Design and Fabrication of Self-Perpetuating Micropump

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May, 2023

Declaration

I certify that this research work titled "*Design and Fabrication of Self-Perpetuating Micropump"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources has been properly acknowledged / referred.

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I am thankful to my Creator Allah Subhana Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual, was Your will, so indeed none be worthy of praise but You.

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Abstract

This research work focuses on the development of high-performance capillary pumps for low-cost point-of-care diagnostic devices using printed circuit board (PCB) technology. The study explores the design and fabrication of capillary pumps using PCBs and polydimethylsiloxane (PDMS) to create microfluidic devices. Two different designs of PCB-based micropumps with hexagonal-shaped micropillars are proposed, offering different vertical distances between rows to achieve varying flow rates and fluid volumes. The fabrication process involves designing the PCB microchannel, cutting the PCB fiber sheet, creating silicon molds, pouring and curing PDMS, bonding the PDMS replicas to a substrate, and testing the micropump's performance. Experimental setups are established to measure the flow rate and pressure drop of different glycerin ratios in the microfluidic system. The results indicate that as the glycerin content increases, the flow rate decreases due to increased fluid viscosity. Design 1 consistently exhibits higher flow rates than Design 2 due to the smaller gap distance between micropillars. The findings demonstrate the effectiveness of PCB-based capillary pumps in controlling fluid flow and offer valuable insights for the development of low-cost point-of-care diagnostic devices. The design of micropumps for studying blood flow at low flow rates offers significant advantages in investigating blood-related conditions. The precise control overflow rates, realistic simulations, integration with microfluidic systems, drug delivery studies, and reduced sample requirements all contribute to a deeper understanding of blood disorders and the development of personalized treatment approaches.

Key Words: *Microfluidics, Capillary action, Micropump, Self -Perpetuating,*

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CHAPTER 1: INTRODUCTION

Self-perpetuating pumps are those which work on capillary action to transfer fluid toward its destination, and it does not require any external source (Nikolaos Vasilakis 2017). The liquid keeps flowing because of the capillary action, the propulsive force that helps cause the flow. The design of a capillary pump is significant in this scenario. Out of all available technologies, the suitable and appropriate method for designing and fabricating capillary pumps assimilates PCB (Printed Circuit Board) technology. It allows a more efficient and reliable capillary pump that can be used in affordable point-of-care diagnostic devices.

1.1 Capillary Micropump

A self-priming capillary micropump works by utilizing the phenomenon of capillary action to pump fluids through small channels. Capillary action is the ability of a liquid to flow in narrow spaces without the assistance of, or in opposition to, external forces like gravity. The micropump typically consists of a channel with a small diameter, which is filled with a liquid. Applying external pressure to one end of the channel results in the liquid being compelled to move through the channel, thanks to capillary action. The flow of the liquid will persist until the pressure is relieved, causing the capillary action to cease and the liquid to stop flowing. The micropump's ability to initiate operation without the presence of liquid is attained through the utilization of a liquid that can easily adhere to the channel walls, enabling the liquid to be drawn into the channel and commence flowing.

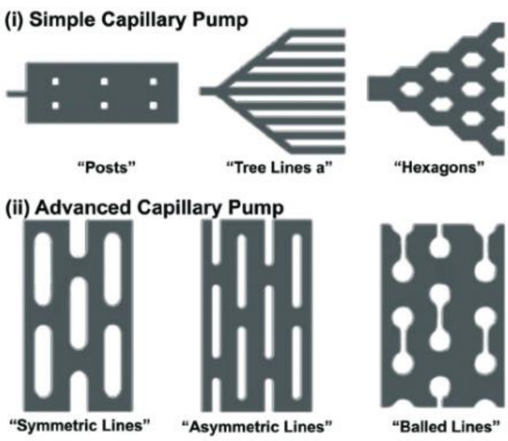


Figure 1: Capillary Micropumps of Different Designs

1.1.1 National Needs

Capillary self-priming micropumps offer numerous potential applications that address important national requirements, including:

- **Medical diagnostics:** Capillary micropumps can be integrated into portable diagnostic devices, such as point-of-care diagnostic systems, to enable efficient and accurate testing in remote or resource-limited settings.
- **Environmental monitoring:** Capillary micropumps can be used to pump and analyze small samples of water or other environmental fluids, making it possible to detect and monitor contaminants or pollutants in remote or hard-to-reach locations.
- **Food and water safety:** Capillary micropumps can be used in food and water safety testing, to detect bacteria, viruses, or other pathogens.

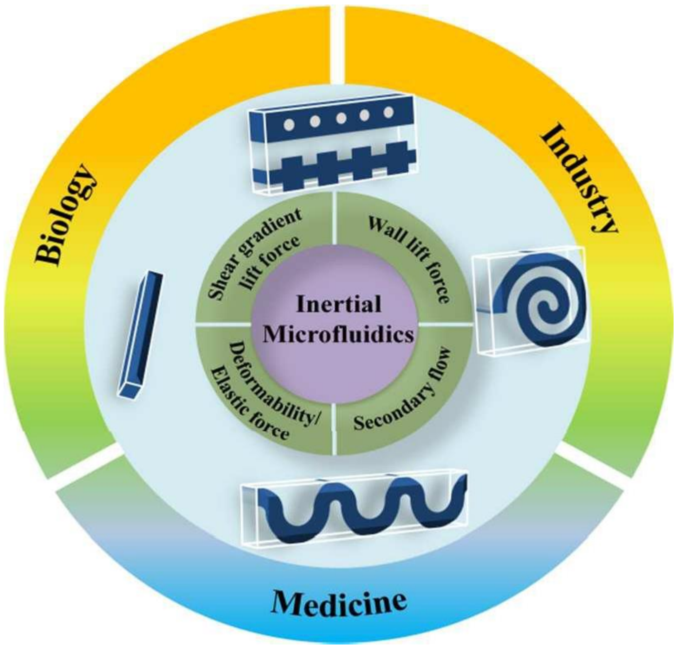


Figure 2: Capillary Pump Usage in Food and Water Safety

1.1.2 Advantages of Capillary Micropumps

Capillary self-priming micropumps exhibit various benefits in comparison to alternative micropump types, including:

- **High flow rate:** The small channel diameter of capillary micropumps enables them to achieve high flow rates, facilitating the rapid pumping of substantial liquid volumes within a brief timeframe.
- **Self-priming:** Capillary micropumps are capable of self-priming, meaning that they can start pumping liquid without the need for manual filling or priming, making them more convenient and user-friendly.
- **Low power consumption:** Capillary micropumps typically use minimal power, making them suitable for portable or battery-powered applications.
- **Compact size:** Capillary micropumps are small and lightweight, making them easy to integrate into microfluidic devices or other compact systems.

