Liquid transport

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Surface-engineered microfibers provide liquid transport flexibility

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Fibers featuring anisotropic structures for liquid transport are often limited to specific liquids and are impractical for large-scale manufacturing. Now, a microfluidic fabrication technique produces continuous hemline-shaped microfibers with improved liquid transport properties and tunable flexibility.

Nature has inspired numerous advancements in liquid transport along slender structures, such as cactus-inspired spine structures[1] and heterostructured fibers mimicking the architecture of spiders' silk[2]. These materials exhibit directional water collection but have limited transport rates and directional control. Furthermore, manufacturing structured fibers for liquid transport is challenging. Advances in microfluidics have partially addressed these limitations by allowing high throughput of non-uniform fibers with cross-sectional anisotropy[3]. However, to achieve continuous liquid transport and directional control, axial anisotropic patterns are required that, until now, have required advanced techniques that limit their accessibility.

Now, writing in *Nature Chemical Engineering*, Luoran Shang, Yuanjin Zhao and co-workers report pulsed microfluidic flow to produce flexible, hemline-shaped fibers that enable liquid-independent transport along flexible fibers[4]. The fibers were fabricated through rapid polymerization of a fluid jet formed in a piezoelectric microfluidic platform that generates a coaxial two-phase flow. The inner fluid was a photocurable solution of polyethylene glycol diacrylate with an added photoinitiator while the outer fluid was pure water. These fluids are miscible, with negligible interfacial tension, and thus have a deformable interface that was controlled by the piezoelectric signal that generates oscillations of the jet that were 'frozen' into the fiber by irradiating with an ultraviolet (UV) light source. The resulting shapes are axially asymmetric due to the advection of the non-constant base flow down the jet axis and defined by azimuthally symmetric cavities connected by sharp wedge corners resembling a hemline (Fig. 1a). Here, we would be remiss for not making the connection between the hemline shapes and the Kelvin–Helmholtz instability readily seen in cloud formations. Nevertheless, the authors demonstrate precise control over the geometry of the hemline microstructures and overall flexibility of the fiber, as these depend on the operating parameters and fluid properties, which is demonstrated at nominal speeds of 1.51 cm s^{-1} in this manufacturing technique.

Directional liquid transport occurs along the microstructured fibers through capillary action; the rear contact-line is pinned at the sharp wedge corner, preventing motion in that direction, while the front contact-line advances through, and fills, the cavity by capillarity, with this process repeating in the subsequent cavity and so forth. Liquid transport along a fiber in contact with a hydrophilic substrate occurs in the interstice region between the fiber and the substrate. Here, the transport speed is injection rate dependent, so long as the liquid does not overfill the cavity, resulting in a bidirectional flow with the components transverse to the fiber. The situation is more complicated when the substrate is hydrophobic, as it is not possible to transport liquid with a single fiber because it is not energetically favorable; however, the authors overcome this challenge by employing two fibers that are co-oriented such that a cavity is formed between the fibers, thus allowing for liquid transport due to the mechanism described above (opposite-oriented fibers show strong drop pinning). This concept can be used for a microfluidic switch (Fig. 1b), where transport can be stopped by simply separating the fibers. Several working liquids were tested showing that qualitative trends for the transport speed are consistent with the coefficient of penetrance $\gamma\cos\theta/\eta$ from the Washburn equation; speed increases with surface tension γ and decreases with contact angle θ and viscosity η.

A myriad of transport applications are demonstrated by the authors. These include the ability to transport liquids over long working distances, including complex curved paths due to the flexibility of the fibers, and through another immiscible liquid, including the recovery of water through an oil layer in the stratified system shown in Fig. 1c. Bulk liquid transport can be increased through parallelization using fiber bundles, which can also be used to separate a single liquid drop into multiple drops or mix different liquid drops, as relevant to microreactors.

Over recent years, the utilization of microfluidics to scale up production of previously impractical materials has exhibited immense industrial impact, as seen in the case of double emulsions[5] now produced in substantial quantities for high-end cosmetics. This is a similar strength of the current manufacturing technique for microstructured fibers. It is not difficult to envision applications such as fog-harvesting nets that would benefit from simply replacing conventional fibers with bundles of hemline-shaped fibers.

The ability to parallelize liquid transport is readily seen in nature such as in spider webs and cactus bristles[1,2]. Developing a 3D printer capable of continuously extruding rapid-curing structured microfibers could expand the current 2D array designs to more intricate 3D structures. These structures could be rigid or pliable, depending on the fiber's flexibility, and closely emulate nature's water-collection designs. Figure 1d illustrates such a concept, where the bristles of a cactus reach outward in many directions from a central anchor point for enhanced fog collection. In nature, the conical shape of the bristles moves water towards its base. Flexible, hemline-shaped fiber bundles, when used in an artificial cactus, could improve transport by coalescence through elastocapillary action[6] during nighttime condensation. As the liquid concentration decreases during daytime drying, the fibers separate to maximize water collection (Fig. 1d).

