TOWARDS FIBER-BASED MICRO- AND NANOFLUIDICS

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Abstract: We describe a new method of controlled manipulation of micro-quantities of fluids by using a conduit formed by two parallel fibers. We show that a droplet of a wetting fluid, which is deposited on the fiber rails, can be either pinned at the point of deposition or driven to spread along the interfiber channel. The principle of controlled manipulation is that the droplet spreads out or comes back spontaneously due to the action of capillary forces, which critically depend upon the interfiber spacing. Compared to conventional microchannel design, the suggested fiber-based conduits significantly reduce the viscous drag. We present a quantitative analysis of the phenomenon of droplet spreading and the critical conditions for droplet pinning. Depending on the fiber diameter, the fiber-based conduits provide an opportunity of fluid manipulation in micro- and nanofluidic devices.

Keywords: Microfluidics, nanofluidics, capillarity, fibers, Lucas-Washburn law, Bosanquet law.

1. INTRODUCTION

In conventional microfluidic devices the fluid is pumped by applying pressure drop, temperature drop or voltage. In this paper, we present a new principle of controlled fluid transport at micro- and nanoscale. As an alternative to the existing microfluidic platforms based on photolithographically fabricated channels, we suggest to exploit the fiber-formed conduits. Recent advances in manufacturing of nanofibers make possible the fabrication of building blocks for fiber-based micro- and nanofluidics. The fiber-based conduits possess unique features that significantly ease the manipulation of fluids in a controllable manner. In particular, capillarity succeeds in governing the droplet self-propulsion without the need for an additional external means. The viscous drag, which is the major obstacle in...
conventional microfluidics, can be significantly reduced due to a relatively small area of the fluid-solid contact surface.

This paper is aimed at the explanation of the physical principle of manipulation of fluids by fiber rails, a conduit composed of two parallel fibers. For these purposes, the details of the fluidic device are not important. For the sake of simplicity, we take aside the design of fluidic devices exploiting this principle and focus on the specifics of droplet spreading over two parallel fibers to demonstrate the advantages of this new technique.

2. SPREADING/PINNING OF DROPLETS ON FIBER RAILS

Droplets on fibers take on the equilibrium configurations, which cannot be realized on planar substrates. Remarkably, if a droplet of a wetting fluid could spread completely over a planar substrate, it would never spread on a fiber to form a sheath-like film. Typically, a spherical droplet deposited on a fiber will

Figure 1. The left is the barrel (hexadecane) and the right is the clam-shell (water) configurations of droplets on a single wire.

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which determines the equilibrium droplet state. As shown in Fig. 2, the shape and the cross-sectional area of the liquid column in the fiber channel depend on the inter-fiber spacing. This distance determines both the capillary pressure and the hydraulic resistance.

Thus, changing the inter-fiber spacing, we can manipulate with the droplet. Fluid can be forced to come into the fiber channel or it can be collected into a droplet. The principal point is that the droplet spreads or shrinks back spontaneously. Moreover, compared to the conventional microfluidic channels, the fiber channels reduce the viscous drag significantly. Indeed, at the surfaces of menisci the fluid slips freely, thus accelerating the fluid flow. The quantitative analysis of rate of droplet spreading and critical condition characterizing the criterion of droplet spreading/pinning are done below.

3. EXPERIMENTAL

3.1. Imaging System

The imaging system consists of a high-speed digital CCD camera (Dalsa CA-D1-0256A) with a video zoom lens (Navitar Zoom 6000), a power
supply, an image acquisition board, a light source and a fiber mounting assembly. The camera connected to PC has a resolution of 256x256 pixels and allows one to record up to 200 frames per second. Most of the images were taken normally to plane of fiber rails (top view) with a frame rate of 45 frames per second. The software developed at TRI provides the direct quantification of the position of the propagating menisci. The fiber mounting assembly was designed to enable a precise control of the inter-fiber spacing by the attached micrometer gauge. The fiber separation and alignment are independently controlled by the image analysis system.

![Diagram of experimental setup and fiber mounting assembly.]

**Figure 3.** a) Experimental setup; b) Schematic diagram of the fiber mounting assembly.

### 3.2. Experimental Protocol

The experimental procedure was as follows. The stainless steel wires of D = 0.1524 mm diameter were taken to form the rails. Spreading experiments were performed with hexadecane (Aldrich). The fibers were cleaned with acetone and mounted providing a desired inter-fiber separation. In order to prevent the droplet from spreading immediately upon deposition, the fiber mounting assembly was equipped with a fiber separator (see Figure 3). The separator temporarily keeps the fibers apart beyond the critical spreading separation. The fiber separator is activated manually. In the normal position, the fiber separation is determined by a micrometer gauge. A droplet of approximately constant volume (1.4 μl) is placed on the fibers kept apart by the fiber separator. At this stage, a stable barrel-shaped droplet is formed and the necessary adjustments of the camera position and setting are done. The recording process is started simultaneously with the release of the handle thus
bringing the fibers instantly to the desired distance. At this moment, the droplet begins to spread. At least 10 runs were conducted for each experimental condition and the average values were reported. All experiments were conducted at the room temperature.

