Paper on a disc: balancing the capillary-driven flow with a centrifugal force†

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This paper describes the active control of the capillary-driven flow in paper using a centrifugal device.

Paper microfluidic devices, in which wicking allows passive transport of fluids, has attracted much attention due to their intrinsic advantages such as low-cost, flexible, and simple fabrication and easiness to store, transport, and dispose.1 Paper absorbs liquid through capillary force, allowing a fluid to be transferred along the paper without any active pumping. A number of methods for constructing paper-based channel networks have been developed to achieve various practical functions such as transport, mixing, and detection of biochemical contents.2–8 In general, liquid transport in paper depends on the structure and material of the pre-manufactured paper, and is always one-way. It has almost never been possible to control the flow in paper by applying an external force in a continuous and active manner. Here, we provide a novel concept for active control of the flow in paper using a centrifugal device. We integrated a paper strip into a disc-shaped centrifugal microfluidic platform, and rotated it with various spin speeds to characterize the flow in the paper under different strength of the centrifugal force. Not only the flow rate could be controlled in a programmable manner but also the fluid could be moved in the reverse direction by applying a comparatively high centrifugal force to balance the capillary force.

The wicking distance, $h$, shown in Fig. 1a can be obtained through the Darcy’s law as follows:

$$\frac{\partial h}{\partial t} = \frac{\kappa}{\eta} \frac{\Delta P}{h}$$

(1)

where $\kappa$ is the permeability of the paper and $\eta$ is the fluid viscosity. When we consider the centrifugal pressure, the net driving pressure for absorption is given by

$$\Delta P = \Delta P_c - \rho \omega^2 \left( \frac{R_0^2 + R^2}{2} \right) (R_0 - R)$$

(2)

where $\Delta P_c$ is the capillary pressure, $\rho$ is the density, and $\omega$ is the angular velocity of the rotating disc. Here, $h = R_0 - R$, thus the pressure is given by

$$\Delta P = \Delta P_c - \rho \omega^2 \left( \frac{R_0^2 + R^2}{2} \right) \frac{h}{5}$$

(3)

Through this theoretical model, we could expect that the flow rate of a fluid along the rotating paper might decrease as the spin speed and the wicking distance increase. There would be no more absorption of the fluid along the paper if the centrifugal force, which depends on both the spin speed of a disc, the radial position of a paper, and the wicking distance of the fluid, toward the outside of the disc completely compensates the capillary-driven flow toward the inside of the disc. We defined the length of the wetted area, at which the fluid front changes no longer, as the equilibrium wicking distance. The theoretical value of the equilibrium wicking distance, $h_0$, against the rotating speed could be calculated by assuming $dh/dt = 0$ as below:

$$h_0 = R_0 - \sqrt{\frac{2\Delta P_c}{\rho \omega^2} - \frac{R_0^2}{R}}$$

(4)

According to eqn (4), the equilibrium wicking distance might significantly decrease as the spin speed increases.

For proof of this concept, a paper strip was integrated into a rotating disc as shown in Fig. 1b. A filter paper (Grade 4; Whatman Ltd., Kent, UK), of which the pore size is 22.5 μm, was cut into a 45 mm × 3 mm strip and fixed on a plastic disc. The water chamber and the holes for water injection and ventilation were milled in the bottom and the top discs, respectively, using a CNC milling machine (3D modeling machine; M&I CNC Lab, Osan, Korea). A double sided tape was cut by a cutting plotter into a specific design for bonding the top and bottom plates, and fixing the position of the paper strips between them. For the experiments, 70 μL of de-ionized water was injected into the chamber, then the disc was spun on a rotor following a specific spin program. The change of the fluid front on the paper was monitored using a charge-coupled device camera with a strobe light synchronized with the spin speed to capture images at a specific position of the rotating disc.

