engineering proceedings

MDPI

Proceeding Paper

Flow Control in Paper-Based Microfluidics Using Variable Porosity Channel †

Mubashar Ali, Gohar Hussain, Hamza Abbas, Hammas Ullah and Ali Turab Jafry *

Faculty of Mechanical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi 23460, Pakistan

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

† Presented at the 2nd International Conference on Advances in Mechanical Engineering (ICAME-22), Islamabad, Pakistan, 25 August 2022.

Abstract: Microfluidic paper-based analytical devices have broadened the scope of microfluidics by offering low-cost, simple, faster fabrication, biodegradability, and environmentally benign devices capable of medical diagnostics, environmental sensing, and food quality control. These devices are incredibly versatile, which is one of their most notable features. Despite recent advancements in paper-fluidics, creating slow flow channels in paper still remains a challenge. Herein, we propose viscous barriers of various concentrations embedded along the paper channel to control its flow velocity by altering the pore size. We used sugar concentrations in the range of 0–40% dried in porous media and then recorded flow behaviors of water and castor oil. From experiments, it was observed that by increasing the sugar concentration, delay time also increased. Moreover, changing the type of fluid (w.r.t viscosity) also varies the flow delays as castor oil took a much longer time to cover the same channel length as compared to water. We believe that our proposed method will play an important part in improving flow delays and can be applied for food quality applications such as time–temperature indicators due to its simple fabrication and cost-effective technique.

Keywords: delay zone; food quality; microfluidic; paper-based microfluidics

Citation: Ali, M.; Hussain, G.; Abbas, H.; Ullah, H.; Jafry, A.T. Flow Control in Paper-Based Microfluidics Using Variable Porosity Channel. *Eng. Proc.* **2022**, *23*, 33. https://doi.org/10.3390/engproc2022023033

Academic Editors: Mahabat Khan, M. Javed Hyder, Muhammad Irfan and Manzar Masud

Published: 26 September 2022

1. Introduction

Global health is the most important challenge that the world faces in improving disease detection and diagnosis precision. Health can be improved by providing an adequate quality of food and a pollution-free environment. Microfluidics devices provide great potential for food safety and inexpensive diagnostics. These devices enable less sample consumption as well as quicker reaction and separation times. Integrated microfluidic devices are used for a wide range of applications. These applications include medical diagnostics, environmental sensing, drug discovery, drug delivery, chemical and biochemical processes in the field of analysis, as well as energy conversion and storage [1–5]. Such devices are mainly used for immunosensing, point of care (POC), and filtration of biological fluid on a chip [6]. Martinez et al. of Whiteside's group at Harvard realized the use of paper for microfluidic devices in 2007 and reported first microfluidic paper-based analytical device (μPAD) [6]. The developing cost of μPADs is minimal, because paper is the cheaper, flexible, portable, and biodegradable material. As a result, there is no external force required to control the flow of the fluid in the paper due to its capillary force.

Understanding of flow control is very important in paper-based microfluidic devices for its accuracy and predictability [7,8]. Flow control in a two-dimensional paper-based microfluidics device can be done by either changing the geometry or by changing the chemical properties of the flowing fluid [9]. A simple geometric control can be done by just changing the channel length to control wicking times [10]. Printing baffles on the paper can also be used to decrease flow time [11]. Chemical flow control can be done by using

sugar and wax to create barriers in the path of the flowing fluid to decrease flow time for food quality control.

For our research, we have used sucrose for creating barriers in the path of the flowing fluid. By adding sugar barriers into the paper channel, porosity will decrease, and as a result, imbibition of the solution into the paper will decrease. Decrease in the pore size of the paper will increase the resistance of the flowing fluid in the paper channel; as the resistance is increased, the flowing fluid will take more time to reach the required point. In this research, we adopted the chemical-based method to control and manipulate fluid flow in paper for food quality devices such as time–temperature indicators to increase the delay time of fluid flow in paper. The flow control was achieved by changing the amount of sucrose in the solution of wetted paper.

