SYMPOSIUM

The Cocktail Boat

Lisa J. Burton,* Nadia Cheng* and John W. M. Bush†

*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA;
†Department of Mathematics, Massachusetts Institute of Technology, Cambridge, MA, USA

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1E-mail: bush@math.mit.edu

Synopsis

We describe the inspiration, development, and deployment of a novel cocktail device modeled after a class of water-walking insects. Semi-aquatic insects like Microvelia and Velia evade predators by releasing a surfactant that quickly propels them across the water. We exploit an analogous propulsion mechanism in the design of an edible cocktail boat. We discuss how gradients in surface tension lead to motion across the water’s surface, and detail the design considerations associated with the insect-inspired cocktail boat.

Introduction

Nature is adept at solving design problems across all scales. The capillary length $L_c$ prescribes the scale at which surface tension and gravity are comparable at the surface of a fluid. At an air–water interface, $L_c = \sqrt{\sigma/\rho g} \approx 0.2 \text{ mm}$, where $\sigma$ is surface tension, $\rho$ is the water density and $g$ is the gravitational acceleration. For creatures with characteristic dimension $L$ that is small relative to $L_c$ (equivalently, for Bond number $Bo = (L/L_c)^2 \ll 1$), interfacial forces dominate gravity. Surface tension, thus, plays a critical role in the lives of water-walking insects, both for their floatation and for their propulsion.

Traditional boats float by virtue of the hydrostatic pressure acting along their submerged surface. For propulsion, motorboats rely on the transfer of momentum to the underlying fluid by way of propellers, and sailboats on wind-induced thrust. Objects, small relative to the capillary length may call upon interfacial forces for floatation; indeed, for water-walking insects, the dominant weight-bearing mechanism is surface tension (Keller 1998). Such creatures also exploit surface tension to generate propulsive forces using a variety of mechanisms (Bush and Hu 2006), one of which served as the inspiration for our cocktail boat (Burton et al. 2013).

Marangoni propulsion in nature

Water-walking insects are known to be water-repellent, an essential feature that enables them to stay on the interface (Dufour 1833). They are water-repellent by virtue of their integument, which consists of a dense matt of waxy, hydrophobic hairs (Bush et al. 2007) as pictured in Fig. 1. Water-walking insects are fastidious about keeping their hair clean; a contaminated layer of hair reduces the hydrophobicity of the insect’s surface and may lead to submergence. Velia and Microvelia are water-walking insects that typically move across the water by rowing and using an alternating tripod gait (Andersen 1976; Bush and Hu 2006). Using the tripod gait, Microvelia’s walking speed is 8–9 cm/s (Andersen 1976). The deformation of the water’s surface is responsible for supporting the weight of the insect. With a mass of $10^{-5}$ g, Microvelia must displace just 1 mm$^3$ of water to stay afloat.

When a quick escape is needed, for instance in the presence of a potential predator, Velia and Microvelia employ a completely different mechanism. By releasing a surfactant through a tongue-like protrusion from the rostrum, these insects create a gradient of surface tension that propels them forward (Andersen 1976; Linsenmair and Jander 1963). This so-called
Marangoni effect is also employed by certain terrestrial insects, not suited to walk on water, when they find themselves unexpectedly on the water’s surface (Bush and Hu 2006).

Marangoni flows are those driven by a difference in surface tension, as may arise from gradients in temperature or in chemistry at an interface (Scriven and Sterling 1960). A well-known tabletop example showcasing the Marangoni effect is the “soap boat” experiment. When one end of a small floating toothpick of width \( w \) is coated with dish soap, the surface tension at the clean end is greater by \( \Delta \sigma \) and the toothpick accelerates, owing to the Marangoni force of \( F_M = w \Delta \sigma \) (Nakata et al. 2005), until balanced by hydrodynamic drag. Surfactants such as dish soap are molecules that find it energetically favorable to reside at the free surface, and decrease the local surface tension. Most soaps decrease the surface tension at an air–water surface, \( \sigma = 72 \) dynes/cm, by a factor of two, resulting in the toothpick achieving speeds of \( \sim 10 \) cm/s.

As observed in the soap boat experiment, using soap as fuel results in relatively short travel times of \( \sim 10 \) s. In a closed geometry, the interface becomes saturated in surfactant, which suppresses the propulsive gradient in surface tension. Nakata et al. (2005) demonstrated that this limitation may be avoided by using camphor, a volatile surfactant that evaporates rapidly from the surface, thus permitting continuous motion.

Marangoni propulsion in insects is analogous to that of the soap boat: the surfactant released by the insect reduces the surface tension behind the insect, and the resulting chemically induced gradient in the surface tension generates a propulsive force (Hu and Bush 2010). Schildknecht (1976) studied the terrestrial rove beetle and found that its surfactant reduced the surface tension from 72 to 49 dynes/cm. Microvelia reaches a speed of 17 cm/s, about twice its walking speed on water (Andersen 1982). In Fig. 2, typical trajectories resulting from Marangoni propulsion are shown by the cleared path behind Microvelia. Hu (2006) observed a variety of trajectories after the insect released surfactant, although motion was predominantly translational rather than rotational. Using Marangoni propulsion, Microvelia can release surfactant about three times before it must regenerate its supply (Hu 2006). Andersen (1976) reported that while releasing the surfactant, the insect braces its legs along its body, presumably to reduce drag and so maximizes its speed.

**Design and mechanics of the cocktail boat**

The cocktail boat likewise moves by virtue of Marangoni propulsion. A successful cocktail boat has three key characteristics: It floats, propels itself forward, and is edible. We first developed a plastic version of the boat, as pictured in Fig. 3a, made of acrylonitrile butadiene styrene (ABS) created on a Stratasys Dimension 3D printer. We then collaborated with chefs to create an edible vessel.