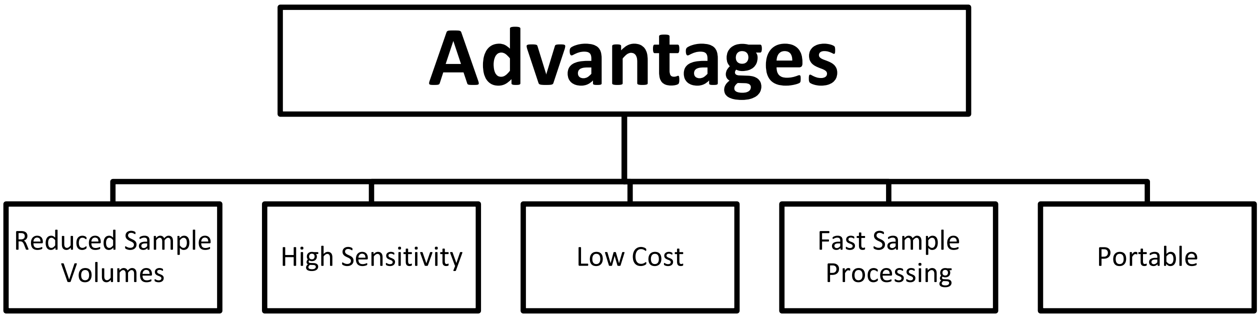


Figure 3: Advantages of Capillary Motor Pump

1.1.3 Area of Application

Capillary self-priming micropumps find utility in a diverse array of applications, encompassing:

- **Medical diagnostics:** Capillary micropumps can be integrated into portable diagnostic devices, such as lab-on-a-chip systems, point-of-care diagnostic systems, and biosensors, to enable efficient and accurate testing in remote or resource-limited settings.
- **Environmental monitoring:** Capillary micropumps can be used to pump and analyze small samples of water or other environmental fluids, making it possible to detect and monitor contaminants or pollutants in remote or hard-to-reach locations.
- **Food and water safety:** Capillary micropumps can be used in food and water safety testing, to detect bacteria, viruses, or other pathogens.

- **Biotechnology:** Capillary micropumps can be used in biotechnology applications, such as cell culture or gene therapy, to precisely control the flow of fluids and maintain optimal conditions for cell growth.
- **Energy:** Capillary micropumps can be seamlessly incorporated into energy production and storage systems, such as micro fuel cells and micro heat exchangers.
- **Automotive:** Capillary micropumps can be integrated into vehicles to pump and control the flow of fuel, coolant, and other fluids, leading to the development of more efficient and reliable vehicles.
- **Industrial:** Capillary micropumps can be integrated into industrial systems to improve the efficiency and precision of fluid handling tasks, and thus leading to the optimization of production processes.
- **Pharmaceutical and chemical industry:** Capillary micropumps can be used to handle small volumes of fluid in chemical and pharmaceutical applications, such as drug delivery, and sample preparation.
- **Analytical Chemistry:** Capillary micropumps are used in the analysis of small samples in analytical chemistry, such as capillary electrophoresis, and capillary chromatography.
- **Microfluidics:** Capillary micropumps are used in microfluidic systems to precisely control the flow of fluids and create complex microfluidic systems with other microscale components.

1.2 Method of Fabrication

The fabrication of microfluidic chips encompasses various methods that can be categorized into two primary approaches: top-down and bottom-up methods.

1.2.1 Top-Down Approaches

In top-down approaches, microfluidic channels and structures are created through direct machining or etching processes on a substrate material, such as glass or silicon. These approaches include photolithography, which uses light-sensitive resists and etching to pattern the substrate; laser ablation, which uses a laser beam to vaporize material from the substrate; and milling, which uses a rotary tool to cut the channels into the substrate.

1.2.2 Bottom-Up Approaches

Bottom-up approaches involve the assembly of microfluidic devices from smaller units or building blocks. These approaches include the use of microfluidic "inks," which are viscous fluids containing particles or other materials that can be printed or drawn into desired patterns; self-assembly.

It relies on the natural forces of attraction or repulsion between particles or molecules to spontaneously form structures; and microinjection molding, which uses a mold to shape molten polymer into the desired microfluidic structure.

There are also hybrid approaches that combine elements of both top-down and bottom-up fabrication methods. As an illustration, microscale 3D printing methods can be employed to construct microfluidic structures by layering materials, effectively merging the accuracy of photolithography with the versatility of various "inks" or materials.

In general, the selection of a fabrication technique for microfluidic chips is contingent upon the demands and limitations of the application. Factors such as the materials employed, the size and intricacy of the structures, and the desired production volume all play a role in determining the most suitable fabrication method.

1.2.3 Rapid Prototyping

Rapid prototyping refers to the swift generation of a physical model for a design or concept using additive manufacturing or other related technologies. This enables designers and engineers to promptly assess and refine their ideas, bypassing the expenses and time associated with traditional manufacturing processes.

Several varieties of rapid prototyping technologies exist, including:

- **3D printing:** This method entails the construction of a physical model by depositing successive layers of materials, such as plastic or metal, in a predetermined pattern.
- **CNC machining:** This technique utilizes computer-controlled cutting tools to selectively remove material from a solid block, thereby shaping it according to the desired specifications.
- **Vacuum casting:** This involves creating a mold of the prototype using a silicone rubber mold, and then casting the prototype using a liquid resin.

Rapid prototyping allows designers and engineers to quickly create physical models of their designs and test them in real-world conditions, which can save time and money in the development process.

1.2.4 PCB Manufacturing

PCB (Printed Circuit Board) manufacturing for microchannels involves the fabrication of a PCB with intricate and miniaturized channels designed for fluid flow. These microchannels are typically used in applications such as microfluidics, where precise control and manipulation of fluids at the microscale are required.

1.3 Aims and Objectives

- **High flow rate:** The micropump should be able to pump large volumes of liquid at a high flow rate.
- **Self-priming:** The micropump should be able to start pumping liquid without the need for manual filling or priming.
- **Low power consumption:** The micropump should be able to pump liquid using minimal power, making it suitable for portable or battery-powered applications.
- **Compact size:** The micropump should be small enough to be integrated into microfluidic devices or other compact systems.
- **Low cost:** The micropump would be relatively inexpensive to manufacture and maintain, making it accessible to many users.
- **Durability:** The micropump should withstand repeated use and exposure to different liquids without experiencing significant wear or damage.
- **Precision control:** The micropump should be able to control the flow rate and direction of the liquid with high precision, making it suitable for applications that require accurate fluid handling.
- **Scalability:** The micropump should be scalable and adaptable to a different volume of liquid, channels, and pressure.
- **Compatibility:** The micropump should work with a wide range of liquids and be compatible.

1.4 Methodology of Research

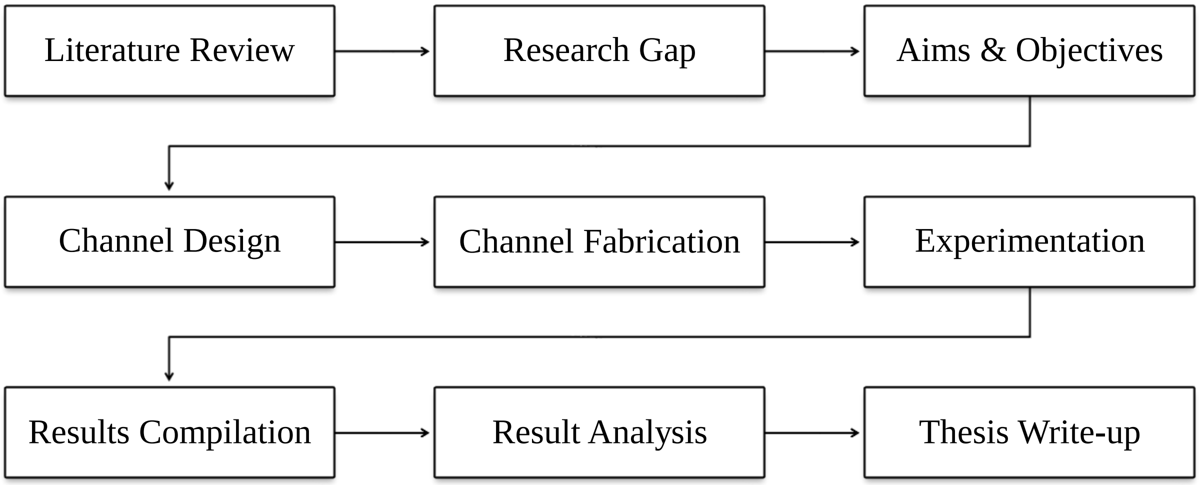


Figure 4: Research Methodology

CHAPTER 2: LITERATURE REVIEW

Numerous designs for self-perpetuating pumps start with Autonomous capillary systems (CSs), a type of self-perpetuating pump that also works on the principle of capillary action (Martin Zimmermann 2007). The vast application of these pumps is bioanalytical because of their amenity, rapidness, and effectiveness. The capillary pump is designed to regulate the flow characteristics of CSs, and the microchannel is devised to offer small flow resistance. Adjusting the microchannel dimensions and pumped liquid properties helps achieve a specific flow rate (Martin Zimmermann 2007). However, the design does not consider the impact of temperature and other external factors on the workings of capillary pumps.

