Flow control in paper-based microfluidic channel by using hydrophobic tape barrier on the paper surface

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Abstract. Paper-based microfluidics offers a simple, cost-effective, and versatile platform for fluid manipulation and analysis. Despite significant advancements in paper fluidics, the flow control in paper channel remains a challenging task. In this regard, we have developed a flow delay channel in paper using rectangular tape patterns on the paper surface. We have investigated the effect of hydrophobic tape barriers with varying widths. The designing and cutting of the hydrophobic tape and paper channel was performed by CO2 laser machine using CorelDraw software. Once cut, the tape barriers were attached to the paper surface and then passed through the roller press machine for proper adhesion of tape pattern onto the paper’s surface. From experiments, we observed that by increasing the width of tape, the delay also increased. The hydrophobic tape on the paper surface caused resistance to the flowing fluid. Due to this surface resistance, flow velocity reduced, and the time delay increased. We believe that our novel approach will provide an alternative method of flow control for paper-based microfluidic devices and can be utilized in various food quality sensors and lateral flow devices.

1 Introduction

Microfluidic paper-based analytical devices (µPADs) are a rapidly growing field for development of low-cost, portable, and easy-to-use diagnostic tools. One of the main advantages of using paper as a substrate for microfluidic devices is its ability to facilitate capillary flow, which is driven by the wicking of fluids through the porous paper material. Paper-based microfluidic devices have been used for a wide range of applications, including medical diagnostics, environmental monitoring, food safety testing, and water quality analysis. They offer several advantages over traditional microfluidic devices, including low cost, simplicity, and portability. Paper-based devices can also be easily fabricated using simple printing and cutting techniques, making them accessible to a wide range of users.

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After the introduction of paper chromatography, paper-based sensors went to commercial scale with the advent of famous glucose test kit for human blood [1] and pregnancy test strip [2] that was launched in 1988. For the detection of contaminants and bacterial activity in food and beverage, these devices provide a low-cost, portable nature and simplicity of operation. For the detection of bacteria in food items, enzymatic activity is important for detection. Live bacteria had been detected in μPADs by using colorimetric detection of enzymes produced by bacteria [3]. Swab sampling from food items has also been investigated by culturing with chemicals and then transferred to the paper device for testing [4].

Controlling flow of fluid in microfluidic devices have been essential for accurate and reliable operation, particularly in diagnostic applications where small variations in fluid flow rates can lead to erroneous results. Despite advantages of paper devices, however, controlling fluid flow in paper can be challenging due to the inherent variability in the paper material as well as passive nature of flow by capillary action.

In this research, we used physical flow control method using hydrophobic tape barriers to enhance the time delay in paper channel. Hydrophobic rectangular tape barrier is attached on the paper surface to experience a resistance of flow in paper channel at the boundary. Due to the adhesive nature, a drag effect is produced, which reduces the flow velocity and increases the time delay. By increasing the width of tape pattern, this time delay also increases as it offers more resistance to flow.

2 Theoretical Background

Flow in porous media is a capillary flow due to surface tension of fluid in paper surface. The fluid flow in straight one dimensional paper channel follows the Lucas Washburn equation, which states that penetration length has a direct relation with square root of time [5]. As the penetration length increases, viscous drag also increases, and it reduces the fluid velocity with time.

\[ L = \sqrt{\frac{\gamma \cos(\theta)}{2\mu}} \cdot \sqrt{t} \]  

(1)

Here \( \gamma \) is surface tension, \( \theta \) is a contact angle of a working fluid with paper channel and \( r \) is the pore radius.

3 Material and Methods

Designing and cutting of Whatman filter paper of grade-1 (Whatman International Ltd. Maidstone, England) and rectangular transparent scotch tape (Tico Brand) patterns were performed by 50W CO2 laser cutting engraving machine (4040, Liaocheng Beike Electronics Information Materials Co. Ltd, China) using CorelDRAW 2020 (64bit) software. After cutting, the paper channel was sandwiched between rectangular and elliptical hydrophobic tape patterns as shown in Fig. 1. Then, it was passed through the roller press machine (AiPai-Fm480) for proper adhesion of the tape patterns onto the paper surface.
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There were eight number of rectangular tape patterns on the paper surface of 40 mm in length as shown in Fig. 2. The height of each single tape barrier was 2 mm and the gap (pitch) between two consecutive tape barriers (which represented by “w”) was 2 mm. Image J software was utilized to measure the wicking length of working fluid. The entire fabrication process is shown in Fig. 3. Oleic acid (Sigma Aldrich chemical GmbH, Germany) as working fluid was used to wet out the paper channel.

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Fig. 3. Schematic illustration of the fabrication process of paper channel with hydrophobic tape patterns

4 Results and Discussion

Rectangular tape patterns on top and bottom side of paper surface functioned as hydrophobic barriers which caused resistance to flow of working fluid in the paper channel. Fluid flow result with time lapse images of flowing oleic acid in paper channel were taken during the experiment are shown in Fig. 4. We used different tape patterns like elliptical and rectangular investigating their effect on flowing fluid (Fig. 5 (a)). The fluid would normally take 10 mins to travel 20 mm in paper channel. However, with the tape patterns added on both sides, we observed a significant flow reduction to 50 mins for 20 mm. It was also observed that the rectangular patterns experienced a higher resistance to flow compared to elliptical ones due to higher contact area with the paper channel. To achieve maximum time delay, we increased the width of rectangular tape patterns. By increasing the tape’s width, time delay also increased from 60 min to ~15 hours as illustrated in Fig. 4 for a full length of 40 mm. Hence, the hydrophobic tape barrier on the paper surface had a pronounced effect on channel resistance to the flowing fluid.

Fig. 4. Time lapse images of oleic acid flowing in paper channel.

Our device is related to food safety applications [6]. For instance, food quality sensors such as time-temperature indicators need their timescale to be as linear as possible for better readout [7]. Moreover, flow control in paper microfluidics is required which can switch the fluid on and off during working [8].
Fig. 5. (a) Length-time curve of flow of oleic acid in paper having different tape patterns. (b) Effect of varying the pitch of patterns (width w) from 3 mm to 5.5 mm on flow velocity.

5 Conclusion

In this research, we successfully achieved a significant flow delay in paper channel by using flow reduction technique of boundary drag using hydrophobic tape barriers on the paper's surface. Several experiments were performed by changing the width of tape barrier on the paper surface. The recorded data from the experiments showed that maximum time delay of 15 hours was achieved by the tape width of 5.5 mm using oleic acid as working fluid. A total of 235% increase in delay was observed as compared to the simple straight channel. We believe, this novel concept will provide benefit to the scientific community working in the field of paper fluidics to alter flow velocities to create cost effective flow control technique which has applications in food quality control such as time temperature indicator.

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References
