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Study of Passive Fluid Mixing in Microfluidic Devices

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Abstract: This study investigates passive fluid mixing in microfluidic devices through experimental evaluation of three geometries: straight channel, zigzag channel, and flow-splitting channel. Mixing was characterized using a custom-built syringe pump, 3D-printed devices, and ImageJ analysis. Results demonstrated that flow-splitting geometries achieved efficient mixing at lower flow rates compared to zigzag geometries. This work provides valuable insights for designing cost-effective micromixers for lab-on-a-chip applications, particularly in biomedical and chemical diagnostics.

Keywords: *Microfluidics, Passive Mixing, 3D Printing, Lab-on-a-Chip, Zigzag Channels, Flow-Splitting Channels.*

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I. INTRODUCTION

Microfluidic devices are extensively utilized in chemical and biological processes requiring precise fluid mixing at microscale levels. These devices leverage laminar flow properties to achieve controlled interactions between fluid streams. However, achieving effective mixing in laminar flow is challenging due to the lack of turbulence. To overcome this, micromixers are integrated into microfluidic devices to enhance mixing performance.

Passive micromixers eliminate the need for external energy sources, relying solely on geometry and channel design to induce mixing [1]. These designs are cost-effective and simple to fabricate, making them ideal for point-of-care diagnostic devices. This study focuses on comparing three geometries—straight channel, zigzag channel, and flow-splitting channel—to assess their mixing efficiency under various flow conditions.

Achieving efficient mixing in microfluidic devices is challenging due to laminar flow, which limits molecular diffusion [2]. While active micromixers provide solutions, they often require complex fabrication and control mechanisms. Passive micromixers offer simpler, cost-effective alternatives. This study addresses the design and evaluation of passive micromixers to enhance mixing efficiency.

This research investigates the mixing performance of three passive micromixer geometries: straight channel, zigzag channel, and flow-splitting channel. The objective is to compare their mixing efficiencies and identify optimal designs for improved performance.

The study encompasses the design, fabrication, and experimental evaluation of passive micromixers. Key geometries explored include zigzag, straight, and flow-splitting designs, focusing on their mixing behaviors at varying flow rates.

II. LITERATURE REVIEW

A. Concept of Micromixing

Micromixing is a critical component of microfluidic systems, enabling rapid and efficient mixing of fluids. Passive micromixers utilize molecular diffusion and chaotic advection without external energy inputs, which simplifies their design and reduces operational complexity. Key geometrical features such as zigzag patterns, obstacles, and split-and-merge configurations are often employed to achieve efficient mixing. Research highlights that the introduction of obstacles in microfluidic channels can significantly disrupt laminar flow, thereby enhancing diffusion rates [1]. Moreover, computational simulations have demonstrated the importance of Reynolds number in optimizing micromixing designs [2]. These findings support the continuous development of innovative passive micromixer geometries for real-world applications.

B. Applications of Micromixing

Micromixers find applications in diverse fields, including drug synthesis, chemical diagnostics, and enzymatic assays. For example, zigzag micromixers are used in biochemical analyses to homogenize reagents, while flow-splitting designs are effective for high-throughput chemical processing. In clinical diagnostics, micromixers facilitate rapid analysis by ensuring homogeneous mixing of reagents with patient samples. Their role in point-of-care devices has been emphasized in recent studies [3]. Additionally, micromixers have proven crucial in food technology, where they optimize flavor mixing and chemical formulations [4].

C. Mixing Efficiency

Mixing efficiency in micromixers depends on parameters such as Reynolds number, Peclet number, and channel geometry [3]. Studies have shown that geometries inducing chaotic advection, such as spirals or serpentine channels, significantly enhance mixing compared to straight channels [4]. This work builds on these principles to evaluate the effectiveness of zigzag and flow-splitting geometries in passive mixing applications. Experimental findings indicate that the zigzag design enhances mixing by increasing the interaction area between fluid layers, while flow-splitting geometries achieve uniform distribution at lower energy inputs [5]. Computational fluid dynamics (CFD) simulations have further validated these observations by quantifying mixing indices under various flow conditions [6].