Temporal change of the wicking distance of water in the paper against the rotating speed is shown in Fig. 2a. We applied various spin speeds from 300 to 6000 rpm. As the spin speed increased, the flow rate of the fluid absorbed by the capillary effect along the paper strip decreased as shown in Fig. 2b. At 300 rpm, all the paper was wetted within 1 min, while the fluid front readily approached the steady state position at 6000 rpm. In addition, the flow rate showed

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a tendency to be gradually decreased as absorbing fluids according to the time. These results were consistent with our expectations on the basis of the theoretical model. The equilibrium wicking distance was also experimentally explored and compared with the values calculated by eqn (4). As shown in Fig. 2c, the experimental values showed excellent agreement with the theoretical values. The flow rate became slower when a filter paper which has a smaller pore size—11 μm (Grade 1)—was applied (see ESI, Fig. S1†). This result is predictable based on the theoretical background that the permeability of the paper, $k$, is proportional to the square of the pore size.$^9$

Active control of the flow rate in a paper has also been demonstrated using a programmable centrifugal microfluidic system. We could realize constant flow rates in paper strips as shown in Fig. 3a, by applying a spin program, which continuously rotates the disc as varying the spin speed (Fig. 3b). In the case of experiments 1 and 2, the wicking velocity was almost constant after 10 s time point—about 0.4 and 0.13 mm s$^{-1}$, respectively—different from experiment 3, in which the wicking distance tended to be saturated. Here the disc was always rotated at 6000 rpm for 10 s at first to stabilize the initial flows for realizing more reproducible flow rates. Based on this scheme, we could also precisely choose the initial time to start to flow the fluid along the paper with a specific flow rate of interest.

De-wetting of the wetted paper could be also possible by rotating the paper with relatively high spin speed. We could determine the immediate change in the whiteness of the paper as well as the increase in the amount of the water in the sample chamber during the spin-drying process at 6000 rpm (see ESI, Fig. S2†). Based on the difference in the intensity, we could define a ‘partially wetted’ area, where residual liquid droplets remain though most of the fluids drained out, as distinguished from the wetted area and the dried area shown in Fig. 1a. The de-wetted water was absorbed by the paper again when the rotating speed was slowed down. Based on these phenomena, we

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**Fig. 1** Schematic illustrations of (a) the force balance in a rotating paper and (b) the configuration of a centrifugal device for rotating paper strips. Paper strips were integrated into a plastic disc to demonstrate the control of flow in a paper by balancing capillary-driven flow with a centrifugal force.

**Fig. 2** The wicking distance of water in paper strips on a rotating disc according to the spin speeds. (a) Pictures of paper strips wicked as rotating on a disc with various spin speeds from 700 to 3000 rpm. The wicking distance at 700 rpm was significantly longer than that at 3000 rpm. (b) Temporal change of the wicking distance against various spin speeds—300, 700, 1000, 2000, 3000, and 6000 rpm. (c) The equilibrium wicking distance against the rotating speed.
demonstrated a repetitive wicking–draining, in which the wicking of water with a specific flow rate and the de-wetting of the paper happen by turns, as shown in Fig. 4a. Here we spin the disc at 2000, 1000, 700, and 300 rpm between each draining process, for which the disc was spin at 6000 rpm for 30 s, as shown in Fig. 4b. The wetted area increased under the same tendency with that in Fig. 2b during the wicking step, while immediately decreased during the draining step. This active control of wicking–draining of water could be precisely conducted, thereby it was also possible to make the wetted level varies like a square wave by applying a repetitive up-and-down spin program (see ESI, Fig. S3†). On the other hand, the position of the interface between the partially wetted area and the dried area was maintained even during the draining step. This phenomenon shows that the residual fluids remained inside the paper until they completely evaporate even when we spin it at 6000 rpm, if the paper has been wetted once.

This active control of the flow in paper using a centrifugal force offers new possibilities and advantages in both aspects of paper microfluidics and centrifugal microfluidics. Here we first demonstrated active control of the flows in paper by applying an external force. Of course, the additional requirement of external instrumentation such as a rotor may fade away the intrinsic advantages of paper-based microfluidic devices, which is one of the simplest types of analytical devices. However, this kind of novel attempt may provide a new chance to exploit advances in that field. In a different point of view, we first integrated a paper into a centrifugal microfluidic device, and characterized the flows being absorbed by the rotating paper. This study implies the possibility of this kind of device as an advanced centrifugal microfluidic platform in various aspects. For example, this paper may work as a component for fluid transport, especially toward the inside of a rotating disc against the centrifugal force, in a lab-on-a-disc device. In addition, the repetitive wicking–draining or the actively controlled flows in paper on a disc can be utilized for in vitro diagnostic test strips based on the principles of immunochromatography.

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Notes and references