While the insects rely on complex set of hairs to avoid wetting, mimicking this dense two-layer structure via manufacturing was unrealistic (features on the order of microns would be needed). At 1.5 cm in
length, the boat is considerably larger than the semi-aquatic insects and relies primarily on buoyancy for floatation. The boat design (Fig. 3) includes an empty cavity to hold “fuel,” that is, the material responsible for lowering the surface tension. Adding fuel on board considerably increased the weight of the boat. To guarantee floatation, we designed the boat to be hollow to minimize the vessel’s weight. A small slit (0.5–1.5 mm in width) on the trailing side of the boat allows the fuel to leak into the bulk fluid. Fine-tuning the cocktail boat’s design was completed after the boat’s fuel was chosen.

After seeking an edible material that was both surface-active and volatile, we found a fuel that far outperformed any other—alcohol. Alcohol reduces both the surface tension and the contact angle on the aft side of the boat, thus decreasing the horizontal force relative to that on the front (as illustrated in Fig. 4). Pure ethyl alcohol reduces the surface tension at an air–water interface from $\sigma_{\text{bulk}} = 72$ dynes/cm to $\sigma_{\text{fuel}} = 22$ dynes/cm. The contact angle between water and plastic is $\theta_{\text{bulk}} \approx 80^\circ$ and between an alcohol–water mixture and plastic is $\theta_{\text{fuel}} \approx 30^\circ$. 
Consequently, a cocktail boat of width $w = 1$ cm is subjected to a propulsive force $F_{\text{prop}} = \left( \sigma_{\text{bulk}} \sin \theta_{\text{bulk}} - \sigma_{\text{fuel}} \sin \theta_{\text{fuel}} \right) w \approx 27 \text{ dynes}$, owing to the fore-aft difference both in surface tension and in contact angle. A horizontal balance of force yields the resulting steady speed $U$. The propulsive force $F_{\text{prop}}$ is balanced by the appropriate high Reynolds number drag force $F_{\text{drag}} = \rho U^2 wd$, where $wd$ is the relevant projection of the boat’s submerged exposed area (Fig. 4). We thus obtain

$$U = \sqrt{\frac{\sigma_{\text{bulk}} \sin \theta_{\text{bulk}} - \sigma_{\text{fuel}} \sin \theta_{\text{fuel}}}{\rho d}}.$$  

Speed increases with a greater fore-aft difference in surface tension and contact angle. A lighter boat leads to a smaller intrusion depth $d$ and therefore faster speeds. Observed peak speeds of the cocktail boat are $\sim 10 \text{ cm/s}$, comparable to the theoretically predicted speeds of $4$–$6 \text{ cm/s}$. Similar to the camphor used by Nakata et al. (2005), alcohol is volatile and evaporates from the interface rapidly relative to the timescale of the boat’s motion, allowing for sustained motion of the cocktail boat until its fuel is spent.

Commercial spirits typically range from 30% to 95% alcohol by volume (ABV), resulting in gradients of surface tension ranging from $\Delta \sigma = 35$ to 50 dynes/cm$^2$. Inclusion of sugar and other flavorings typically increases the spirit’s surface tension, thus decreasing the difference with water. We tested five different liquors, Domaine de Canton (28% ABV), Absolut Vodka (40% ABV), 99 Bananas (49.5% ABV), Bacardi 151 (75.5% ABV), and ethyl alcohol (100% ABV) with different boat designs, slit sizes, and sizes of the cavity for fuel. Figure 3b shows a sample of
different boat designs. Each combination of boat design and liquor was tested and filmed in a square (23 × 23 cm) glass container filled with clean water at room temperature. A MATLAB-based tracking algorithm was applied to trace the speed and trajectory of each boat (Fig. 5), and mean and maximum speeds were recorded. As expected, speeds were higher for liquors with higher alcohol content. The effect of the design of the vessel was also considered. Different angles of tilt were tried, and found to alter the typical trajectories, with greater tilt giving rise to spiraling rather than to rectilinear motion. Motion is inhibited when the boat encounters a boundary, so rotation is preferred for longer travel times (typically 1–2 min), as it tends to prevent the boat colliding with the wall.

Finally, we teamed with chefs from ThinkFoodGroup to explore various materials for an edible boat. After 3D printing mold negatives out of ABS plastic, we created flexible food molds using silicone gels (Zhermack Elite Double 8). Edible materials were then cast into the flexible boat molds (Fig. 5a–c) and tested. An edible (but not digestible) wax performed the best, resulting in the highest speeds (11 cm/s) and travel times (2 min) recorded. Gelatin boats were capable of sustained motion, but this performance was improved by using a cold fluid, which prevented the gelatin from dissolving. Moreover, they tended to adhere to the walls. In their favor, gelatin lends itself to taking on a wider range of flavors.

**Discussion**

On the basis of a natural example of Marangoni propulsion, we created the cocktail boat. Although the underlying propulsive mechanism for the insect and boat are similar, there are several fundamental differences in design between the two. The cocktail boat is relatively large and need not be hydrophobic; it is thus partially submerged in the bulk fluid rather than suspended on the interface like the insect (Fig. 1). Unlike the surfactant released by the insect, the boat’s fuel (alcohol) is evaporative and so enables sustained motion. The choice of fuel for the boat was the dominant design consideration, with higher speeds resulting from spirits with higher alcohol content. Some degree of rotational motion (spinning) was observed with every boat design, whereas insect trajectories were primarily translational. Through a collaboration with chefs, we created an edible vessel so that the cocktail boat and its fuel are both consumable.

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**References**


