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Flow Control in Passive 3D Paper-Based Microfluidic Pump by Variable Porosity †

Syed Farhad Shah, Gohar Hussain and Ali Turab Jafry *

Faculty of Mechanical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi 23460, Pakistan; gme1967@giki.edu.pk (S.F.S.); gme2024@giki.edu.pk (G.H.)

* Correspondence: ali.turab@giki.edu.pk

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Abstract: Active pumps are often used in microfluidic devices for programmable fluid flowrate in a microchannel. Active pumps have some drawbacks due to their large size and requirement of external power. To overcome them, a new class of passive pumps based on capillary action in cellulose material, known as paper-based microfluidic pumps, has recently been explored. In this study, fluid flow in 3D paper-based pumps was investigated using flowrate measurements in microchannels. In order to develop 3D cylindrical pumps, Whatman filter paper grade 1 was shredded, mixed with water, molded and dried. The patterned serpentine channel was created using a CO_2 Laser Cutting/Engraving machine. The 3D paper-based pump was integrated with microfluidic channel. The effect of paper pumps of different porosities on the fluid flowrate through a serpentine microchannel was investigated. It was found that flowrate of the fluid flowing through the channel increases with an increase in the pump's porosity. Moreover, these pumps have the ability to transport larger volumes of liquid with improved flowrate, programmability and control, in addition to being inexpensive and simple to design and fabricate. These 3D pumps will help researchers move closer to developing an effective miniaturized diagnostic platform for point-of-care (POC) diagnostic applications.

Keywords: 3D paper-based pump; porosity; passive pumping; microfluidics; paper-based microfluidics

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1. Introduction

Micropumps are critical components of integrated microfluidic devices that can control and manipulate small volumes of liquids. These pumps are intended to deliver a constant flow rate, fast delivery and easy flow rate adjustment [1]. A wide range of pumping methods have been proposed [2]. Active pumping methods including peristaltic pumps and other positive displacement pumps can quickly transport small sample volumes, but their complexities and external power requirements make them unsuitable for point-of-care (POC) uses [3]. Over the years, a number of passive pumping methods have been proposed as an alternative to active pumps, allowing considerable pumping simplification [4]. These passive pumping methods mainly employ capillary action, surface tension and evaporation to drive fluid flow [5].

Liquid can move passively through porous media, e.g., paper due to its capillarity. Capillary-based liquid transport in various paper shapes including rectangular, circular, triangular and various other geometry-based 2D paper pumps have recently been studied [6]. Two-dimensional fluid imbibition in complex shaped porous membranes has also been discussed [7]. The origami-driven 3D paper pumps for POC applications have been presented [8]. Other 3D paper-based pumps have been explored by stacking different paper sheets one above the other [9]. Two-dimensional and three-dimensional paper-based pumping, despite their many positives, still face challenges in transporting large volumes of liquid with improved flowrates. Moreover, the effect of porosity of the paper pumps on fluid flow through microchannel has not been investigated yet.

In this study, we examined a 3D paper-based microfluidic pump for passively transporting liquid through a microfluidic platform. The proposed pump is a continuous cylindrical structure unlike other 3D stacked pumps. Pumps with same sizes and different porosities were developed to investigate the effect of paper pumping on the flowrate of fluid through microchannel. The suggested approach has several benefits including the ability to carry large sample volumes of liquid, cost-effectiveness and widespread availability of pumping material.

2. Materials and Methods

Whatman filter paper grade 1 was cut into small pieces and mixed with water using a high-rpm grinder. The soaked paper was then inserted in cylindrical molds with sieves at one end to filter the water out. Molds were removed once the paper in cylindrical molds has dried in the oven and hence 3D cylindrical paper-based pumps were developed. The cylindrical structure had a 12 mm diameter and 14 mm height for all samples. To change the porosity of the 3D pump, additional paper was added into the grinder and sieved with a slightly higher pressure from the top to increase structural density of the fibers.

Microfluidic channel was fabricated by creating a serpentine pattern on a double-sided pressure adhesive sheet using a CO_2 laser engraving/cutting machine. This patterned adhesive sheet was covered with transparent plastic from bottom and with acrylic sheet covering the top side. The total length of serpentine channel was 792 mm. Figure 1A shows the top view and side view of the integrated microfluidic channel and the 3D paper-based microfluidic pump as an experimental setup, whereas Figure 1B shows its physical model.