D. Visual Representation and Analysis

The effectiveness of passive micromixers is often evaluated using visual and quantitative methods. **Fig 1** illustrates the schematic representation of the three geometries studied in this research: straight-channel, zigzag-channel, and flow-splitting devices. Each geometry has unique design features intended to improve mixing by either inducing chaotic advection or increasing the fluid contact surface.

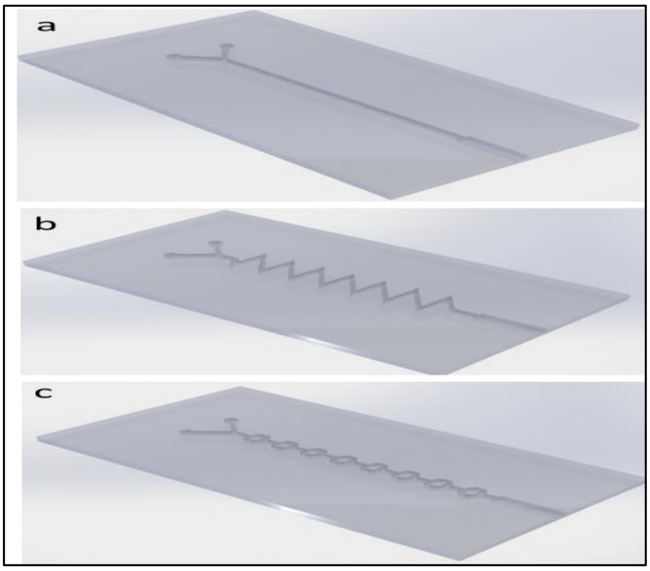

Fig 1: Schematic of Zigzag, Straight, and Flow-Splitting Device

Fig 2 presents the dimensions of the a) straight channel, b) zigzag channel and c) flow-splitting channel in unit of mm.

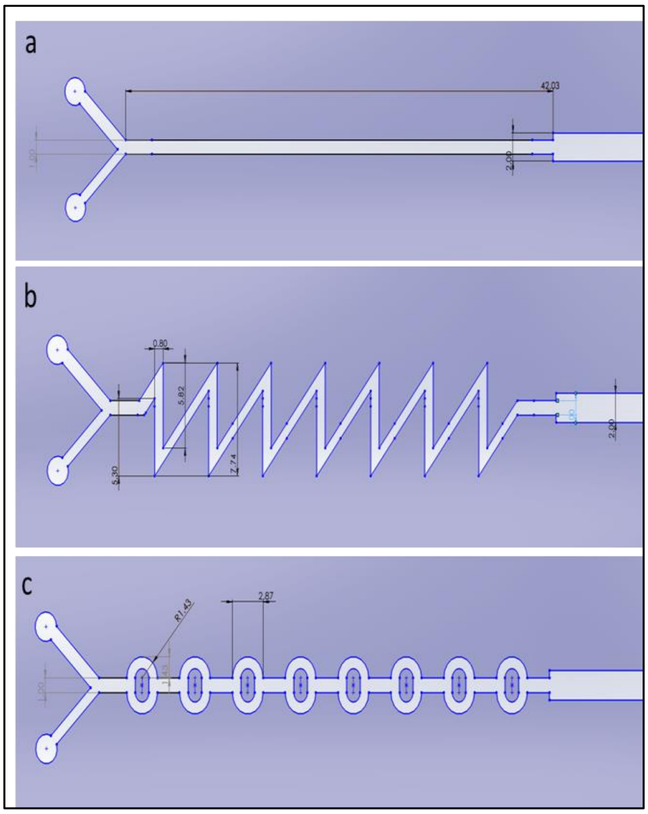

Fig 2: Dimensions of The a) Straight Channel, b) Zigzag Channel and c) Flow-Splitting Channel are Given. Dimensions are in Unit of mm