2. Theoretical Background

Flow can be classified as wet-out flow and fully-wetted flow. One-dimensional fluid flow into a dry porous paper channel is termed as wet-out flow. The classic Lucas–Washburn (L–W) concept of wet-out in a paper pore does not take part in the complicated reduction process of sugar-treated strips; it would provide a useful framework for describing the origin of time delays. The L–W equation is derived from the capillary force due to surface tension of the paper and the viscous force of fluid flow. It explains that the length of liquid imbibition is proportional to the square root of time.

$$L^2 = \frac{r\gamma cos\theta}{4\mu}t \quad (1)$$

where L is the penetration length of the wicking fluid, r is the pore size radius of the paper strip, γ is the surface tension force, θ is the contact angle and μ is the dynamic viscosity of the flowing fluid. The capillary force responsible for fluid flow in paper is caused by the surface tension γ at the fluid surface. The higher the capillary pull, the higher the surface tension at the liquid interface, and hence the higher the fluid flow in the paper channel.

3. Materials and Methods

The delay time of wet-out flow through the paper strip is increased by creating the delay zone of different sugar concentrations. A sugar solution is prepared by mixing the sucrose in distilled water at room temperature. Solubility of sucrose in water at 200 °C is 66.7% by mass. We prepared the sugar solution in distilled water of 30% and 40% sucrose by mass. Whatman filter paper strips of grade 40 were inserted in 30% and 40% sugar solution until the solution was wicked at the desired point on the strip. Wicking strips were dried at room temperature. Figure 1 shows the preparation of the sugar delay zone of different concentrations.

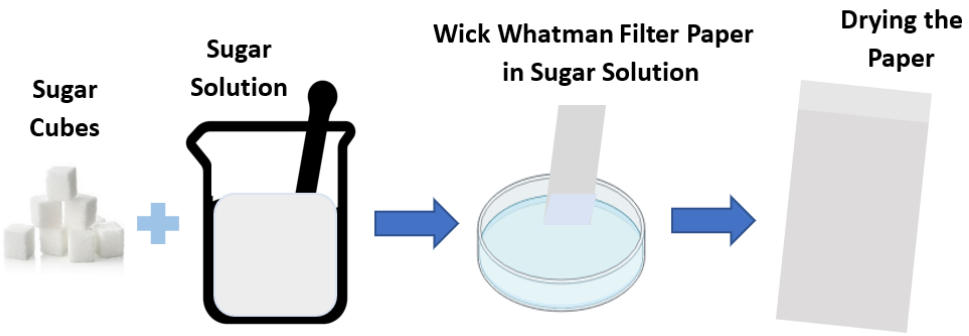
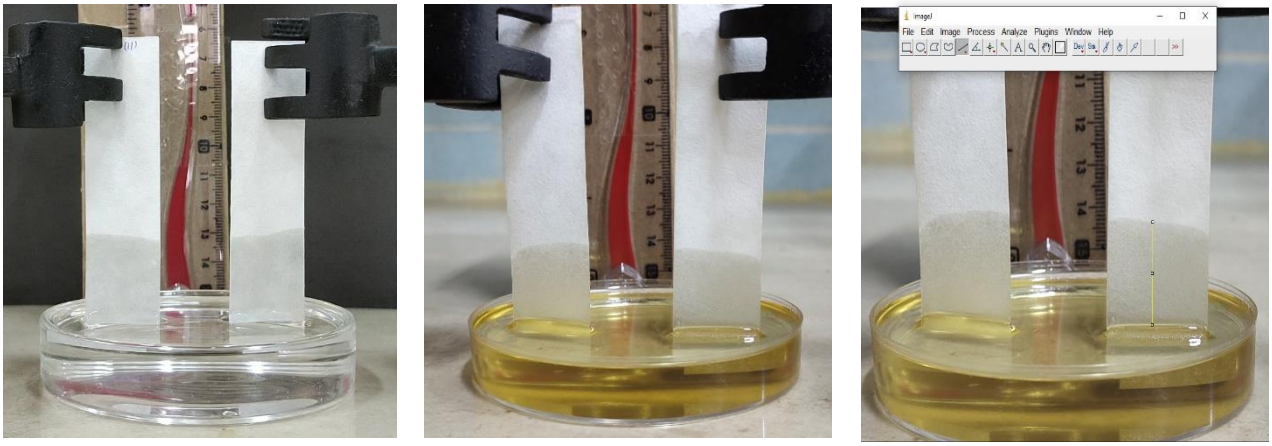


Figure 1. Preparation of sugar delay zone.