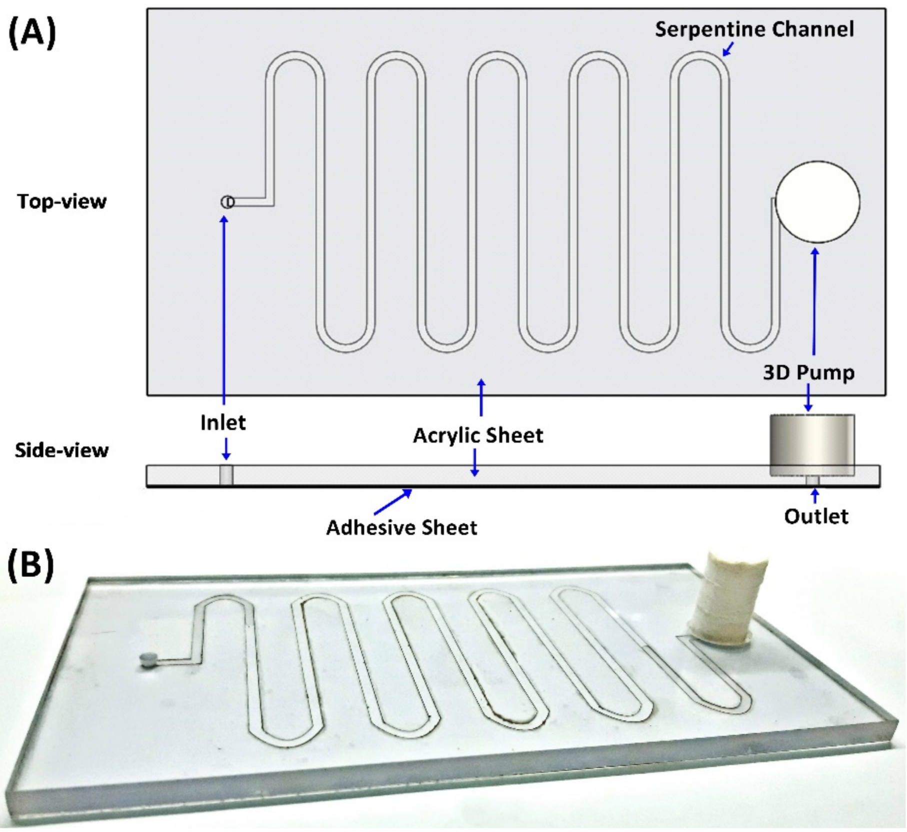

Figure 1. 3D paper-based pump integrated with microfluidic channel (**A**) CAD model showing top and side views; (**B**) fabricated microfluidic channel with cylindrical 3D paper-based pump positioned at the outlet.

The experimental setup is tested for two pumps of different porosities. Porosity, also known as void fraction, is a measure of a material's empty spaces and is expressed as the fraction of the pore volume to the total volume, ranging from 0 to 1 [10].

$$\varphi = \frac{\text{pore volume}}{\text{total volume}} \tag{1}$$

where φ is porosity and total volume is sum of pore volume and solid volume.

Porosity of the 3D pump was determined by imbibition method. The weight of a dry sample was determined initially. Then, the pump was inserted in a flat plate containing water at a minimal height. After the sample was completely imbibed with water, the saturated sample was weighted again. Imbibed fluid volume was determined and as a result, the porosity of the sample was calculated using above equation.

Initially, water was injected to completely fill the serpentine microchannel through the inlet port and then, a passive 3D paper-based pump was integrated with microchannel at the outlet port of microfluidic platform to absorb water. Flow measurements were taken using a camera and image processing by ImageJ to determine flowrate.

3. Results and Discussion

Two cylindrical 3D paper-based pumps of different porosities and the same sizes were experimentally tested to investigate the effect of the pumps' porosity on the flowrate of water flowing through the microfluidic serpentine channel. Porosities of pumps were determined by imbibition method and came out to be 0.72 and 0.48. These cylindrical pumps can carry large sample volumes of water depending on their size with improved flowrates. Figure 2A shows the length of microchannel covered by water with respect to time. Higher gradient of length against time for high porosity pump recorded higher flowrate of water when compared with low porosity pump. This is due to the availability of an emptier (pore) volume to absorb water. Length against time gradient is also higher for low porosity pump initially. This is due to the 3D fluid flow in the pump. However, with an increase in the amount of water absorbed, this gradient begins to decrease gradually, following a similar trend of the Lucas–Washburn equation for 1D flow. This happens due to lesser available surface area to the liquid front compared with the initial condition making it into the 1D flow.

