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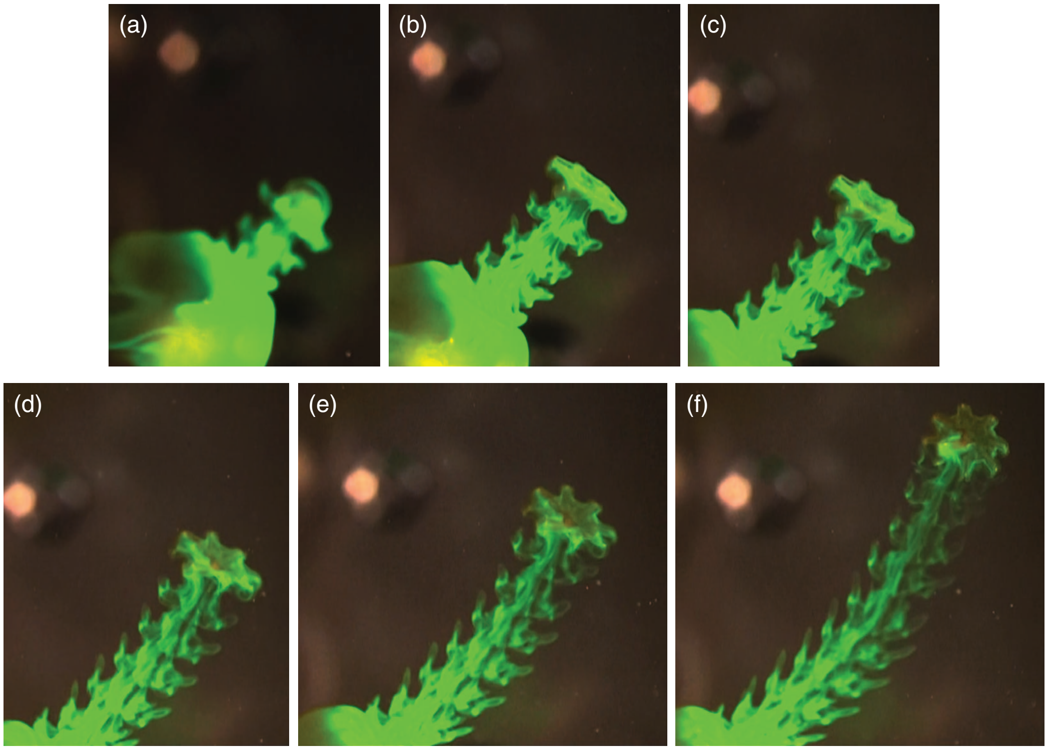

FIG. 1. Evolution of the wake structure generated by induced drift and periodic boundary layer shedding. (a) Just after release, the jellyfish emerges from the dyed fluid bolus, propagating along a layer of dyed fluid. (b)–(e) Pulsatile self-propulsion creates a complex wake pattern: Induced drift forms the central pole of fluid trailing the jellyfish trajectory, and periodic boundary layer shedding contributes the branches. (f) Over time, induced drift, and boundary layer generate a periodic viscous wake that distributes the original volume of dyed fluid into an interlaced structure, hence greatly increasing the interface for molecular diffusion between dyed and surrounding fluid.

Induced drift by a self-propelled swimmer at intermediate Reynolds numbers

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Swimming organisms have been proposed to contribute to the mixing of stratified water in the ocean, thereby facilitating the vertical transport of nutrients and dissolved gases.[1–3] In general, mixing results from increasing the interface available for molecular diffusion between neighboring fluid volumes.[4,5] At high Reynolds numbers (Re), swimmers generate such interfaces through their turbulent wake structures. At lower Re, however, turbulent mixing becomes ineffective as viscous effects dissipate small-scale fluid motions as heat, and diffusion is not significantly enhanced.[6,7] In

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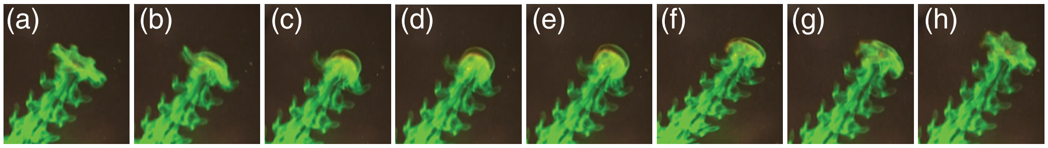

FIG. 2. Boundary layer build-up and shedding during a single stroke cycle. (a) At t=0, the extended jellyfish bell is coated by a boundary layer connecting the individual lappets. (b)–(f) As the bell contracts, part of the boundary layer is shed and stays behind as the jellyfish moves forward. (h) At t=1 s, the contraction cycle is complete, and the shed boundary layer extends the existing periodic wake structure.

this regime, it appears that the dominant mechanism for mixing by a swimmer is induced drift, i.e., the propagation and stretching of a fluid volume by a moving body's pressure field, which increases the diffusion-enabling interface between the drift volume and surrounding fluid. The ratio of drift volume to body volume is called the "added-mass" coefficient and depends on the shape of the body.[8] Importantly, previous computational analysis suggested that the total drift volume increases at low and intermediate Re,[3] implying that in contrast to turbulent mixing, mixing through induced drift becomes more efficient in viscous conditions. As pointed out by others,[9] the limitation of previous numerical simulations, however, is that the simulated objects were towed through viscous fluid, which is dynamically distinct from a self-propelled swimmer. Using qualitative flow visualization, we here demonstrate the presence of induced drift in self-propelled swimmers operating at intermediate Re (1–100). In these experiments, the spatiotemporal pattern of a fluid volume initially surrounding a juvenile Moon jellyfish (*Aurelia aurita*) is visualized using Fluorescein dye (see Fig. 1). For details on the experimental methods see supplemental material in Ref. 13.

Paddling at Reynolds numbers on the order of 10, the jellyfish lappets are subject to viscous effects causing a boundary layer to form around the lobed bell.[10–12] During each contraction cycle, a portion of the boundary layer is shed from the top of the bell, rolling into an 8-fingered skirt (Fig. 2). This effect becomes more prominent at lower Reynolds numbers since boundary layer thickness δ relative to the lappet width **b** scales as $\delta/b \sim Re^{-1/2}$. Furthermore, a portion of the surrounding fluid is set into motion by the body's pressure field and trails along with the jellyfish. This induced drift volume forms the central pole of the emergent wake structure, as seen in Figs. 1(a)–1(e). As the jellyfish continues to swim away from the dye bolus, the effects of induced drift and periodic boundary layer shedding combine to grow a complex, interlaced wake structure, as shown in Fig. 1(f). Our results suggest that at intermediate Re, the interaction of viscous boundary layers and induced drift generate complex wake structures that greatly enlarge the surface area between neighboring fluid volumes and hence facilitate fluid mixing.

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[13] See supplementary material at http://dx.doi.org/10.1063/1.4893537 for Fig. S1 and additional text showing further details regarding a juvenile Moon jellyfish (Aurelia aurita) and dye. The full movie can be seen at: http://goo.gl/7fMjlW.