In some situations, high flow rates for capillary pumps are preferred. High flow rates are achievable by creating micropillars and integrating them into microfluidic devices, which provides diverse applications in micro-fluidic based analytical systems (Hojjat Madadi 2013). Two designs for acquiring high flow rates with low-pressure one is a serpentine pump. It has a series of serpentine channels that increase in width to create flow by setting up a pressure gradient along the length of the channel. Second is a leading-edge pump in which the liquid flows over the sharp leading edges, creating a pressure gradient (Roozbeh Safavieh 2014).

Pulmonary alveolar capillaries are small blood vessels that interchange oxygen and carbon dioxide between the blood and the air in the lungs. Red blood cells depict a range of behaviors and are prone to adhere to the walls of microfluidic channels causing blockages in blood flow. A mathematical model can predict the behavior of Red Blood Cells (RBCs) in a biomimetic microfluidic device of pulmonary alveolar capillaries which aids in formulating better blood flow models in the lungs (Hagit Stauber 2017). A portable device that tracks fluid flow and temperature changes are beneficial in the biomedical field. This device can supervise fluid flow in microfluidic chips and then sends the data to a person's smartphone, where it can be kept an eye on, and in case of blockages, adequate measures can be taken (Emmanuel Delamarche 2018).

The fluid flow in microchannels can be directed by utilizing capillary forces in a capillary-based microfluidic system. The wet and tension forces assist in the flow. The phenomenon proves instrumental in creating capillary pumps, valves, and mixers. Nevertheless, these forces have some restraints, such as weak driving fluid flow and less regulation over the flow direction and rate (Ayokunle Olanrewaju 2018).

A low-cost, high-performance design on a printed circuit board (PCB) is another novel approach for designing and fabricating a capillary pump. The design creates a series of pressure-driven pumping chambers that move the liquid without external power (Nikolaos Vasilakis 2017). The microfluidic device is developed for executing complicated biological and chemical processes for its rapidness measurements and efficiency of using microscopic devices (U. M. al 2006) (Yetisen AK 2013). The midget devices are made of polymers and paper, which are cost-friendly, easily disposable, and multifunctional. The challenge is to design point-of-care (PoC) tests that execute numerous functions monolithically while fulfilling requirements. The assimilation of microfluidics, sensing, and signal processing in a single platform is critical for a successful PoC device (Coltro WKT 2014) (Yager P, Edwards T, Fu E, Helton K, Nelson K, Tam MR, Weigl BH 2006) (Zanoli LM 2013). As a result, an alternative microfluidic system based on PCB manufacturing technology, the LoPCB (Lab-on-PCB), merges microfluidic components with electronics, heaters, electrodes, and biosensors into a monolithic device (Lammerink TSJ 1996) (Merkel T 199) (Xia YY 2016). The O2 plasma treatment is used, and the wetting qualities of the core material flame retardant grade 4, FR-4 can be adjusted, resulting in channels with varied capillary flow characteristics. The essential component of this technique is a capillary pump that uses the super hydrophilic characteristics of O2 plasma treated FR-4 [16] [17] [18]. The micro pump is based on micropillar arrays and enables precise and adjustable fluid flow control across a wide range of flow rates. The LoPCB technology's overall design meets most of the criteria for autonomous monolithic PoC platforms [19] [20].

The technique is created through a series of steps, including the development of the capillary pump's circular chamber design. Several chambers on the PCB are connected to the microfluidic system. During the fabrication process, capillary pumps are constructed on the PCB using a mix of photolithography and electroplating processes. Initially, the PCB is coated with photoresist and subjected to UV light through a mask. The exposed areas are then covered over, producing a network of canals and reservoirs. To reinforce the channels and establish a stronger structure, the PCB is electroplated with copper. The capillary pumps' efficacy and performance are evaluated. This requires measuring the flow rate, pressure, and ability of the pumps to pump fluids of varied viscosities.

CHAPTER 3: MANUFACTURING METHODOLOGY

3.1. Design of Micropump

The micropump is essential in microfluidic systems because it allows for exact control and manipulation of fluids on a microscopic scale. Among various options, PCB-based micropillar designs with a hexagonal shape are widely favored for micropumps due to their

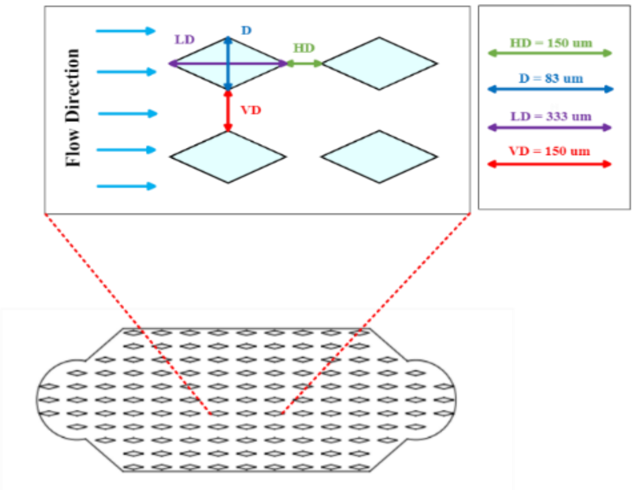


Figure 5: Design 1

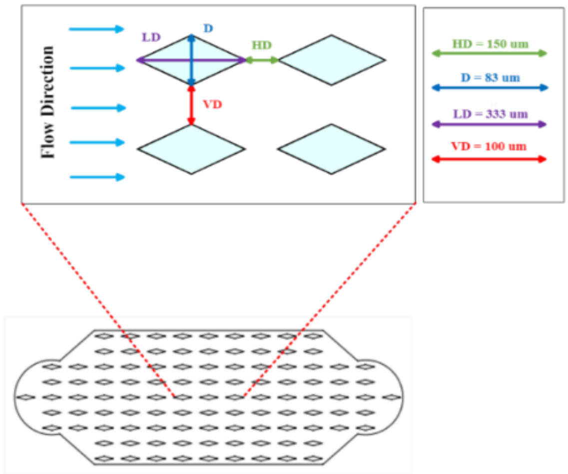


Figure 6: Design 2

easy fabrication process and capability to generate high flow rates. Two unique designs of PCB-based hexagonal micropillars have been created, with both designs maintaining a constant space between columns. However, the vertical distance between rows differs, with one design set at 100um and the other at 150um. The first design features a vertical distance between rows of 100um, which facilitates high flow rates owing to the smaller gap between rows, allowing for a larger number of pillars to be densely packed within a given area.

Table 1: Dimensions of Design 1 and 2

		LD (um)	VD (um)	HD (um)	D (um)
Design 1		333	100	100	83
Design 2		333	150	100	83

The greater concentration of pillars leads to an expanded fluid interaction surface area, which in turn improves mixing and reaction rates. The second design features a vertical gap of 150um between rows, offering increased versatility by accommodating larger fluid volumes for transportation via the micropump. The wider spacing between rows also facilitates convenient sample loading and unloading, making it an ideal option for applications that involve frequent fluid changes.

