10-1-2021

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Proceedings of the ASME 2021
Fluids Engineering Division Summer Meeting
FEDSM2021
August 10-12, 2021, Virtual, Online

FEDSM2021-65572

SIMPLE, COST-EFFECTIVE FABRICATION, AND FLOW DYNAMICS ANALYSIS OF A PASSIVE MICROFLUIDIC MIXER USING 3D PRINTING AND SOFT LITHOGRAPHY

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ABSTRACT

Simple and low-cost fabrication of microfluidic devices has attracted considerable attention among researchers. The traditional soft lithography fabrication method requires expensive equipment like a UV exposure system and mask fabrication facility. In this work, an alternative and low-cost UV exposure system was introduced along with an alternative mask fabrication system. A previously reported passive microfluidic mixer was fabricated successfully using this modified soft lithography method. Challenges were presented during this modified fabrication method. Another emerging potential alternative for the fabrication of microfluidic mixers is 3D printing. It was also used in this experiment to fabricate a passive micromixer. This method is well known for rapid prototyping and the creations of complex structures. However, this method has several disadvantages like optical transparency, lower resolution fabrication, difficulties in flow characterization, etc. These problems were addressed, and the solutions were discussed in this work. Comparative analysis between 3D printing and soft lithography fabrication was presented. Flow characterization inside the 3D printed micromixer was carried out using the microparticulate image velocimetry (micro-PIV) system. It explains how the geometrical shape of the micromixer accelerates the natural diffusion process to mix the different fluid streams. Finally, a 3D numerical simulation of the passive micromixer was carried out to visualize the flow dynamics inside the micromixer. The flow pattern found from the numerical simulation and the experimental flow characterization is analogous. These observations could play an important role to design and fabricate cost-effective micromixers for lab-on-a-chip devices.

Keywords: Micromixer, Soft-lithography, 3D-printing, Numerical simulation, Micro-PIV system.

1. INTRODUCTION

The most common way to fabricate microfluidic devices is the soft-lithography method. It is an optimized lithography process. It is done in two steps. First, the SU-8 mold is prepared on top of a silicon wafer. Second, the pattern is transferred to the Polydimethylsiloxane (PDMS) using a stamping process. Normally, it is viewed as an extension of photolithography. However, this lithography process requires several expensive equipment and a well facilitated cleanroom [1,2]. So, it is difficult to carry out the process in a normal set-up. But some researchers showed that this work can be carried out in a normal lab set-up without using cleanroom facility [3,4]. Researchers replaced expensive UV exposure system by a cheapest UV exposure system commonly used in printed circuit board industry. They also successfully used printed mask instead of highly expensive chromium mask. Motivated by those works, a cheap equipment set-up with normal lab environment was successfully used in this experiment to fabricate a previously used [4] passive microfluidic mixer. Passive micromixers rely on the mass transport phenomena provided by molecular diffusion and chaotic advection. These devices take the advantage of the channel geometry that increases the surface area between the different fluids and decreases the diffusion path. The chaotic advection is enhanced by modifying the channel design. This chaotic advection manipulates the laminar flow inside the mixing chamber. The modified flow pattern must follow a shorter diffusion path that improves the mixing velocity. Researcher used microfluidic mixer as an integrated system with lab-on-a-chip device to handle and mix biomolecules [5]. These devices become prominent in the areas of cell biology, medical diagnostics for their low-cost, several functionalities in biomedical sectors, and customizable fluid handling at a very small scale [6]. However, most of the microfluidic devices were fabricated using PDMS soft-lithography method. This traditional method has several drawbacks. It requires manual labor and long processing time [7]. This method has limitations on making 3D microfluidics devices. So, a new alternative method 3D-printing becomes popularized among the researchers these days [8]. It requires no manual labors and small processing time. It can be used to fabricate 3D-structures in contrast to soft-lithography method. The geometry is drawn using a CAD tool and then, it is directly fed to the printer. It takes as low as fifteen minutes to print a simple microfluidic mixer. There are different techniques used for 3D printing. Stereolithography (SLA) is the most popular technique because of the low-cost printing material and high precision surface resolution. Many commercialized 3D printers were built based on this technique [9]. This 3D printing technique used by many researchers for their biomedical device fabrication [10]. Lee and his team designed a flow immunomagnetic assay using this technique. It is a very good example making a small on chip laboratory using a 3d printing device. However, 3D printing devices has some drawbacks too. Some of these drawbacks were pointed out in this experiment. After fabrication of microfluidic mixer using 3D printing, fluid flow inside this device was characterized using micro-PIV system. The flow pattern obtained from micro-PIV system was compared with numerical result from simulation using COMSOL.