III. MATERIALS AND METHODS

This section outlines the design, fabrication, and experimental procedures used in evaluating passive micromixers. The fluidic devices were designed using SolidWorks CAD software. Three geometries—straight channel, zigzag channel, and flow-splitting channel—were developed to evaluate their mixing performance [5]. Zigzag geometries force the fluid to change direction multiple times, while flow-splitting designs divide and merge streams to enhance interaction [6]. The devices were fabricated using a Creality Ender 3 S1 3D printer with PLA filament shown in fig 3. To enable optical access, rectangular glass capillaries were integrated into the devices. This setup allowed detailed visualization of fluid mixing behavior using an inverted optical microscope. Mixing experiments were conducted using a custom-built syringe pump capable of delivering precise flow rates. Fluid streams were labeled with dye to assess mixing visually, and grayscale intensity profiles were analyzed using ImageJ software. A mixing index was calculated to quantify mixing efficiency across the geometries.

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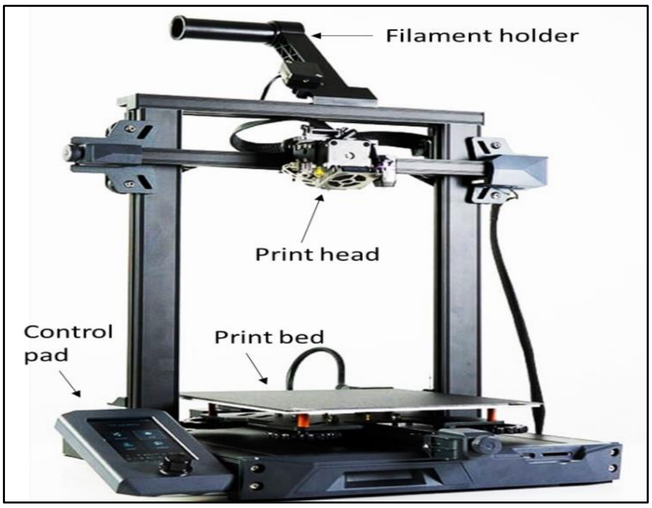

Fig 3: 3D Printer Used

IV. RESULTS AND DISCUSSSION

A. *Flow Profiles*

Laminar flow profiles were observed in the straight channel, characterized by parallel fluid layers moving side by side with minimal interaction. This resulted in limited fluid mixing, as shown in **Fig 4a**. In contrast, the zigzag channel disrupted laminar flow by introducing sharp directional changes, leading to chaotic advection and enhanced mixing, as illustrated in **Fig 4b.** These results highlight the role of channel geometry in influencing fluid behavior. The flow-splitting channel demonstrated superior performance by creating repeated interfaces through splitting and merging of streams. This mechanism enhanced mixing efficiency even at lower flow rates, making it particularly suitable for low-energy applications.

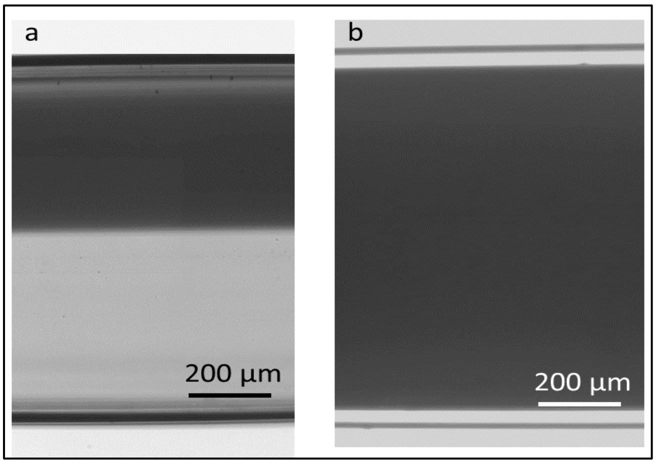

Fig 4: (a) Unmixed Flow Profile from the Straight Channel. (b) Mixed Flow Profile from the Zigzag Channel