3.2. Fabrication of Micropump

The technology uses the Printed Circuit Board (PCB), a practical and affordable alternative, to build a capillary pump. To create the micropump, a PCB microchannel and Polydimethylsiloxane (PDMS), a silicon-based polymer substance that creates the capillary pump system, are used. To create the different geometries required to create microfluidic channels, PDMS can be molded. To make a completely working device, it can also be seamlessly combined with glass, plastic, or other materials. Multiple steps are involved in the fabrication of a micropump from a PCB microchannel and PDMS, although the procedure is quite simple and yields precise results.

3.2.1. PCB Microchannel

Designing the PCB microchannel is the first step, which is completed with the use of CAD (Computer-Aided Design) software. The PCB's copper layer has the design for the microchannel etched onto it. It is an important step that must include the necessary breadth and depth to permit fluid movement. The following stage includes using a laser or mechanical cutter to cut the PCB fiber sheet along the planned microchannel layout. The PCB will develop microchannels as a result. The creation of a PCB (Printed Circuit Board) with detailed, miniature channels intended for fluid flow is referred to as PCB (Printed Circuit Board) production for microchannels. These microchannels are frequently employed in microfluidic applications, where precision control and microscale fluid manipulation are necessary.

Here is a broad outline of the PCB manufacturing process for microchannels:

- **Design:** Making the PCB layout, which includes the microchannels, is the first step. The design is created using specialized software, such as computer-aided design (CAD) tools, while accounting for the appropriate microchannel diameters, forms, and connectivity.

- **Substrate selection:** Based on the needs of the application, the substrate material for the PCB is chosen. Common materials include FR-4 (Flame Retardant 4), an epoxy laminate reinforced with fiberglass, or specialized materials with superior thermal or electrical qualities like polyimide or ceramic substrates.

- **Substrate preparation:** The chosen substrate is prepared by cleaning and ensuring its surface is free from contaminants or debris. This step is crucial to ensure good adhesion and quality of the subsequent layers.

- **Copper deposition:** A thin layer of copper is deposited onto the substrate surface through various techniques such as electroless deposition, electroplating, or sputtering. This copper layer serves as the conductive pathway for electrical connections and will also form the walls of the microchannels.

- **Photoresist application:** A layer of photosensitive material, called photoresist, is applied over the copper layer. The substrate is then exposed to ultraviolet (UV) light through a photomask that defines the microchannel pattern. The photoresist undergoes a chemical change upon exposure, either becoming soluble (positive resist) or insoluble (negative resist).

- **Photolithography:** The UV-exposed photoresist is developed, selectively removing either the exposed or unexposed areas, depending on the type of photoresist used. This step transfers the microchannel pattern onto the photoresist layer.

- **Etching:** An etching process is performed to remove the exposed copper or the copper in the unexposed areas, depending on the type of resist used. This creates the channels in the copper layer, following the microchannel pattern defined by the photoresist.

- **Resist removal:** The remaining photoresist is stripped away, leaving behind the copper microchannels embedded in the substrate. This exposes the copper surfaces for further processing and ensures the microchannels are open for fluid flow.

- **Surface finish:** The exposed copper surfaces are treated with surface finish techniques, such as immersion tin, immersion gold, or HASL (Hot Air Solder Leveling), to protect them from oxidation and improve solderability.

- **Assembly and testing:** After the PCB manufacturing process, the microchannels are integrated with other components, if necessary, and undergo testing to ensure functionality and quality.

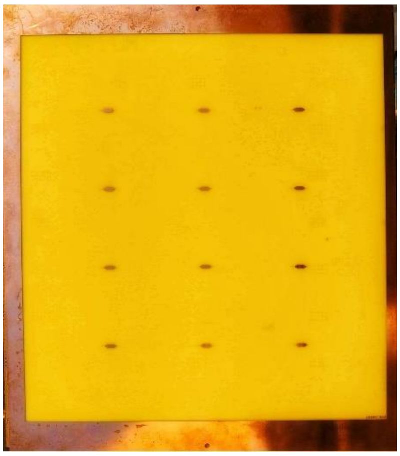


Figure 8: PCB Sheet

Figure 7: PCB Microchannel

3.2.2. Mold Fabrication

After that, using photolithography or other microfabrication methods, flat silicon molds are created as the next step. It is essential to note that the molds have a flat, smooth, and level surface. In order to ensure that the PDMS will take the shape of the micropump, the micropumps are then adhered to silicon molds.

3.2.3. PDMS Preparation Procedure

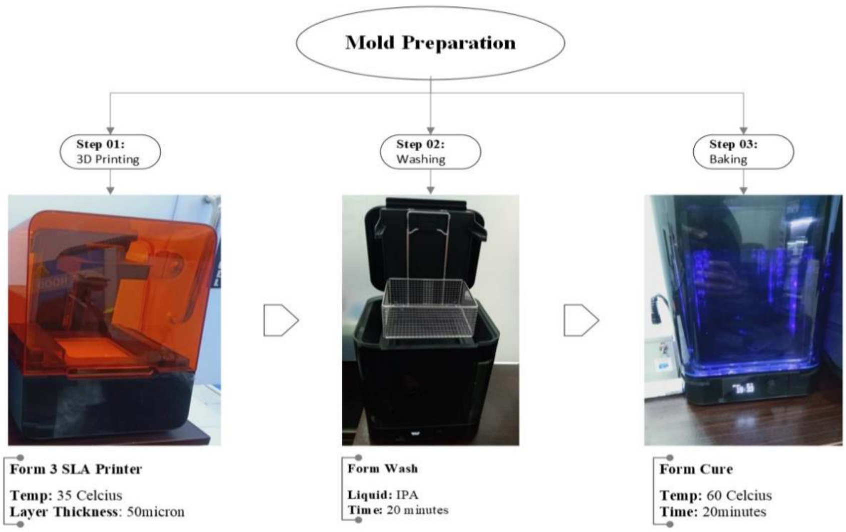


Figure 9: Flow Chart of Mold Preparation

To thoroughly mix the two components, it is also important to combine the PDMS base and curing agent in a 10:1 ratio and rapidly swirl the mixture. The PDMS mixture is then carefully poured over the silicon molds, making sure to completely cover the micropumps and the surrounding area. It's crucial to check that the PDMS has a uniform thickness and covers the mold's whole surface.

In the following step, the PDMS is cured by putting the molds in an oven or incubator. The PDMS is normally solidified and shaped to fit the molds during the curing process, which usually lasts several hours at a temperature of about 80°C. After the PDMS has fully hardened, the replicas are carefully removed from the molds while being careful to trim away any additional PDMS that may have built up around the borders of the micropumps. Next, a substrate made of glass, or another polymer is placed on top of the PDMS copies, and a plasma cleaner is used to permanently glue the two surfaces together. This bonding procedure creates a solid bond between the substrate and the PDMS, guaranteeing the stability and dependability of the micropump. The PDMS replicas are punched or laser-cut with holes to allow for fluid input and output. The intake and outlet ports are furthermore connected by tubing. Lastly, fluids are pushed to test the micropump's

