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Flagellar dynamics in viscous fluids

Mahmut-Selman Sakar
University of Pennsylvania, sakarmah@seas.upenn.edu

C. Lee
University of Pennsylvania

Paulo E. Arratia
University of Pennsylvania, parratia@seas.upenn.edu

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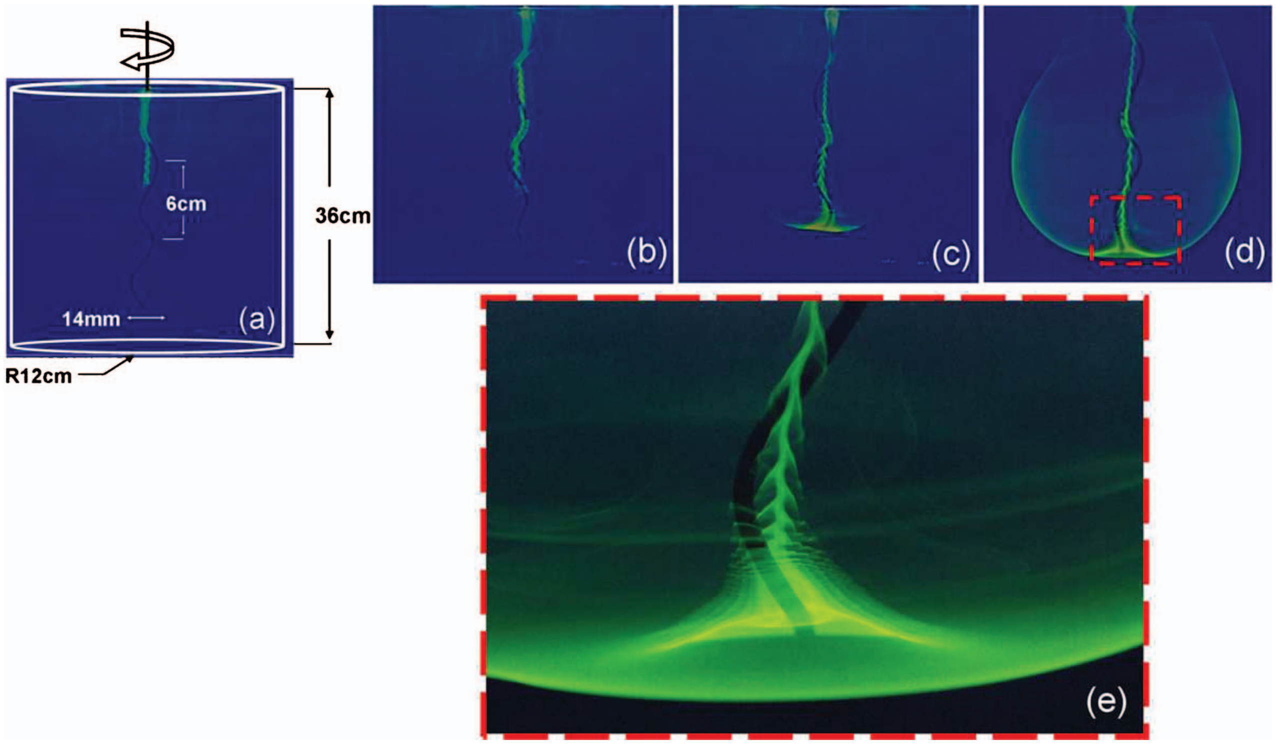

FIG. 1. (Color)

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M. S. Sakar,[1,2] C. Lee,[1] and P. E. Arratia[1]
[1]*Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[2]*Department of Electrical Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
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Many, if not most, living organisms move at low Reynolds number (Re), where linear viscous forces dominate nonlinear inertial effects. In such a regime, locomotion results from nonreciprocal deformations in order to break time-reversal symmetry; this is the so-called "scallop theorem."[1] Examples of low Re swimmers include bacteria, sperm cells, and various kinds of protozoa. In particular, flagellated bacteria swim by rotating thin helical filaments, each driven at its base by a rotary motor. Direct visualization of the flow patterns around individual flagellar filaments is quite challenging due to the filament small length scale (≈20 nm).

In this paper, we investigate the flow behavior of a helical impeller rotating in a viscous fluid at low Re, defined as $\mathrm{Re}=\rho\Omega\lambda^2/\mu$, using a macroscopic-scale model system.[2,3] Here, Ω is the angular velocity, λ is the helical pitch, and ρ and μ are the fluid density and viscosity, respectively. Experiments are performed in a transparent flat-bottom cylindrical vessel. In order to correct the optical distortion due to the vessel curvature, the tank is placed in a cubic chamber made of acrylic. Both chamber and tank are filled with the same working fluid in order to match the refraction index. The working fluid is pure glycerol ($\rho\approx 1.2$ g/cm^3, $\mu \approx 800$ cP). The tank height and diameter are 36 and 24 cm, respectively. A rigid helical filament, which is attached to an electric motor, is immersed in the fluid [Fig. 1(a)]. The motor typically rotates at 1.2 Hz and the helical pitch is 6 cm. Under such conditions, $\mathrm{Re}\approx 0.8$. The flow is visualized using ultraviolet fluorescence. The flow behavior is assessed by the location of a neutrally buoyant dye as a function of time.

Figures 1(a) and 1(b) display the gradual movement of the dye downwards while wrapping around the filament and producing a fishscalelike pattern until it reaches an unstable point at the tip of the helix. This instability forms due to the helical shape of the flagellum and continues to be generated at the tip of the helix [Fig. 1(c)]. A fully developed flow pattern is shown in Fig. 1(d), where the flow in the far field falls off inversely with distance. The geometry of the cylindrical tank seems to be the main factor determined the symmetrical bowl shape of the envelope. Over time these envelopes become cyclic. Figure 1(e) shows a close-up of the tip of the flagellum revealing complex flow patterns.

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