2. DEVICE FABRICATION

The passive micromixer was fabricated using both soft-lithography and 3D printing method. The geometry of the passive micromixer is illustrated in figure 1. This geometry is used for both fabrication technique. But the dimensions were varied. The dimensions in the figure 1 is used for 3D printing and 3D numerical simulation. The similar geometry with smaller dimensions was used for soft-lithography fabrication.

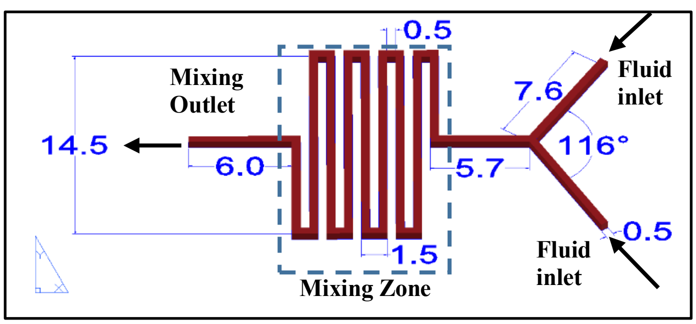

FIGURE 1: GEOMETRICAL MODEL OF THE 3D PASSIVE MICROMIXER. ALL DIMENSIONS ARE IN MILIMETRE.

2.1 Soft-lithography fabrication

Soft lithography was used in this experiment as a fabrication technique for making a microfluidic mixer. It is done in two steps. First, the SU-8 mold is prepared on top of a silicon wafer. Second, the pattern is transferred to the Polydimethylsiloxane (PDMS) using a stamping process. The mold fabrication process was taken from manufacturer **Microchem**. It is followed by manufacturing guidelines (www.microchem.com). The SU-8 mold fabrication process flow diagram is presented in figure 2.

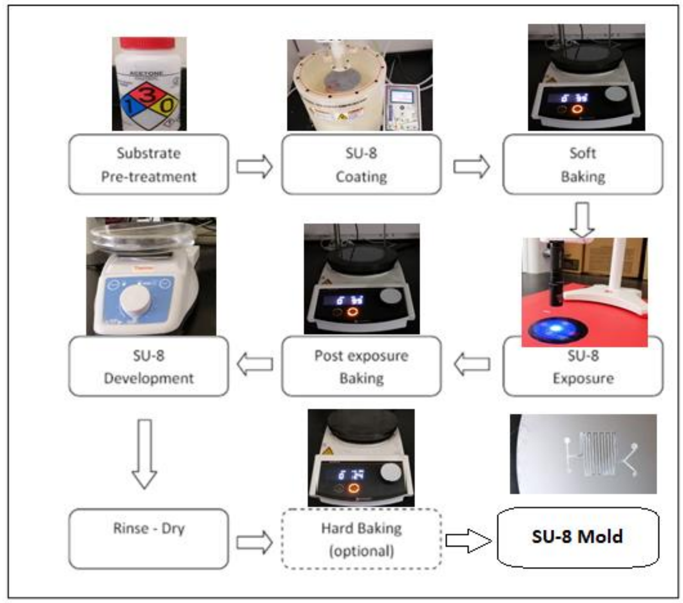

FIGURE 2: SU-8 MOLD FABRICATION FLOW DIAGRAM.

The second step is the PDMS replication process of the SU-8 mold. The PDMS is a polymer widely used in microfluidics to make devices such as lab on a chip. The replication process is mainly divided into 8 steps. The replication process is illustrated in figure 3.