As the length travelled by liquid in the rectangular channel increases, viscous drag acting on it also increases, which causes the flow velocity to decrease with time. Figure 2 shows the image during the experiment. The flow speed of the water is high in the low

concentration delay zone. For the high concentration sugar delay zone, the liquid flow is slow. Time to reach the fluid at the finish line is increased by increasing the sugar concentration from 0–40%. The length of liquid flow in the paper strip is measured by the Image J software (National Institutes of Health and LOCI, 1.48 v, Bethesda, MD, USA, and Madison, WI, USA), as shown in Figure 2c.

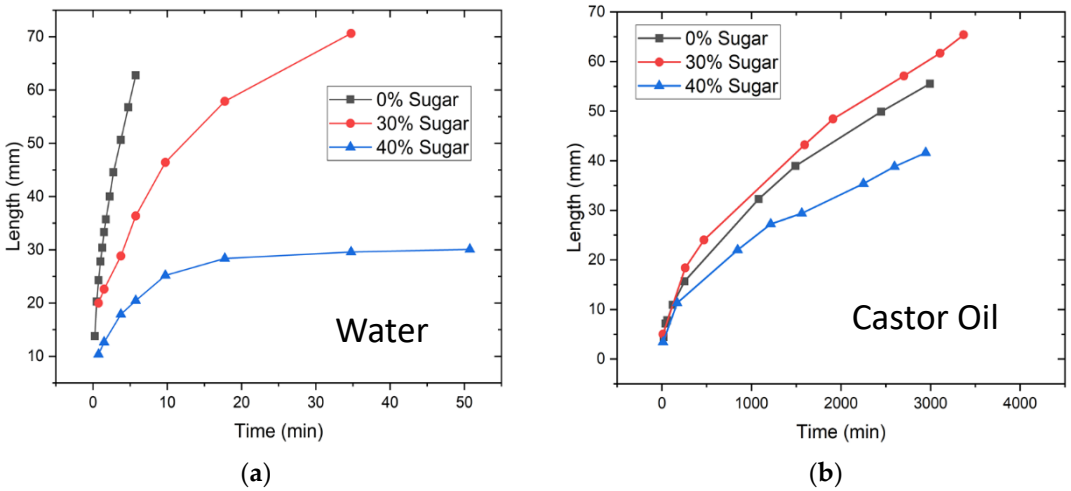


(**a**) (**b**) (**c**)

Figure 2. Image during experiment: (**a**) Water flow untreated strip; (**b**) flow of castor oil in 30% sugar concentration strip; (**c**) penetration length measured with Image J software (1.48 v).

4. Results and Discussion

Figure 3a shows the flow of water in the paper strips of different sugar concentrations. Water flows in the untreated 0% sugar concentration strip for 7 min to reach a length of 60 mm. At the creation of a delay zone of 30% sugar concentration, it takes 18 min to reach the finish line of the 60 mm length. Water flowing in a created delay zone of 40% sugar concentration, on the other hand, takes 20 min to reach a length of 28 mm. So, this indicates that wicking delay time can be increased by increasing the sugar concentration to some extent.



(**a**) (**b**)

Figure 3. Length–time curve: (**a**) Flow of water in sugar delay zone of different concentrations; (**b**) flow of castor oil in sugar delay zone of different concentrations.

To increase the delay time from hours to days, we used the high viscous fluid of castor oil, which has a viscosity of 14 times more than water. The flow of castor oil in the untreated paper strip of 0% sugar solution takes two and a half days to reach the same length of 60 mm as shown in Figure 3b. However, in the delay zone of 40% sugar

concentration, castor oil takes much more time, 2 days, to cover the length of 40 mm. Hence, the results show that time delay can be increased by creating a sugar delay zone of different concentrations and changing the wicking fluid from water to a high viscosity liquid.