B. *Fluid Profile Characterization*

Fluid profiles for the zigzag and flow-splitting geometries were analyzed across the channel width using grayscale intensity profiles. As shown in **Fig 5**, the zigzag channel required higher flow rates (up to 3 mL/min) to achieve uniform mixing, whereas the flow-splitting channel achieved similar results at a lower flow rate of 2.2 mL/min. This demonstrates the efficiency of the flow-splitting design in promoting interfacial interaction and diffusion. The characterization also revealed that the zigzag channel relied heavily on directional changes to disrupt laminar flow, whereas the flow-splitting geometry leveraged repeated merging of streams to achieve superior mixing. These findings align with computational studies emphasizing the importance of geometric design in passive micromixing.

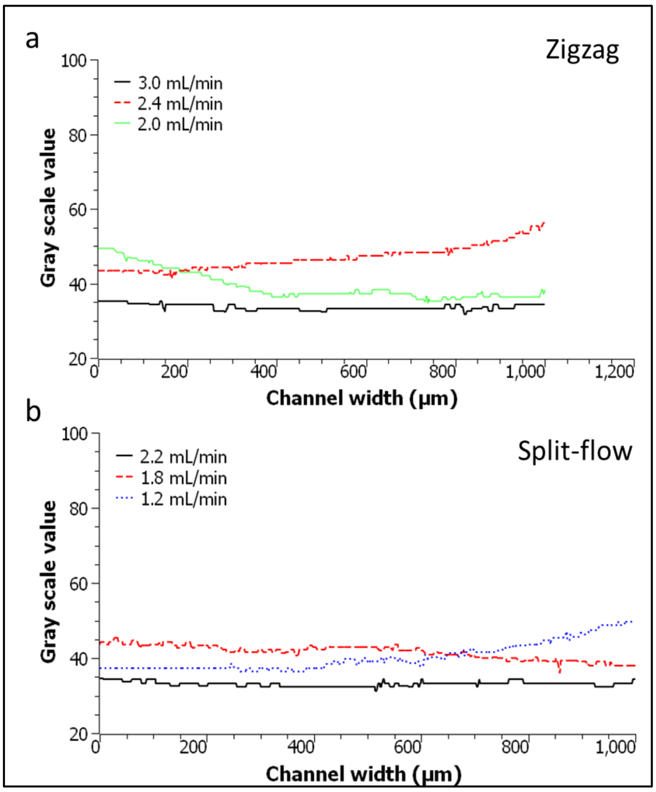

Fig 5: Flow Profile Characterization for (a) Zigzag and (b) Flow-Splitting Device Geometries.

C. *Mixing Index Analysis*

The mixing index, a quantitative measure of fluid homogeneity, was calculated using grayscale intensity data. **Fig 6** depicts the mixing index values for zigzag and flow-splitting geometries.

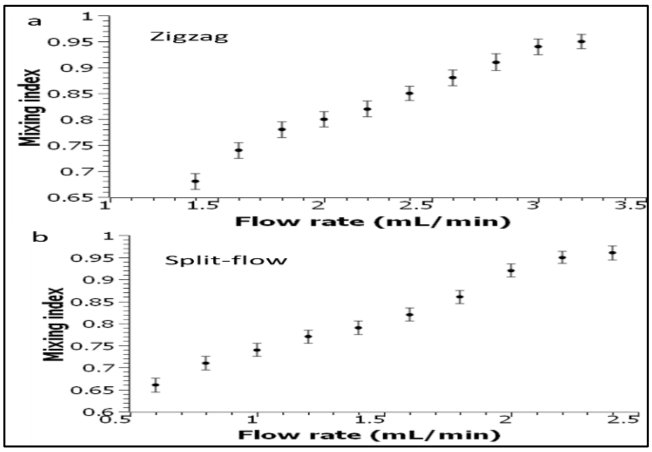

Fig 6: Mixing Index Values for (a) Zigzag and (b) Flow-Splitting Geometries. Error Bars Represent the Standard Deviation of Three Experiments

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The flow-splitting device achieved a mixing index exceeding 0.85 at a flow rate of 2.2 mL/min, indicating highly efficient mixing. In comparison, the zigzag device required a higher flow rate (3.5 mL/min) to reach a similar mixing index. The superior performance of the flow-splitting geometry is attributed to its ability to create multiple fluid interfaces and promote rapid diffusion. The straight channel, however, showed minimal improvement in mixing index, highlighting its limitation in passive micromixing applications.