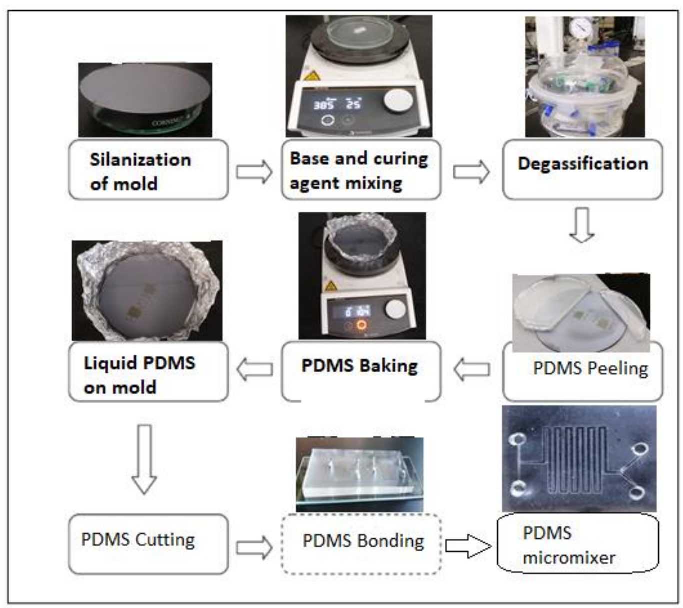

FIGURE 3: PDMS REPLICATION PROCESS FLOW DIAGRAM.

The most important part of soft lithography is UV exposure. Two things are needed to do the UV exposing. One is the UV source and another one is the mask to obstruct the UV. The optimal light wavelength for SU-8 exposure is 365nm. To fulfill the UV wavelength requirement a UV flashlight (Model-UV301D-plus) was bought from Amazon. It is commercially used by the UV glue curing professional. The UV exposure set-up is highlighted in figure 4(b). The maximum light emission energy was 200mW/cm^2. It depends on the distance the exposing object is kept. The exposure energy also depends on the photoresist thickness. From manufacturer guidelines, the optimum exposure energy for 40 microns is 150mJ/cm^2. The exposure time is calculated from the formula, exposure time = (required exposure energy/ the lamp emission energy). Another important thing for UV exposing is the mask. It is allowed the UV light only in the desired exposing area. Normally, it is made of a glass plate. But we don't have that facility in our lab. It is printed on transparent plastic paper using a high resolution (1200dpi) office printer. First, the pattern was drawn using AutoCAD software. Then, it was printed. The mask is illustrated in figure 4(a).

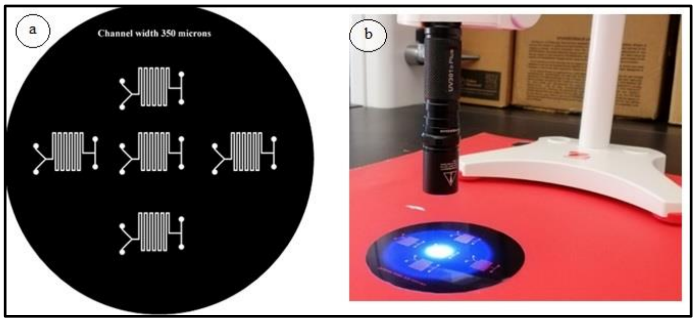

FIGURE 4: a) PRINTED MASK IN THE TRANSPARENT PLASTIC PAPER, b) UV EXPOSURE SET-UP.

2.2 3D printing of micromixer

In this study, stereolithography (SLA 3D) was used for 3D printing. It is a method and apparatus for making solid objects by successively printing thin layers of a UV curable material one on top of the other. Objects are built in a layer-by-layer manner by spatially controlled photopolymerization of a liquid resin which is performed with either a scanning laser or a digital light projector. A UV beam traces a 2D cross section onto a support platform submerged in a tank of photoactive resin. This photoactive resin undergoes a polymerization reaction upon UV illumination. After completion of the 2D cross section, the platform is lowered further into the resin and the UV beam begins the addition of the next layer. The product is ready after the completion of the final layer. The 3D geometry of the microfluidic mixer was designed using AutoCAD software. The drawing file is exported as a 3D printable file format (STL). The 3D model of the microfluidic mixer is sliced using CHITUBOX software. The different features can be added to this software to make it a stable 3D printing object. Because it will be printed in the 3D printer in a layer by layer manner. The setting of each layer like the amount of UV light, exposure time, printing time, amount of materials, and cost of the printing can be adjusted in this software. ELEGOO Mars UV Photocuring LCD 3D printer was used for 3D printing purposes. The 3D drawing file after processed by CHITUBOX software was fed into the printer by a pen drive. Before starting the printing process, the standard photocuring liquid was supplied to the printing chamber. The printing process flow diagram is illustrated in figure 5.