5. Conclusions

Flow delays were achieved by using sucrose solutions of various concentrations in paper media to study their effect on flow delays. Several experiments were performed by changing sucrose concentrations in distilled water in a range of 0–40%. Moreover, the flow behavior of highly viscous fluid, e.g., castor oil, was also studied and compared with distilled water. From experiments, it was recorded that a flow delay of 40 min was achieved by using a 40% sucrose concentration. To achieve a flow delay of two days, castor oil is also promising in this regard. We believe that this study will help researchers to develop more sustainable and efficient methods of flow delays for food quality and environmental sensing applications of paper-based microfluidic devices.

Author Contributions: Conceptualization, M.A. and G.H.; methodology, M.A. and A.T.J.; software, M.A. and H.A.; validation, M.A. and H.A.; formal analysis, M.A. and H.U.; investigation, M.A. and A.T.J.; data curation, H.U.; writing—original draft preparation, M.A.; writing—review and editing, M.A. and A.T.J.; supervision, A.T.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by Higher Education Commission (HEC), Pakistan under the Technology Transfer Support Fund (grant no. TTSF-74).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

References

1. Dittrich, P.S.; Manz, A. Lab-on-a-Chip: Microfluidics in Drug Discovery. *Nat. Rev. Drug Discov.* **2006**, *5*, 210–218. [CrossRef] [PubMed]
2. Aryasomayajula, A.; Bayat, P.; Rezai, P.; Selvaganapathy, P.R. Microfluidic Devices and Their Applications. In *Springer Handbook of Nanotechnology*; Bhushan, B., Ed.; Springer: Berlin/Heidelberg, Germany, 2017; pp. 487–536. ISBN 978-3-662-54357-3.
3. Safdar, M.; Jänis, J.; Sánchez, S. Microfluidic Fuel Cells for Energy Generation. *Lab Chip* **2016**, *16*, 2754–2758. [CrossRef] [PubMed]
4. Nguyen, N.-T.; Wereley, S.T.; House, A. *Fundamentals and Applications of Microfluidics*, 2nd ed.; Artech House: Boston, MA, USA, 2002.
5. Khan, I.U.; Serra, C.A.; Anton, N.; Vandamme, T.F. Production of Nanoparticle Drug Delivery Systems with Microfluidics Tools. *Expert. Opin. Drug Deliv.* **2015**, *12*, 547–562. [CrossRef] [PubMed]
6. Li, X.; Chen, W.; Liu, G.; Lu, W.; Fu, J. Continuous-Flow Microfluidic Blood Cell Sorting for Unprocessed Whole Blood Using Surface-Micromachined Microfiltration Membranes. *Lab Chip* **2014**, *14*, 2565–2575. [CrossRef] [PubMed]
7. Martinez, A.W.; Phillips, S.T.; Butte, M.J.; Whitesides, G.M. Patterned Paper as a Platform for Inexpensive, Low-Volume, Portable Bioassays. *Angew. Chem.-Int. Ed.* **2007**, *46*, 1318–1320. [CrossRef] [PubMed]
8. Lim, H.; Jafry, A.T.; Lee, J. Fabrication, Flow Control, and Applications of Microfluidic Paper-Based Analytical Devices. *Molecules* **2019**, *24*, 2869. [CrossRef] [PubMed]
9. Fu, E.; Lutz, B.; Kauffman, P.; Yager, P. Controlled Reagent Transport in Disposable 2D Paper Networks. *Lab Chip* **2010**, *10*, 918–920. [CrossRef] [PubMed]
10. Whitesides, G.M. Viewpoint on "Dissolvable Fluidic Time Delays for Programming Multi-Step Assays in Instrument-Free Paper Diagnostics". *Lab Chip* **2013**, *13*, 4004–4005. [CrossRef] [PubMed]
11. Preechakasedkit, P.; Siangproh, W.; Khongchareonporn, N.; Ngamrojanavanich, N.; Chailapakul, O. Development of an Automated Wax-Printed Paper-Based Lateral Flow Device for Alpha-Fetoprotein Enzyme-Linked Immunosorbent Assay. *Biosens. Bioelectron.* **2018**, *102*, 27–32. [CrossRef] [PubMed]