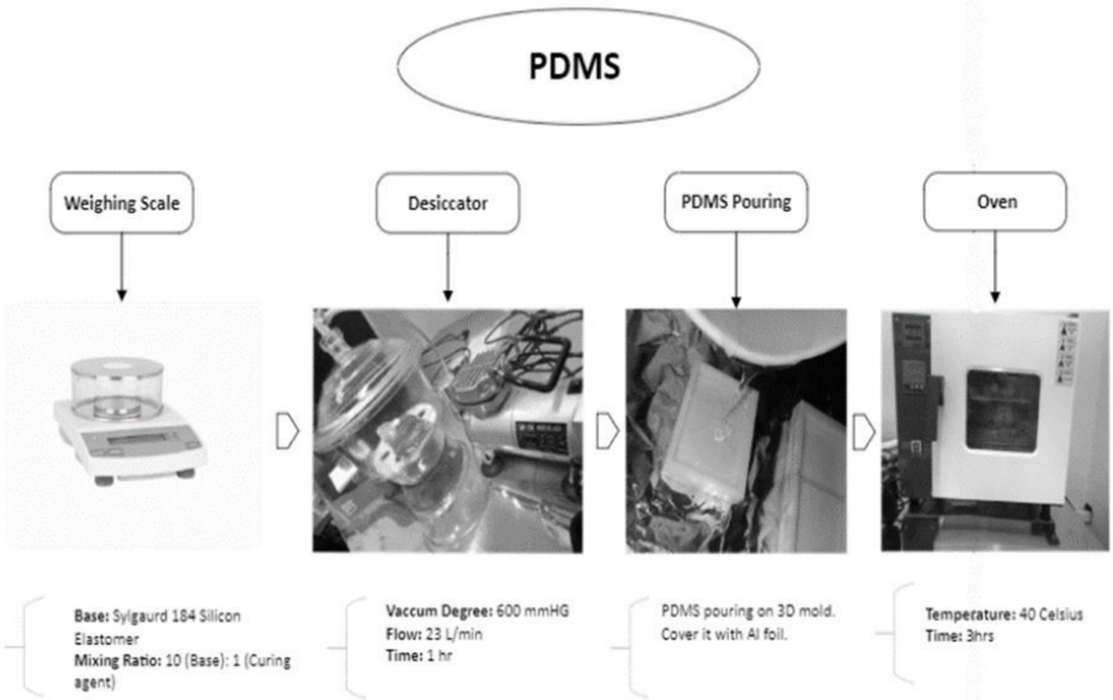


Figure 10: PDMS Preparation

performance. through it, while measuring the flow rate and assessing the pressure. This step holds great significance as it serves to optimize the design of the micropump and validate its performance.

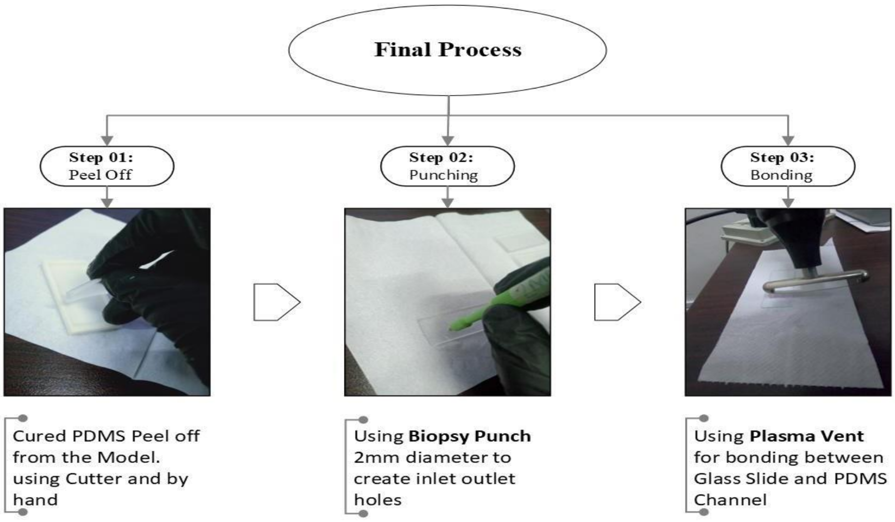


Figure 11: Final Steps of Microchannel Fabrication

In general, this process can be customized to accommodate diverse applications, rendering it a versatile and invaluable technique for researchers and engineers operating within the realms of microfluidics and nanotechnology. The design and fabrication of micropumps using PCBs and PDMS necessitate meticulous and methodical procedures to develop functional microfluidic devices with varying degrees of intricacy. Consequently, the meticulous execution of each step guarantees the precise and dependable performance of the micropumps.

Figure 12: PCB Capillary Micropump in Silicon Mold

Figure 13: Final Design 1 and Design 2

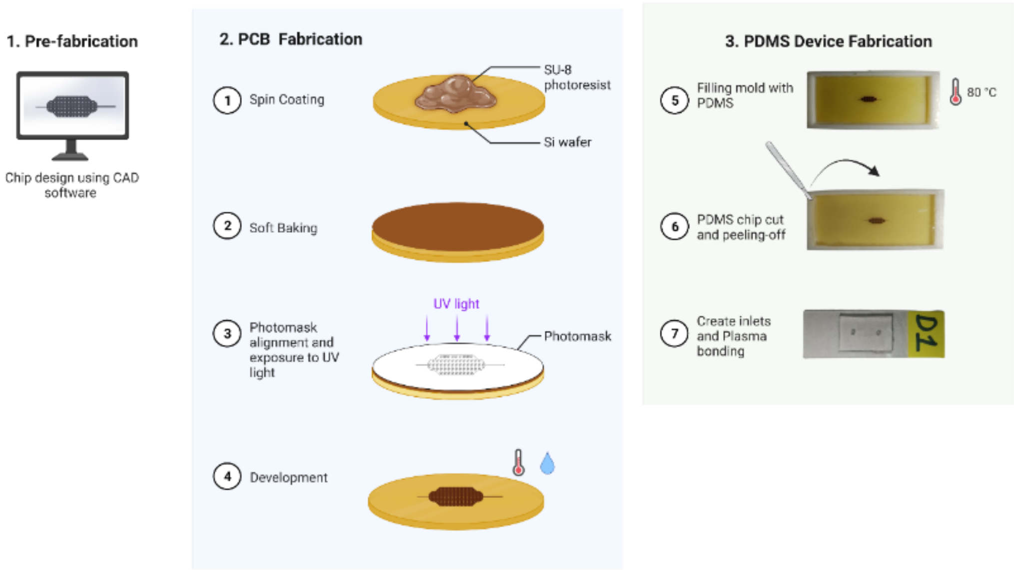


Figure 14: Flow Chart of Fabrication Process

CHAPTER 4: EXPERIMENTATION

4.1. Experimental Setup

4.1.1. Sample Preparation

For the experiment, 7 samples of glycerin and water were prepared using different concentrations: 5%, 7%, 12%, 24%, 40%, 60%, and 79%. To add color to each sample, one drop of ink was added. After preparing each sample, they were filtered using a syringe filter to remove any impurities or particles that may have been introduced during the experiment.

Figure 15: Seven Glycerin Solutions of Different Viscosities

4.1.2. Flow Rate

The experiments were conducted in a sterile environment, specifically a clean room, to minimize any external contamination that could affect the results. The working fluid was dropped onto a capillary micropump inlet to ensure controlled and precise delivery. A 1-ml syringe filled with the working fluid of different glycerin ratios, one or two drops were dispensed onto the capillary micropump for controlled delivery through the microchannel.