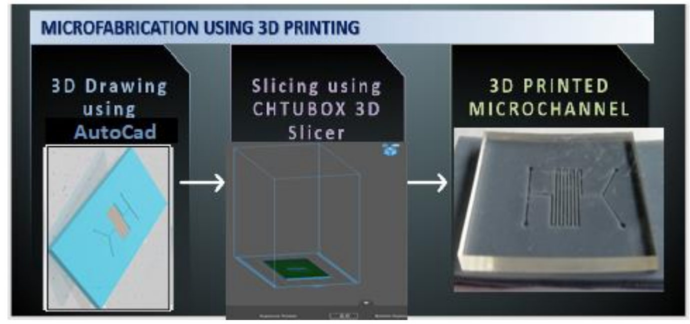

FIGURE 5: 3D PRINTING PROCESS FLOW DIAGRAM.

3. EXPERIMENTAL SET-UP

The experiments were carried out at room temperature. First, the fabricated micro-channel was combined with a silicon wafer. The soft lithography fabricated microchannel was combined with silicon wafer by means of adhesion force between the PDMS and the wafer. The adhesion force is enough for a leakage proof connection. PTFE tubing was used to supply liquid to the microchannel. The silicon wafer along with the microchannel was attached on top of the microscopic stage (a part Micro-PIV system) using adhesive tape. It was attached under the microscopic lens such a way that the microchannel can be focused to observe fluid movement inside the microchannel. The 3D printed microchannel was combined with a PDMS layer on top as it is transparent to observe the fluid flow movement inside the microchannel. The experiment was done on dynamic fluid flow through system. Two types of fluid were used in this experiment, i) DI water (10 µS/cm), ii) PBS (Phosphate buffered saline) solution (12 mS/cm). FluoSpheres polystyrene 1.0 µm particles were used as the tracer particle. Before injecting the fluid into the mixing chamber, 1µl of polystyrene particles were mixed with 10 ml of the liquid. These polystyrene particles are excited at a wavelength range from 540-640 nm by exposing under laser light. Then, the particles emit light at a wavelength range of 580-700 nm. which will be captured by an integrated camera in the microscope through an optical filter (XF2017-660DRLP). It is illustrated in figure 6.

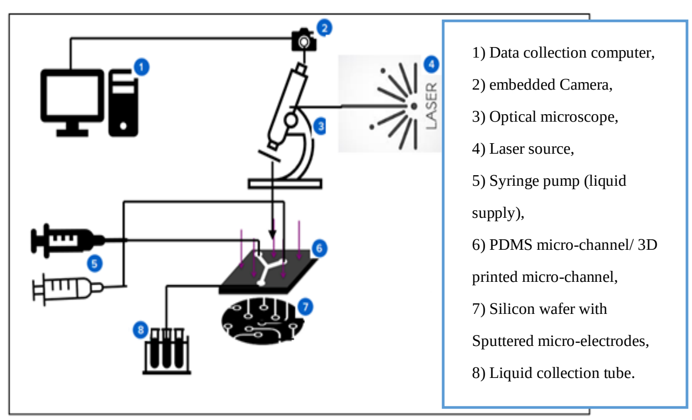

FIGURE 6: SCHEMATIC OF THE EXPERIMENTAL SET-UP.

4. RESULTS AND DISCUSSION

After several attempts, the micromixer was fabricated successfully using in house soft lithography technique. The lowest channel width achieved so far was 300 microns. It was not possible to go beyond that dimension for the following reasons. First, the limitation in the mask printing process. A normal office printer is used to print the mask, which limits the minimum dimension of the channel width. Because in the lower dimension the quality of the printing resolution decreases rapidly.

4.1 Microscopic analysis of the micromixer

Soft-lithography fabrication: A microscopic view of the micromixer shows that it has some irregularities at edge of the channel. It will create obstacles in the fluid flow. So, the target is to make the edges as smooth as possible. These edges were created due to low resolution mask. It is shown in figure 7, that the plastic mask has a similar edge to final PDMS micromixer. The UV light passed through the irregular edges of the mask. To reduce those irregularities high resolution printer is recommended to use for mask printing.