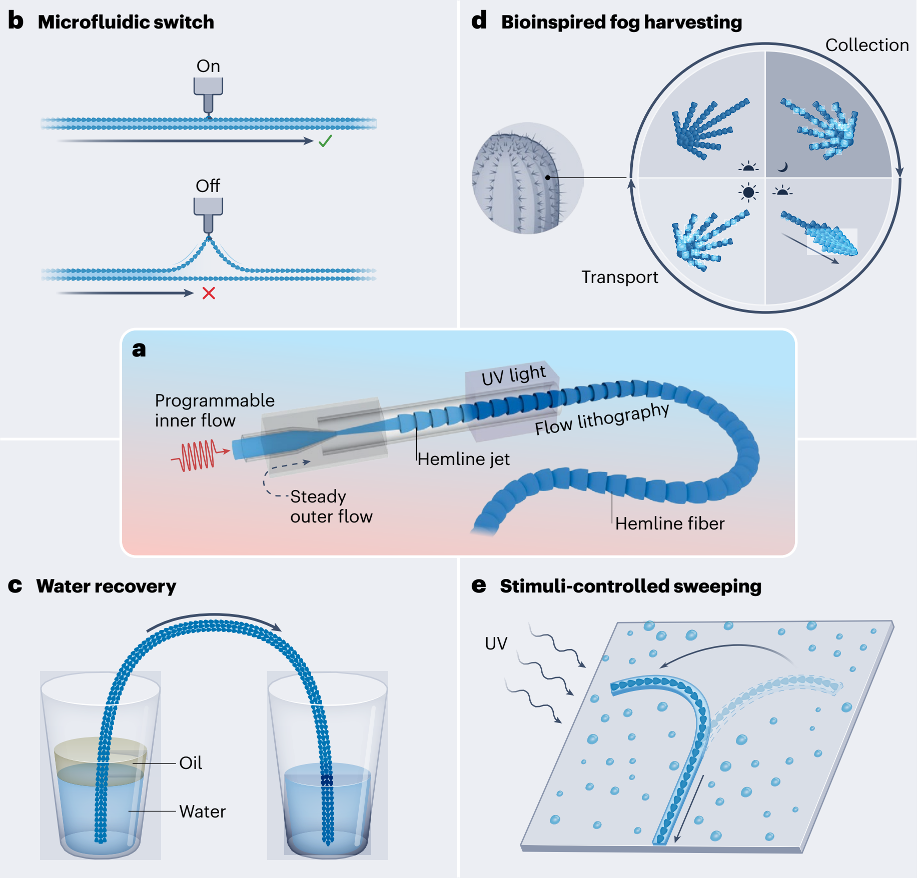

Fig. 1 | Applications using hemline-shaped fibers for liquid transport. **a**, Microfabrication of hemline-shaped fibers using piezoelectric microfluidics. **b**, A microfluidic switch allows liquid transport when two hemline-shaped fibers are in contact but restricts flow when the fibers are separated. **c**, Transport can be parallelized by using a bundle of co-oriented fibers that can transport water through an oil layer. **d**, An artificial cactus with hemline-shaped bristles can be used for water harvesting. The magnified region illustrates the daily cycle of the bristle bunch where the fibers' flexibility permits elastocapillary 'zipping' during their nocturnal collection phase and corresponding 'peeling' during the diurnal drying and transport phase. **e**, Flexible, UV-responsive, hemline-shaped fiber 'sweeps' a droplet-laden surface to collect the liquid in the swept region. Panel **a** adapted with permission from ref. 4, Springer Nature America, Inc.

Responsive materials offer the potential for actively controlling liquid transport; material motion activated by UV light has been demonsrated[7]. Manufacturing structured fibers from such responsive materials holds strong potential. For instance, UV signaling of a hemline fiber could be used to sweep wet surfaces for liquid capture (Fig. 1e). Moreover, notable strides have been made by developing chemically treated fibers capable of simultaneously collecting and purifying water[8]. Combining this chemical treatment with active material response has the potential to create multifunctional surface-engineered fibers.

The potential applications for surface-engineered microfibers are extensive, but they come with several practical challenges and unanswered questions that warrant further research. To enhance fiber production rates, it is imperative to develop rapid-curing liquid solutions, while the determination of the optimal hemline shape for maximizing liquid transport demands more rigorous experimental testing and theoretical considerations. Moreover, the uniqueness of the hemline shape as a means of inducing liquid transport is yet to be firmly established, as there may be other transport-inducing shapes achievable through microfluidic techniques. Nonetheless, Shang, Zhao and co-workers have developed a structured microfiber with wide-ranging applications and opened the door for many new studies involving liquid–fiber interactions.

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Competing interests

The authors declare no competing interests.