4. RESULTS AND DISCUSSION

4.1. Spreading/Pinning Criterion

In Fig. 4 we show the complete wicking time as a function of the fiber separation for hexadecane droplets. The complete wicking time is the time interval counted from the start of droplet spreading (i.e. the moment of release of the handle) to the droplet disappearance. For closely spaced fibers the spontaneous wicking was found to be very slow. In particular, at the inter-fiber spacing of 0.0145 mm, the wicking time was about 4 minutes. However, the wicking time gradually decreased with the increase of the inter-fiber spacing. At the inter-fiber spacing of 0.105 mm, the wicking time was about 20 s. The fastest wicking occurred within ~10 s at the spacing of 0.121 mm. Beyond this distance, the wicking time increased with the increase of the inter-fiber spacing. At the inter-fiber spacing of 0.1238 mm (that is about \( d = 0.83 \) \( D \)), the liquid wicked out very slowly, but still completely depleting the droplet reservoir. Intermediate situation with a slight movement of liquid column (partial wicking) was observed instantly before reaching the critical \( d_c \). The critical inter-fiber spacing, at which hexadecane droplet remained stable without wicking, was found to be 0.1275 \( \pm 3 \times 10^{-3} \) mm. For \( d > d_c \), the menisci did not move and the droplet remained in its stable barrel-shaped configuration. Schematic pictures of the cross-sectional shapes of liquid columns between parallel fibers at different \( d \) are shown in Figure 2.

![Figure 4](image)

**Figure 4.** a) Critical spreading condition found by the dynamic method. The spreading/pinning criterion for hexadecane is \( d_c = 0.1275 \) mm. As \( d \) approaches the fiber diameter, \( D = 0.1524 \) mm, the wicking time increases steeply. b) Meniscus displacement versus square root of time. The inter-fiber spacing is 0.0955 mm.
4.2. Wicking Kinetics

The selected images in Figure 2 show the process of spreading of hexadecane droplet along the fiber rails. The velocity of the meniscus propagation is determined by the ratio of the driving force (capillary pressure) to the viscous drag. This velocity is generally presented by the Lucas-Washburn-type (LW) equation:\(^{14,15}\):

\[
\frac{dL}{dt} = \frac{k}{\eta L} (P_d - P_c)
\]  

(1)

Here the \(L\) is the length of liquid column, \(k\) is the permeability of the inter-fiber channel, \(\eta\) is the viscosity of the liquid, \(P_d\) is the pressure in the droplet, \(P_c\) is the capillary pressure at the meniscus, and \(t\) is time. The permeability \(k\) is almost independent of the length of the liquid column. It is proportional to the cross sectional area of the liquid column. The capillary pressure at the meniscus is much larger than the pressure in the droplet. Thus, the right hand side of Eq.1 is proportional to \(-1/L\). Therefore, in the intermediate stage of wicking, a plot of the meniscus displacement (\(L\)) versus square root of time (\(t^{1/2}\)) should be linear. It is linear indeed, see Fig. 4b). Although the LW equation describes the intermediate and late stage of wicking fairly well, the initial velocity is finite in accord with the Bosanquet law\(^{16-19}\). According to Bosanquet, in the very beginning of spreading the wetting force, which is proportional to the surface tension times the fiber diameter, \(F_w = 2\pi d \sigma \cos \theta\) are balanced by the inertial forces, proportional to the velocity squared times the column cross-section, \(F_{in} \propto U^2 dD \rho\), where \(\rho\) is the fluid density. Thus, the meniscus velocity scales as

\[
U_{\text{Bosanquet}} \propto (\sigma / d \rho)^{1/2},
\]

(2)

where \(\sigma\) and \(\rho\) are the surface tension and density of the liquid, respectively. In the most interesting regime of near-critical inter-fiber spacing, since \(d_c \sim D\), the estimate (2) can be rewritten as

\[
U_{\text{Bosanquet}} \propto (\sigma / D \rho)^{1/2}.
\]

(3)

The experiments show that the droplet spreading along fibers follows the Bosanquet law at the very beginning of its run and the Lucas-Washburn laws at late times. To double check the applicability of the Bosanquet and Lucas-Washburn models, we tested the flow patterns by adding TiO\(_2\) particles into hexadecane. As expected, the streamlines are monotonous lines starting from the droplet surface and ending at the menisci. At the transition zone near the
droplet edges, the streamlines condense to form a stream tube in the inter-fiber channel. No vortices were observed.

5. CONCLUSIONS

As shown, the fiber rails can be used for controlled delivery or collection of micro-quantities of wetting fluids in the form of droplets. Determined by the inter-fiber spacing, the rate of fluid transport through the inter-fiber channels can be controlled by external fields or forces. Compared to flow through the micropipes and microchannels, the viscous drug is reduced due to a partial replacement of the supporting walls by the free surfaces of menisci. The viscous drag can be further decreased by addition of specific surfactants that form the lubricating layers at the liquid/solid interfaces. Although we demonstrated the principle of droplet manipulation by fiber rails on the submillimeter scale, the capillary mechanism should be effective at the micrometer and submicrometer scales as well. The fiber rails can be built of any fibers and scaled down by using, in particular, composite carbon nanotube-polymer fibers, carbon nanopipes, or electrospun polymer nanofibers. The proposed principle of exploiting fiber-based conduits opens new perspectives in micro- and nanofluidic technologies.

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References


