Gallery of Fluid Motion

Thin film flow between fibers: Inertial sheets and liquid bridge patterns

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Fluid flow down closely packed vertical fibers has attracted significant attention due to its potential use in desalination [1], particle capture [2], and fog harvesting [3,4]. The unique "bead-on-fiber" formations that emerge from these flows have demonstrated the ability to enhance heat and mass transfer, offering a means for developing sustainable and energy-efficient processes using large fiber arrays. However, as the spacing between the fibers is reduced, or when the liquid unevenly protrudes from the fibers [5–7], the flow can interact with neighboring fibers, leading to new flow patterns and dynamics. Here, we explore such flows through experiments using nylon fibers and glycerol-water mixtures.

We perform experiments using the setup shown in Fig. 1(a). Our custom-built apparatus features a linear actuator controlled by an Arduino, microstep driver, and stepper motor, allowing precise control over the position and separation rate of two vertically anchored nylon fibers. We introduce glycerol-water mixtures—dyed orange for contrast—at a flow rate Q between two fibers with equal radius $0.15\ \text{mm} \leqslant r_f \leqslant 0.35\ \text{mm}$ separated by a distance $0.5\ \text{mm} \leqslant w \leqslant 6\ \text{mm}$. We varied the ratio of glycerol to water to achieve a range of viscosity $25\ \text{m Pa s} \leqslant \mu \leqslant 405\ \text{m Pa s}$. The surface tension of these solutions was $59.5\ \text{m N/m} \leqslant \sigma \leqslant 62.7\ \text{m N/m}$ and a strict testing protocol was followed to ensure no contamination altered the liquid properties. The magnified region of Fig. 1(a) shows the two distinct flow types we observed: thin sheets (enclosed by the left gray box) and bridge patterns (enclosed by the right gray box). The flow type depends on how the flow is applied to the fiber. When the liquid initially spans the gap w, wetting both fibers as it exits the nozzle, it forms a thin, continuous liquid sheet that extends the full length of the fibers. Above a critical flow rate Q_c, the sheet persists indefinitely until the flow is stopped. The liquid sheet is stable against external perturbations and can be stretched, gradually thinning until eventually rupturing along the midpoint between the fibers. Alternatively, if the flow is applied to a single fiber, the liquid destabilizes into discrete beads that can interact with a neighboring fiber when w is small. These interactions result in a pattern of isolated liquid bridges flowing down the fibers with uniform spacing and velocity.

The shape of flowing liquid bridges exhibits similar features to that of static bridges between fibers [8,9]. Notably, as the separation distance w between the fibers increases, the vertical length

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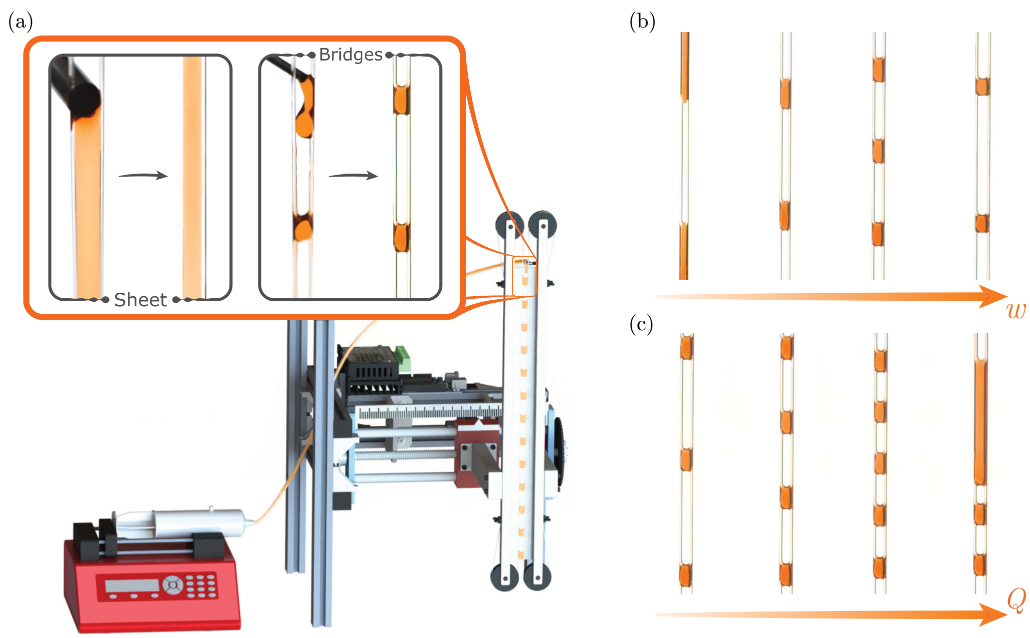

FIG. 1. (a) Experimental setup with magnified region showing how the liquid is applied to the fiber through a nozzle, giving rise to either a self-sustained sheet (left) or a liquid bridge pattern (right). (b),(c) The liquid bridge patterns depend upon (b) fiber gap w and (c) flow rate Q with the arrows indicating the direction of increasing w and Q, respectively.