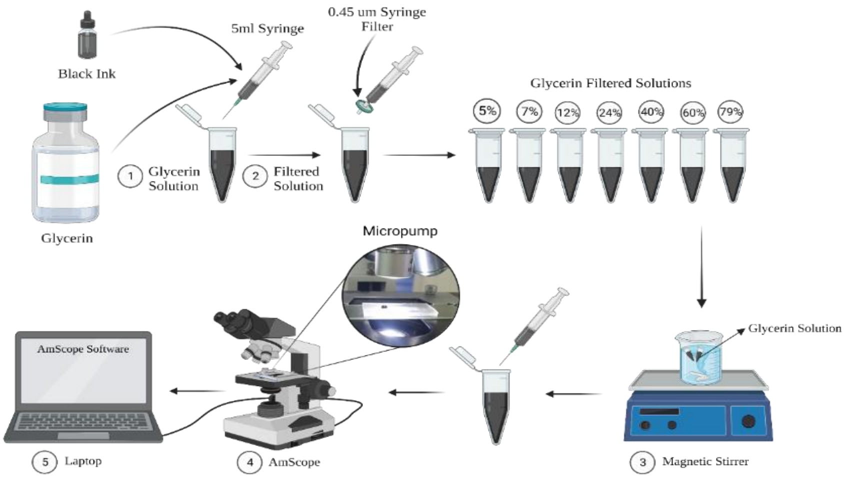


Figure 16: Schematic of Flow Rate Experiments

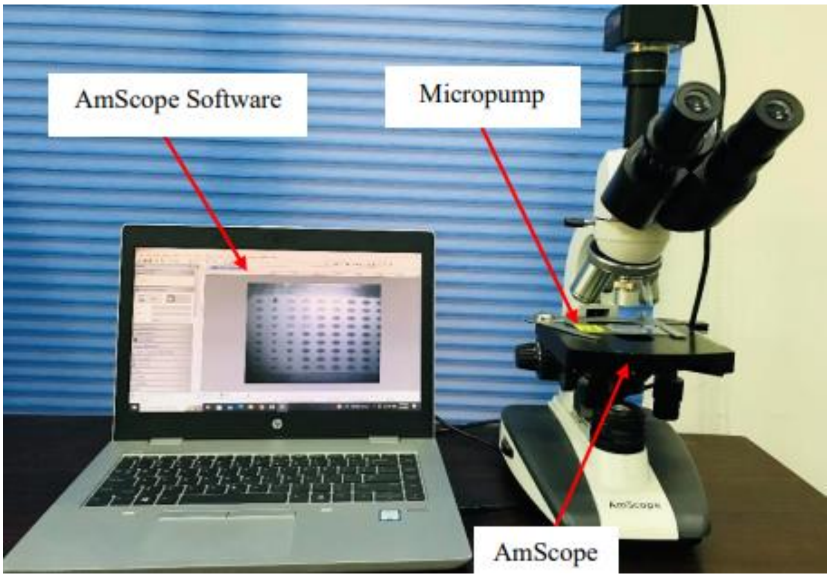


Figure 17: Experimental Setup for Flow Rate Experiments

4.1.3. Pressure Drop

The experiments were performed in a clean room. The working fluid was pumped through the microfluidic chip using a syringe pump (Darwin Microfluidic Pump). A 1-ml syringe filled with the working fluid containing the mixture of particles was passed through the microchannel by varying the flow rates from the syringe pump. The flow from the chip was observed through a vertical microscope equipped with a camera (BioCam Microscopy BIC-E3S-1.5C, 1.5MP) and connected to a laptop to collect the data of under observed microchip. The tubes (Scalp Vein Infusion set) were connected for inlet fluid flow between the syringe pump and the microchip.

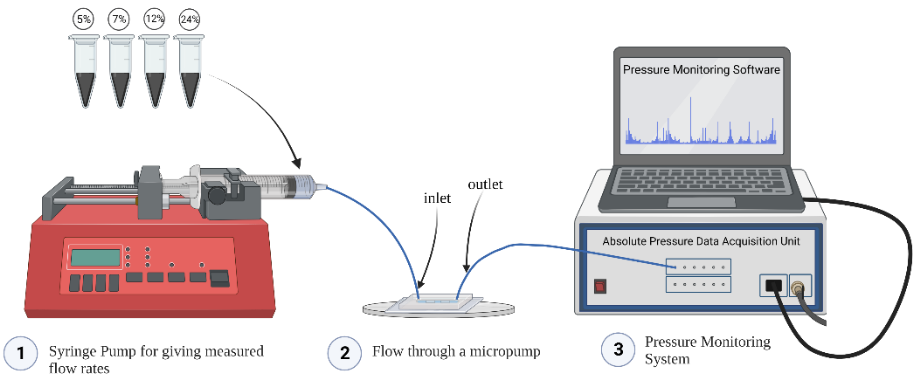


Figure 18: Schematic of Pressure Drop Experiments

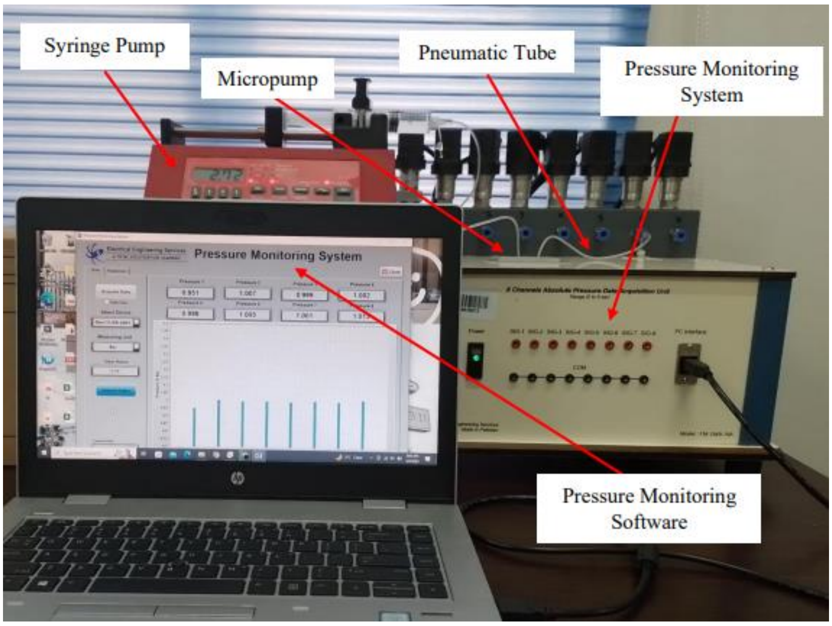


Figure 19: Experimental Setup for Pressure Drop Experiments

CHAPTER 5: RESULT AND DISCUSSION

The study investigated the effect of glycerin content on the flow rate in two microchannel designs, namely Design 1 with a 100 µm gap distance and Design 2 with a 150 µm gap distance. The flow rate was measured for different glycerin ratios, including 5%, 7%, 12%, and 24%, using a microfluidic system. The results showed that both designs experienced a decrease in flow rate as the glycerin content increased. However, due to the narrower gap distance and higher pressure drop, Design 1 consistently demonstrated higher flow rates than Design 2 for all glycerin ratios.

The observed relationship between the glycerin ratio and the associated decrease in flow rate can be explained by the fluid's increased viscosity. Glycerin has a higher viscosity than water, and as the glycerin ratio in the solution increases, so does the total viscosity of the fluid. Because of the greater barrier to flow caused by the increased viscosity, the flow rate is reduced. The pressure drop was also monitored for both configurations to quantify the effect of glycerin concentration on flow rate. The data showed a similar trend: as the glycerin concentration grew, so did the pressure decrease, which corresponded to the increased fluid viscosity. The data gathered for each glycerin ratio and design is summarized in the table below.

Table 2: Recorded Data for Different Glycerin Ratios

Glycerin Ratio	Flow rate D1	Pressure Drop D1	Flow Rate D2	Pressure Drop D2
%	ul/min	bar	ul/min	Bar
5	0.04527	0.011	0.02964	0.006
7	0.04069	0.009	0.02731	0.006
12	0.03525	0.007	0.02377	0.005
24	0.01981	0.004	0.0174	0.003

The flow rate was found to be affected by the distance between the diamonds as well as the vertical space between them. The vertical distance between two diamonds in Design 1 was narrower than in Design 2, resulting in a higher flow rate. A graph displaying the flow rate data for both Design 1 and Design 2 is shown below to graphically highlight the influence of the diamond-shaped hollow cut design on the flow rate. The graph continuously shows that Design 1 has a larger flow rate than Design 2, emphasizing the importance of using a diamond-shaped hollow cut design when building a capillary micropump.