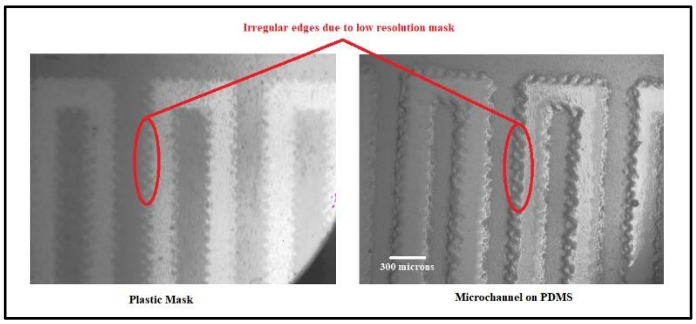

FIGURE 7: MICROSCOPIC VIEW OF THE MICROMIXER CHANNEL WALL FABRICATED USING SOFT LITHOGRAPHY.

It was also observed that some portion of the micromixer has some irregularities like the microchannel in some areas was not properly developed. It is due to the intensity difference during UV exposure. The UV light used in this experiment has two different light intensity zone. During UV exposing it might occur that some part of the micromixer was not get proper UV light. For this reason, some portion of the micromixer like inlet, T-section and some edges were not properly developed. It was illustrated in figure 8.

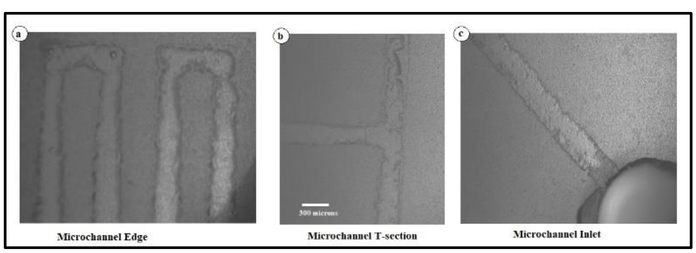

FIGURE 8: IRREGULARITIES IN MICROMIXER FABRICATED USING SOFT LITHOGRAPHY.

3D printing: The microscopic view is important to analysis the internals of the micromixer. Flow-through a microfluidic chamber is largely dependent on the surface and the smoothness of the channel. Because viscus force is dominant in the microfluidic mixer which governs fluid flow patterns and the mixing in the microscale strongly depends on the fluid flow pattern. The fluid flow pattern depends on the surface of the microstructure. It was observed that the internal surface of the micromixer is not smooth. There are small porous points observed on the internal surface. These porous points attract the water molecules due to adhesion force. These create hindrance in the fluid flow which is also responsible for low mixing between two different streams of fluid. The smoother the surface of the internals, the better it creates a favorable environment for microfluidic mixing. The surface of the 3D printed microfluidic device depends mostly on the photopolymer resin used during 3D printing. This resin is specially designed for reducing volume shrinkage during the photocuring process, which ensures the high precision of the print model with a smooth finish. If the surface roughness of the microstructure is needed to be improved, a better-quality resin is needed to be used. The microscopic view of the 3D printed passive micromixer is presented in figure 9.

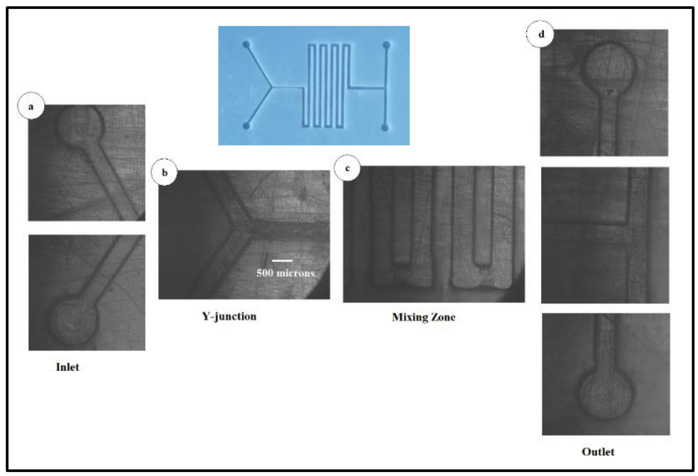

FIGURE 9: MICROSCOPIC VIEW OF THE 3D PRINTED PASSIVE MICROMIXER.

After completion of fabrication, the micromixer needs to be tested for flow through system and possible leak test in the channel. Potassium permanganate solution was used to make colored water solution. Then the colored water passed through the micromixer by using a syringe pump. It is observed that the colored water passed easily through the micromixer. The is no observable leak found in the micro mixer. Two micro fabrication technique was used in this experiment. One is soft lithography and other one is 3D printing. The 3D printing technique is the most recent and advanced method. Apart from that, each technique has their advantages and disadvantages. In table 1, it is discussed based on the fabricated device based on those techniques.