D. Comparative Performance

A comparison of the three geometries is summarized in **Table 1**. The flow-splitting channel demonstrated the best overall performance, achieving efficient mixing at lower flow rates and energy requirements. The zigzag channel, while effective at higher flow rates, exhibited limitations under low-flow conditions. The straight channel, with its linear flow path, showed the least efficiency, making it unsuitable for applications requiring rapid and uniform mixing.

Table 1: Comparison of the Three Geometries

Geometry	**Mixing Index (at Optimal Flow Rate)**	**Optimal Flow Rate (mL/min)**	**Energy Efficiency**	**Application Suitability**
Straight Channel	0.35	3.0	Low	Limited to high flow, low mixing needs
Zigzag Channel	0.85	3.5	Moderate	Effective for high flow scenarios
Flow-Splitting Channel	0.9	2.2	High	Ideal for low-energy, high-efficiency applications

V. CONCLUSION

This study highlights the significant influence of geometric design on the performance of passive micromixers. Among the three geometries analyzed, the flow-splitting channel demonstrated the highest mixing efficiency, achieving uniform fluid distribution at lower flow rates compared to the zigzag and straight channels. This makes it particularly suitable for applications requiring low energy consumption, such as point-of-care diagnostic tools and portable lab-on-a-chip devices.

The zigzag channel, while effective, exhibited limitations at low flow rates, suggesting its suitability for scenarios where higher flow rates can be maintained. The straight channel showed minimal mixing improvement and is unsuitable for passive micromixing applications that demand rapid and efficient mixing.

These findings underscore the potential of flow-splitting designs in advancing microfluidic technologies for chemical synthesis, biomedical research, and diagnostic applications. Future work should focus on integrating these geometries into multifunctional devices, exploring their performance with non-Newtonian fluids, and evaluating their scalability for industrial applications. Additionally, computational modeling combined with experimental validation can further optimize micromixer designs for specific use cases.

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REFERENCES

[1]. A. D. Stroock, S. K. W. Dertinger, A. Ajdari, I. Mezić, H. A. Stone, and G. M. Whitesides, "Chaotic mixing in microfluidic systems," *Science*, vol. 295, no. 5555, pp. 647-651, 2002.

[2]. N. T. Nguyen and Z. Wu, "Micromixers—A review," *J. Micromech. Microeng.*, vol. 15, no. 2, pp. R1-R16, 2005.

A. Ozcelik, D. Ahmed, Y. Xie, N. Nama, Z. Qu, and T. J. Huang, "Sharp-edge-based acoustofluidic micromixers," *Lab Chip*, vol. 14, no. 23, pp. 4593-4602, 2014.

[3]. C. S. Kim, S. H. Lee, and J. H. Kim, "Three-dimensional serpentine lamination micromixer," *Lab Chip*, vol. 5, no. 6, pp. 739-747, 2005.

[4]. Z. Zhang, J. Wang, J. Zhou, and X. Yan, "Passive micromixer designs for enhanced mixing efficiency," *Micromachines*, vol. 10, no. 3, pp. 142-150, 2019.

[5]. I. Glasgow and N. Aubry, "Enhancement of microfluidic mixing using periodic forcing," *Lab Chip*, vol. 3, no. 2, pp. 114-120, 2003.

[6]. R. H. Liu, J. Yang, R. Lenigk, J. Bonanno, and P. Grodzinski, "Passive micromixers for microfluidic systems," *Anal. Chem.*, vol. 72, no. 18, pp. 6164-6171, 2000.