOW:  
KMOL/HR         13.4392  

391
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14
--
STREAM ID 14
FROM: E-103
TO: C-102

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
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<thead>
<tr>
<th>COMPONENT</th>
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<td>64.7477</td>
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<td>ACETA-01</td>
<td>8.4649-05</td>
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<td>METHY-01</td>
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<td>N-BUT-01</td>
<td>0.0</td>
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<tr>
<td>N-BUT-02</td>
<td>0.5053</td>
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<tr>
<td>2-BUT-01</td>
<td>0.5027</td>
</tr>
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TOTAL FLOW:
| KMOL/HR | 65.9665 |
| KG/HR   | 5784.8294 |
| L/MIN   | 111.6711  |
| STATE VARIABLES: |
| TEMP     | 50.0000  |
PRES BAR     4.0000
VFRAC        0.0
LFRAC        1.0000
SFRAC        0.0

ENTHALPY:
   CAL/MOL  -1.1280+05
   CAL/GM   -1286.3539
   CAL/SEC  -2.0670+06

ENTROPY:
   CAL/MOL-K -114.0496
   CAL/GM-K  -1.3005

DENSITY:
   MOL/CC    9.8454-03
   GM/CC     0.8634
   AVG MW    87.6934

15

STREAM ID    15
FROM:        C-102
TO:          ----

SUBSTREAM: MIXED
PHASE:       VAPOR
COMPONENTS:  KMOL/HR
   HYDROGEN   5.3214-02
   WATER      2.0305-12
   ETHANOL    2.7463-05
   ETHYLACE   7.1538-03
   ACETA-01   7.5604-08
   METHY-01   0.0
   N-BUT-01   0.0
   N-BUT-02   2.3306-09
   2-BUT-01   3.7018-06

TOTAL FLOW:
   KMOL/HR    6.0399-02
   KG/HR      0.7391
   L/MIN      13.0626

STATE VARIABLES:
   TEMP C     38.9962
   PRES BAR   2.0000
   VFRAC      1.0000
   LFRAC      0.0
   SFRAC      0.0
ENTHALPY:
   CAL/MOL            -1.2474E+04
   CAL/GM             -1019.3547
   CAL/SEC            -209.2818

ENTROPY:
   CAL/MOL-K          -11.2755
   CAL/GM-K           -0.9214

DENSITY:
   MOL/CC             7.7063E-05
   GM/CC              9.4303E-04
   AVG MW             12.2372

16
--
STREAM ID      16
FROM:          C-102
TO:            ----

SUBSTREAM: MIXED
PHASE:         LIQUID
COMPONENTS:   KMOL/HR
   HYDROGEN      4.3909E-02
   WATER         6.9433E-09
   ETHANOL       0.1136
   ETHYLACE      64.6111
   ACETA-01      8.4574E-05
   METHY-01      0.0
   N-BUT-01      0.0
   N-BUT-02      1.0062E-04
   2-BUT-01      6.9289E-02
TOTAL FLOW:
   KMOL/HR        64.8381
   KG/HR          5703.1167
   L/MIN          108.1413

STATE VARIABLES:
   TEMP C         38.9962
   PRES BAR       2.0000
   VFRAC          0.0
   LFRAC          1.0000
   SFRAC          0.0

ENTHALPY:
   CAL/MOL        -1.1389E+05
   CAL/GM         -1294.7479
   CAL/SEC        -2.0511E+06
ENTROPY:
   CAL/MOL-K       -115.6130
   CAL/GM-K        -1.3144

DENSITY:
   MOL/CC           9.9928-03
   GM/CC            0.8790
   AVG MW           87.9593

17
--
STREAM ID     17
FROM:          C-102
TO:            ----

SUBSTREAM: MIXED
PHASE:          LIQUID
COMPONENTS: KMOL/HR
   HYDROGEN       0.0
   WATER          4.3172-16
   ETHANOL        3.9967-08
   ETHYLACETATE   0.1294
   ACETATE-01     7.6290-16
   METHYL-01      0.0
   N-BUTYL-01     0.0
   N-BUTYL-02     0.5052
   2-BUTYL-01     0.4334

TOTAL FLOW:
   KMOL/HR        1.0680
   KG/HR           80.9736
   L/MIN           1.9276

STATE VARIABLES:
   TEMP   C       128.4443
   PRES   BAR     2.0000
   VFRAC   0.0
   LFRAC   1.0000
   SFRAC   0.0

ENTHALPY:
   CAL/MOL         -7.7388+04
   CAL/GM           -1020.7144
   CAL/SEC          -2.2959+04

ENTROPY:
   CAL/MOL-K       -109.9721
   CAL/GM-K        -1.4505

DENSITY:
MOL/CC 9.2344-03
GM/CC 0.7001
AVG MW 75.8174

CH2OIN
-----
STREAM ID CH2OIN
FROM : ----
TO : E-103

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
HYDROGEN 0.0
WATER 2575.5914
ETHANOL 0.0
ETHYLACE 0.0
ACETA-01 0.0
METHY-01 0.0
N-BUT-01 0.0
N-BUT-02 0.0
2-BUT-01 0.0
TOTAL FLOW:
KMOL/HR 2575.5914
KG/HR 4.6400+04
L/MIN 783.5485