Table 1: Comparison between 3D printing and soft lithography microfabrication.

3D Printing Microfabrication	Soft lithography Microfabrication
The wall of the microchannels has a smooth finish.	The wall of the microchannels has a rough finish.
Smaller dimensions are very difficult to achieve	Smaller dimensions can be achievable
Fabrication time very short. For this experiment, it took 16 minutes to print	Fabrication time is very long. It took almost 240 minutes to fabricate.
The fabrication process is easy and has three steps	The fabrication process is complex and has 12 steps
The only raw materials used is photopolymer resin	There are more than five raw materials involved
The raw material is cheap. So, the total fabrication cost is low	The raw materials are expensive. So, the fabrication cost is high
The only equipment needed is the 3D printer	There is several equipment needed like spin coater, vacuum pump, UV exposer, developer station, heating arrangement etc.
The 3D printed material is not transparent. So, another layer of transparent PDMS is needed.	Transparent materials like PDMS can be directly used for microfabrication
The 3D printed material is not a suitable flexible lab on a chip device	It is suitable for flexible lab on a chip device

4.2 Flow characterization using the micro-PIV system

For experimental analysis, the average inlet velocity was 212 µm/s. The calculated Reynolds number was 0.178. This small Reynolds number created a laminar profile in the channel. Flow dynamics inside the micromixer is illustrated in figure 10. When two fluid streams meet each other at the Y-junction of the mixer, they tend to flow parallel to each other. They do not mix with each other as the direction of the flow does not change. If we imagine a boundary line in the middle of the channel which separates two fluid streams from each other. It is represented by a red dotted line. It is observed that in the straight part of the channel the velocity vector does not change direction. It means the upper fluid stream remains in the upper portion of the channel and the lower fluid stream remains in the lower side. The lower fluid stream moves to the upper portion of the microchannel after passing bend 1. It is highlighted by the red dotted line in figure 10(c). The same event also occurs in bend 2 (figure 10(d)). The fluid velocity vectors change the direction more vigorously in bend 3 (figure 10(e)). The upper fluid stream goes to the lower part of the microchannel and comes back to the upper portion again. This increases the contact between the two-fluid stream. As a result, the two fluid streams mix with each other. This is also true for the subsequent bend of the micromixer. So, ultimately a mixer of fluid is observed at the outlet of the micromixer.