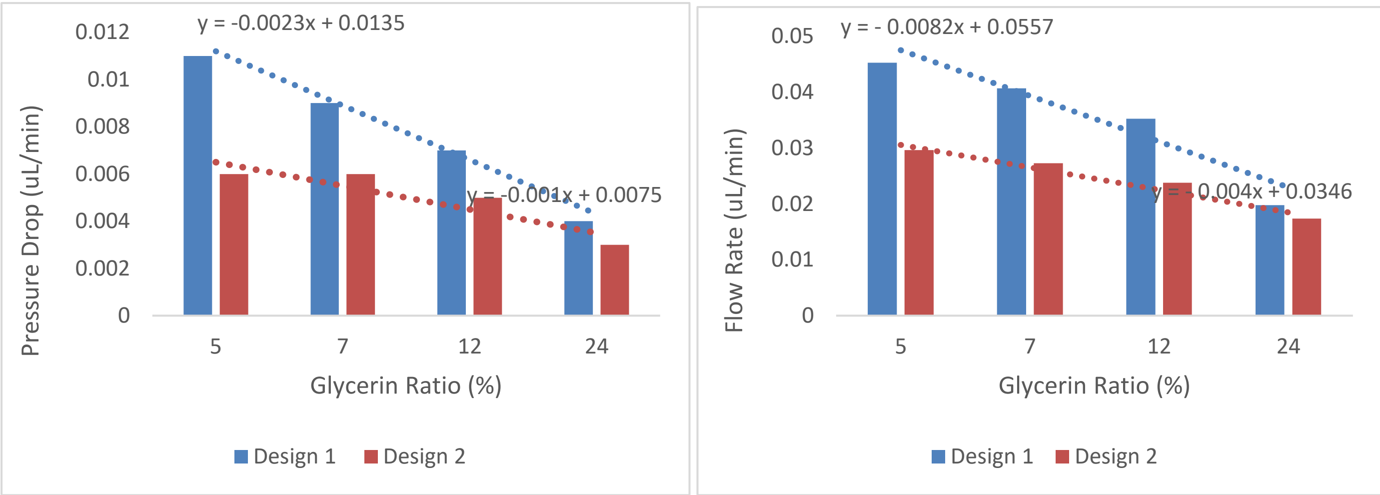


Figure 20: Graph Showing Flow Rate of Design 1 and 2

In the pressure drop vs. glycerin content graph, Design 1 has a slope of -0.00034, suggesting that for every 1% increase in glycerin content, the pressure drop drops by 0.00034 bar. Design 2 has a slope of -0.00017, suggesting a pressure reduction of 0.00017 bar for every 1% increase in glycerin content. As a result of its increased sensitivity, Design 1 appears to be more sensitive to variations in glycerin content. Similarly, Design 1 exhibits a slope of -0.0013 in the flow rate vs. glycerin content graph, suggesting a drop of 0.0013 ul/min in flow rate for every 1% rise in glycerin concentration. Design 2 has a slope of -0.00062, suggesting a drop-in flow rate of 0.00062 ul/min for every 1% increase in glycerin content. This emphasizes that Design 1 is more sensitive to glycerin content fluctuations.

The steeper slopes in Design 1 indicate that it is more sensitive to changes in glycerin content than Design 2. This might be attributable to Design 1's smaller gap distance between diamonds, which results in a larger total pressure drop and flow rate. The negative slopes in both figures can be explained by glycerin's greater viscosity than water. Glycerin provides higher flow resistance, resulting in a drop-in flow rate as the glycerin concentration of the micropump increases.

In summary, the negative slopes, and differences in steepness between the designs show that glycerin content has a significant impact on micropump performance, and various designs may respond differently to changes in glycerin concentration.

The flow rate difference can be linked to the venturi effect, which happens when a decrease in flow area results in an increase in flow velocity, resulting in a greater flow rate. The smaller vertical space between the diamonds in Design 1 generates a tighter flow area, encouraging a faster flow velocity and, as a result, a higher flow rate. Because of the conservation of mass principle, the fluid's velocity rises as it passes through this constriction. According to Bernoulli's principle, this increase in velocity corresponds to a drop in fluid pressure. This pressure loss adds to the pressure decrease measured over the micropump.

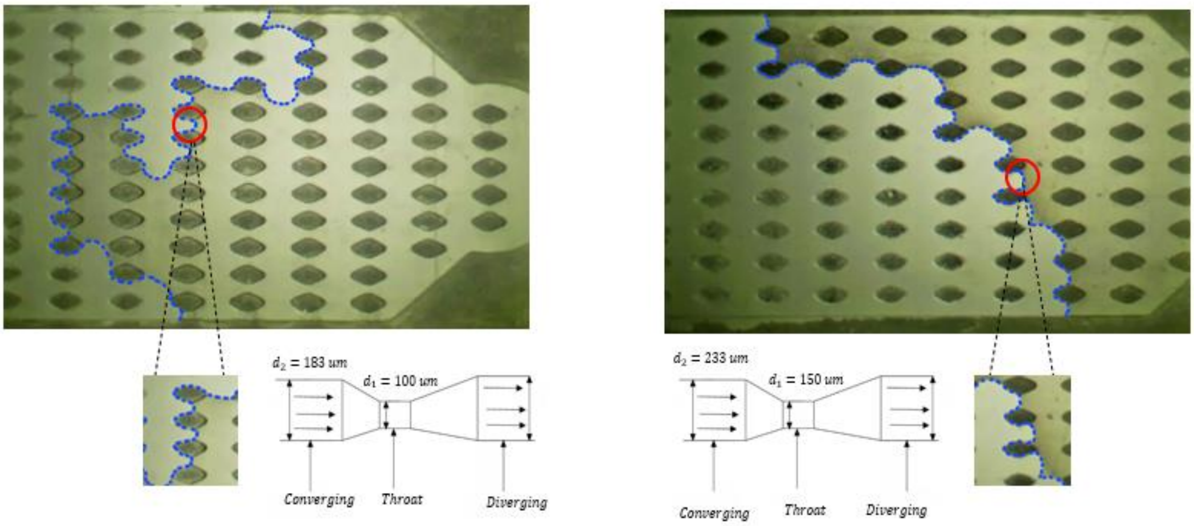
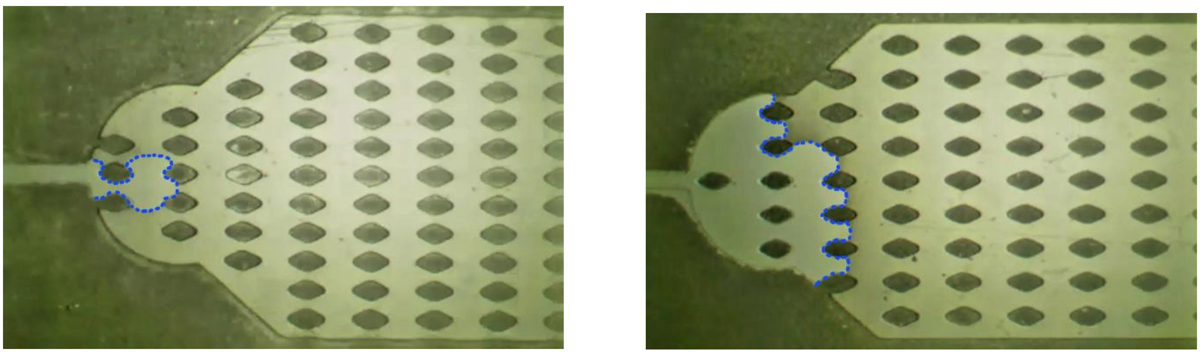


Figure 21: Venturi Effects in both designs

The existence of the Venturi effect in Design 1 of the micropumps results in a larger pressure drop due to a smaller gap distance between micropillars. This causes increased fluid velocity and, as a result, higher flow rates. Design 2, on the other hand, has a reduced Venturi effect, resulting in a smaller pressure drop and slower fluid velocity, resulting in lower flow rates. However, it is critical to recognize that the Venturi effect is not the only element impacting variations in pressure drop and flow rates within the micropump. The viscosity of the glycerin, as previously noted, also plays a crucial role in causing these variances.