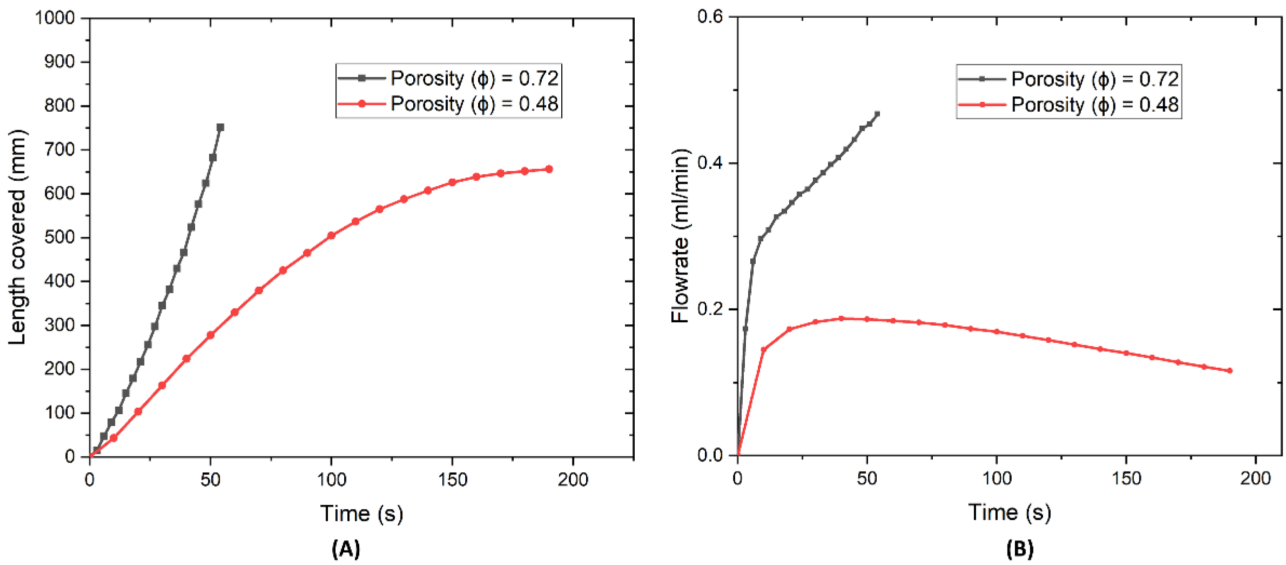

Figure 2. (**A**) Length–time curve for two porosities using a 3D paper-based pump; (**B**) flowrate of water in serpentine microchannel by 3D paper-based microfluidic pump.

Figure 2B illustrates the effect of pumping on flowrate of water flowing through the microchannel. For the higher porosity pump, the flowrate of the fluid moving through the microchannel increases with respect to time, whereas the flowrate of the fluid for the low porosity pump can be partitioned into two segments. For some initial time, the flowrate of water increases due to the 3D fluid flow in the pump, but starts to decrease afterwards, resembling the 1D vertical flow. Available pore volume has increased for the higher porosity pump, and this caused the high capillary pull for water to flow at a higher flowrate. The maximum flowrate achieved was 0.467 mL/min and 0.188 mL/min for the high porosity pump and low porosity pump, respectively. The high porosity pump moved 0.40 mL of water in less than a minute, whereas the low porosity pump took 3 min to move 0.31 mL of water through the channel.

4. Conclusions

In this study, fluid flow in a passive 3D cylindrical pump based on the paper's capillarity was investigated by measuring the flowrate in microchannels. The proposed paper-based microfluidic system can be easily integrated with the existing diagnostic platforms. An inexpensive Whatman filter paper grade 1 was used as a pumping material. The effect of porosity on paper pumping demonstrated that the flowrate of the fluid flowing through the microchannel increases with an increase in the pump's porosity. Moreover, these pumps carried a large sample volume of fluid and absorbed 0.40 mL of volume, with the maximum flowrates achieved being 0.467 mL/min. These pumps are simple, inexpensive with better control and programmability and will drastically improve the miniaturization and commercialization for a successful point-of-care diagnostic platform.

Conflicts of Interest: The authors declare no conflict of interest.

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