STATE VARIABLES:
TEMP C 32.2222
PRES BAR 1.0000
VFRAC 0.0
LFRAC 1.0000
SFRAC 0.0

ENTHALPY:
CAL/MOL -6.8134+04
CAL/GM -3781.9979
CAL/SEC -4.8746+07

ENTROPY:
CAL/MOL-K -38.5412
CAL/GM-K -2.1394

DENSITY:
MOL/CC 5.4785-02
GM/CC 0.9870
AVG MW 18.0153
CH2OOUT
------
STREAM ID    CH2OOUT
FROM :       E-103
TO :         ----

SUBSTREAM: MIXED
PHASE:       LIQUID
COMPONENTS:  KMOL/HR
  HYDROGEN    0.0
  WATER       2575.5914
  ETHANOL     0.0
  ETHYLACE    0.0
  ACETA-01    0.0
  METHY-01    0.0
  N-BUT-01    0.0
  N-BUT-02    0.0
  2-BUT-01    0.0
TOTAL FLOW:
  KMOL/HR    2575.5914
  KG/HR      4.6400+04
  L/MIN      796.7406

STATE VARIABLES:
  TEMP   C    48.8731
  PRES   BAR  1.0000
  VFRAC   0.0
  LFRAC   1.0000
  SFRAC   0.0
ENTHALPY:
  CAL/MOL  -6.7834+04
  CAL/GM   -3765.3615
  CAL/SEC  -4.8531+07
ENTROPY:
  CAL/MOL-K -37.5895
  CAL/GM-K   -2.0865
DENSITY:
  MOL/CC    5.3878-02
  GM/CC     0.9706
  AVG MW    18.0153

STEAMIN
------
STREAM ID    STEAMIN
FROM :       ----
TO : E-102

SUBSTREAM: MIXED
PHASE: VAPOR
COMPONENTS: KMOL/HR
HYDROGEN 0.0
WATER 17.7627
ETHANOL 0.0
ETHYLACE 0.0
ACETA-01 0.0
METHY-01 0.0
N-BUT-01 0.0
N-BUT-02 0.0
2-BUT-01 0.0
TOTAL FLOW:
KMOL/HR 17.7627
KG/HR 320.0000
L/MIN 994.3450
STATE VARIABLES:
TEMP C 185.5767
PRES BAR 11.3554
VFRAC 1.0000
LFRAC 0.0
SFRAC 0.0
ENTHALPY:
CAL/MOL -5.6449E+04
CAL/GM -3133.3975
CAL/SEC -2.7852E+05
ENTROPY:
CAL/MOL-K -11.9045
CAL/GM-K -0.6608
DENSITY:
MOL/CC 2.9773-04
GM/CC 5.3637-03
AVG MW 18.0153

STEAMOUT
--------
STREAM ID STEAMOUT
FROM : E-102
TO : ----

SUBSTREAM: MIXED
PHASE: LIQUID
COMPONENTS: KMOL/HR
HYDROGEN  0.0
WATER      17.7627
ETHANOL    0.0
ETHYLACE   0.0
ACETA-01   0.0
METHY-01   0.0
N-BUT-01   0.0
N-BUT-02   0.0
2-BUT-01   0.0
TOTAL FLOW:
KMOL/HR     17.7627
KG/HR       320.0000
L/MIN       5.9348

STATE VARIABLES:
TEMP C      118.2789
PRES BAR    11.3554
VFRAC       0.0
LFRAC       1.0000
SFRAC       0.0

ENTHALPY:
CAL/MOL    -6.6507+04
CAL/GM     -3691.6959
CAL/SEC    -3.2815+05

ENTROPY:
CAL/MOL-K  -33.9158
CAL/GM-K   -1.8826

DENSITY:
MOL/CC     4.9883-02
GM/CC      0.8987
AVG MW     18.0153

WATER

-----
STREAM ID  WATER
FROM :      S-100
TO :        ----

SUBSTREAM: MIXED
PHASE:      LIQUID
COMPONENTS: KMOL/HR
HYDROGEN    0.0
WATER       1.0126
ETHANOL     0.0
ETHYLACE       0.0
ACETA-01        0.0
METHY-01        0.0
N-BUT-01        0.0
N-BUT-02        0.0
2-BUT-01        0.0

TOTAL FLOW:
KMOL/HR          1.0126
KG/HR            18.2419
L/MIN            0.3832

STATE VARIABLES:
TEMP C          207.1942
PRES BAR        20.1310
VFRAC           0.0
LFRAC           1.0000
SFRAC           0.0

ENTHALPY:
CAL/MOL         6.4484e+04
CAL/GM          3579.4042
CAL/SEC         1.8138e+04

ENTROPY:
CAL/MOL-K       29.5373
CAL/GM-K        1.6396

DENSITY:
MOL/CC          4.4037e-02
GM/CC           0.7933
AVG MW          18.0153