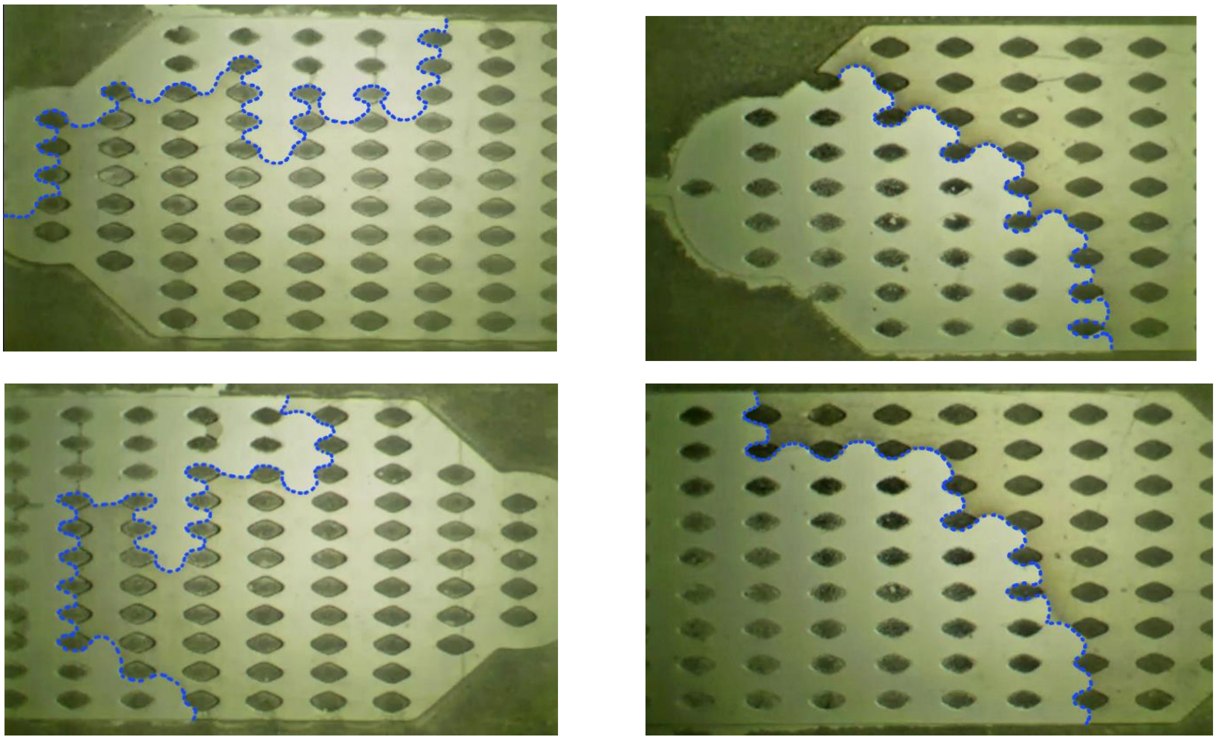


Figure 22: Visualization of flow through Design 1 and Design 2

The diamond-shaped hollow cuts used in the experiment were made of PDMS, a polymer with a low surface energy and a high surface tension. The surface tension of the fluid influences the flow rate within the micropump by creating a negative pressure or suction at the vena contracta, which designates the flow path's narrowest portion. This negative pressure can increase the flow rate and improve the micropump's self-priming capabilities.

Additionally, the wall shear stress was identified as another factor impacting the flow rate. As the fluid traverses the surface of the PDMS diamond-shaped hollow cuts, friction arises between the fluid and the PDMS surface, generating a shear stress referred to as wall shear stress. The heightened surface tension of the PDMS can yield a hydrophobic surface, thereby intensifying the wall shear stress and resulting in a reduction in the flow rate.

CHAPTER 6: CONCLUSION AND FUTURE RECCOMENDATION

6.1. Conclusion

The presented study introduces a methodology for designing and fabricating cost-effective capillary pumps suitable for point-of-care diagnostic devices, employing printed circuit board (PCB) technology. These capillary pumps leverage the self-perpetuating action of capillary forces, eliminating the need for external power sources and rendering them suitable for portable and affordable diagnostic devices. The integration of PCB technology enhances the efficiency and reliability of these capillary pumps. The research primarily focuses on the design and fabrication of micropumps utilizing PCBs and PDMS (Polydimethylsiloxane). Two distinct designs of PCB-based micropillars with hexagonal shapes were developed, offering desirable characteristics such as high flow rates and adaptability to varying fluid volumes. The fabrication process involved creating microchannels on the PCB, shaping PDMS replicas through silicon molds, curing the PDMS to achieve desired properties, and bonding it to a suitable substrate. The functionality and performance of the micropumps were evaluated through flow rate and pressure testing, affirming their successful operation. Experimental findings revealed a decrease in flow rate with increasing glycerin content due to the corresponding rise in fluid viscosity. Notably, Design 1 consistently exhibited higher flow rates compared to Design 2, attributed to its smaller gap distance, which resulted in a greater pressure drop. Furthermore, the pressure drop increased as the glycerin content rose, confirming the significant influence of fluid viscosity on the performance of the micropumps.

6.2. Future Recommendations

There are numerous essential recommendations for moving capillary micropump technology forward. Priority should be given to optimizing performance factors such as flow rates, power consumption, and control accuracy. This can be accomplished through investigating sophisticated microfabrication processes, new designs, and the use of novel materials with superior characteristics.

Furthermore, capillary micropumps should be integrated with modern sensing technologies such as biosensors and lab-on-a-chip systems. This connection would allow for real-time fluid monitoring and analysis, bringing up new opportunities for applications in sectors such as medical diagnostics, environmental monitoring, and chemical analysis.

Another significant area of study is increasing the compatibility of capillary micropumps with a broader range of fluids. This involves dealing with the difficulties that come with handling complicated biological samples, viscous liquids, and multiphase systems. Capillary micropumps can find larger application in sectors such as biotechnology, pharmaceuticals, and industrial processes if techniques to address these problems are developed. It is critical for the actual deployment of capillary micropumps to provide durability and long-term dependability. Thus, future research efforts should focus on enhancing the robustness and lifespan of these devices. This involves investigating suitable materials, improving device sealing and bonding techniques, and conducting thorough long-term reliability tests.

Scalability of manufacturing processes is another essential aspect that requires attention. Developing scalable manufacturing methods will enable cost-effective production and mass customization of capillary micropumps, making them more accessible to a wider range of users and industries.

Lastly, recognizing the significance of application-specific design considerations is vital. Different fields and applications have specific requirements, and tailoring the design parameters, channel geometries, and materials accordingly will optimize the performance and functionality of capillary micropumps in each application domain.

By focusing on these future recommendations, capillary micropumps can continue to evolve, offering enhanced capabilities, reliability, and versatility. This, in turn, will pave the way for their widespread adoption and revolutionize fluid handling and analysis in various fields, driving advancements in medicine, environmental monitoring, industry, and beyond.

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