of the liquid bridges quickly reduces, as shown in Fig. 1(b). This observation concurs with the findings of Protiere *et al.* [9] regarding static bridges between fibers and results in the formation of rounded, swiftly moving liquid bridges. The bridge spacing decreases as Q increases, resulting in tightly spaced bridges, as illustrated in Fig. 1(c). It is worth noting that the underlying base flow's characteristics influence these bridges' behavior. For high Q, the base flow can become convectively unstable, giving rise to coalescence events that propagate into the subsequent bridge pattern, as exemplified in the rightmost image in Fig. 1(c). Bead-on-fiber patterns interacting with adjacent fibers within fiber arrays for heat and mass transfer have traditionally been considered a system limitation. However, the insights revealed by Fig. 1 suggest an exciting opportunity to harness these interactions for enhanced liquid control. While the speed of periodic beads moving along a fiber is only slightly tunable through the flow rate Q, the velocity of liquid bridges between fibers can be readily adjusted across a wide range by varying the fibers' separation distance w. This presents a practical and effective means to optimize the liquid's retention time within heat and mass transfer systems.

The exploration of liquid bridge patterns and self-sustained sheets can be extended by introducing added degrees of complexity to the system. For example, liquid bridges are readily observed in systems with more than two fibers ($n > 2$), as demonstrated in Fig. 2(a). Princen [8] predicted several exotic interfacial shapes for static liquid between fibers when $n > 2$. These have yet to be explored for liquid flow between fibers but could yield new dynamic behaviors and complex shapes with implications for the design of innovative interfacial heat and mass transfer applications. Additionally, these results can be applied to many fiber-based liquid transport techniques, such as the Chinese brush [10] and bioinspired methods [11], and establish the framework for developing novel transport methods. Liquid bridges and sheets can flow between curved fibers if the inclination angle and fiber gap are small enough to ensure sufficient capillary adhesion between the liquid and fibers. Figure 2(b) shows three illustrative examples of flow between curved fibers: (left) a liquid

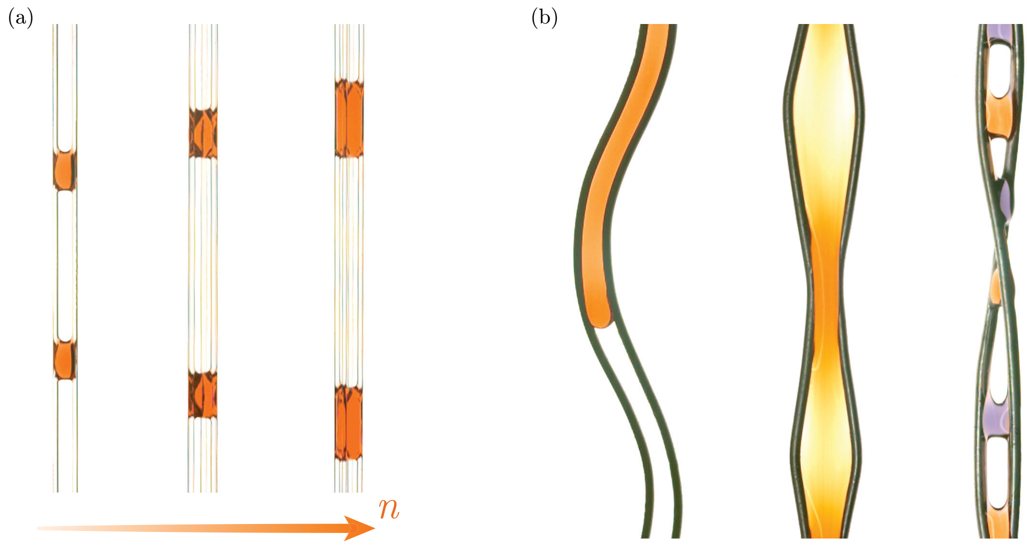

FIG. 2. (a) Liquid bridge patterns as the number of fibers n increases from two (left) to three (middle) to four (right). (b) Liquid flowing between curved fibers can result in liquid sheets with curved paths (left) and variable thickness (middle), and liquid bridges that rotate about an axis (right).

sheet flowing down a sinuous path; (middle) a liquid sheet flowing down a varicose path; and (right) liquid bridges rotating between helical fibers. Note that these curved paths require a malleable metal wire and its associated change in wetting properties from nylon alters the flow properties. Thus, these images are purely illustrative, and future work into wettability and fiber curvature effects would be valuable. The middle image of Fig. 2(b) is particularly noteworthy as the darker and lighter regions indicate thicker and thinner regions of the sheet. This demonstrates how flow down curved fibers can passively control liquid sheet thickness—an intriguing observation considering the sheet remains stable without the need for surfactant. When the working fluid is curable, such as a silicone elastomer, flow down curved fiber provides a potential method for creating long, twisted ribbons with variable thickness.

About the video. This video provides a comprehensive and visually engaging overview of experiments investigating liquid flow between two vertical fibers. The video begins by guiding the viewer through the experimental procedure using strategic camera shots. The two flow types observed in experiments, liquid sheets and bridge patterns, are introduced by demonstrating their formation. A stable liquid sheet is formed, which eventually breaks when the fiber spacing increases to a critical length. The dependence of experimental parameters, including flow rate, fiber gap, and the number of fibers on the liquid bridge patterns, is shown using side-by-side comparisons to provide clear and compelling visual effects. The video concludes by showcasing the beautiful patterns that result from flow between curved fibers, which adds visual interest and highlights the potential of these flows in science, engineering, and art.

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