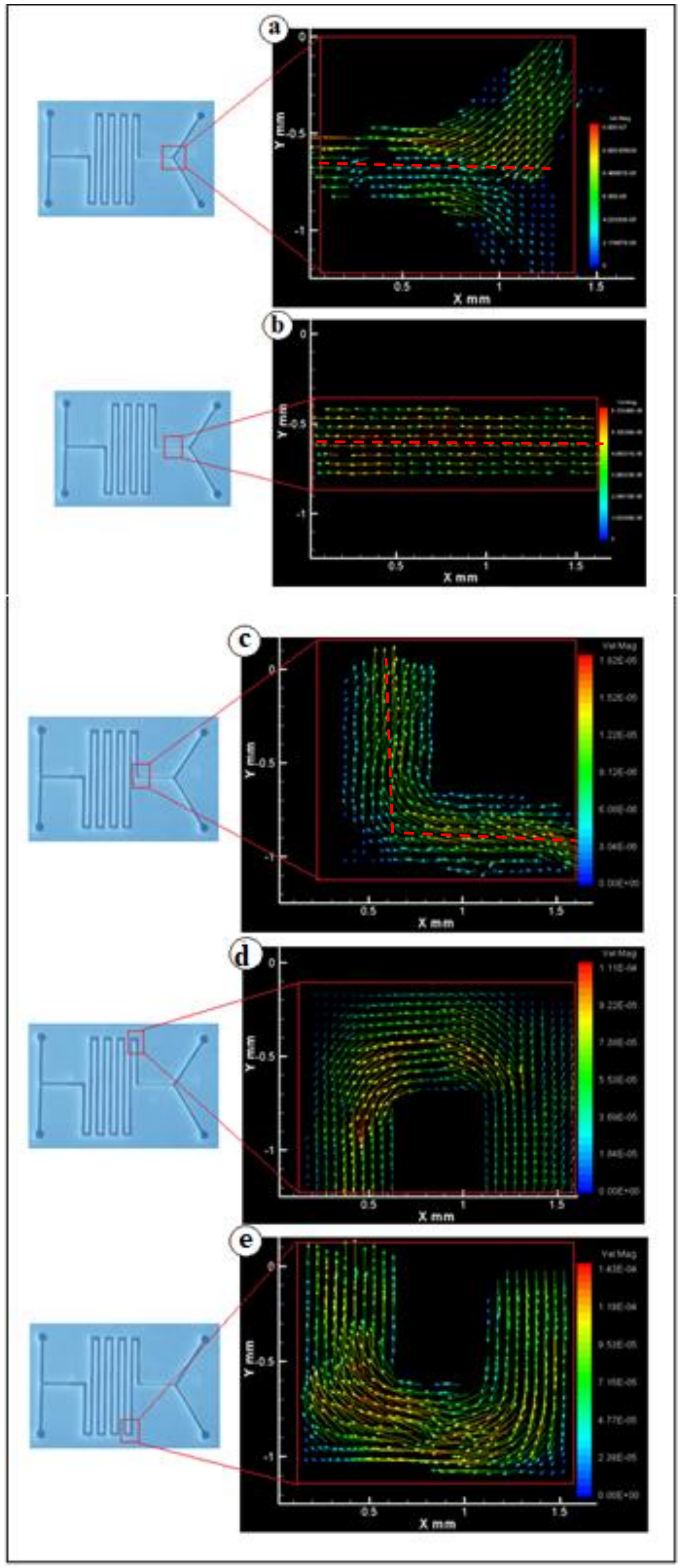

FIGURE 10: FLUID VELOCITY VECTOR INSIDE THE 3D PRINTED MICROMIXER.

4.3 Numerical simulation of the micromixer

The concept of designing a device for 3D numerical simulation is quite different from 3D printing. For 3D printing, the device is designed keeping the fluid occupying part empty. It is illustrated in figure 11(a). The whole block is solid other than the microchannel part. For numerical simulation, Only the fluid occupying part is designed. Because only the fluid movement is going to be observed. So, only the fluidic part of the microchannel is drawn. Another part of the device is omitted for numerical simulation. It is illustrated in figure 11(b). The part having used for numerical simulation has the exact dimension as the micromixer designed for 3D printing. So, the results obtained from numerical simulation can be compared with the experimental results. COMSOL Multiphysics was used to simulate flow inside the micromixer. The simulation procedure was followed from our previous work [11].

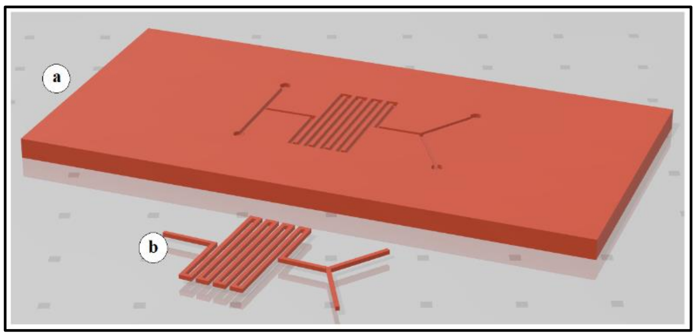

FIGURE 11: a) 3D VIEW OF THE MICROMIXER FOR 3D PRINTING, b) 3D VIEW OF THE MICROMIXER FOR 3D SIMULATION.

High concentration (1 mol/m^3) fluid passes through one inlet of the micromixer. Low concentration (0 mol/m^3) fluid passes through another inlet of the micromixer. It is illustrated in figure 12. This figure represents the concentration distribution inside the micromixer after giving two different concentration fluid in the inlet. It is observed that after passing through the inlet two different concentration fluid meet with each other in the Y-junction. The two different fluid streams flow side by side without interacting up to bend 1. From bend 1 to bend 2, two fluid streams interact heavily with each other. The two fluid streams continue interacting with each other in the subsequent bend in their way through the outlet. In the outlet, it is observed that the concentration is almost 0.5 mol/m^3. This is the average of the high concentration of 1 mol/m^3 and low concentration 0 mol/m^3. So, it can be said that the two fluids mix with each other completely at the outlet of the micromixer. To explain the concentration distribution inside the micromixer, flow pattern inside the micromixer is presented in figure 13. Two different concentration fluid mix with each other because of two reasons mainly. One is the natural diffusion occurs between the fluid layers and another one is due to complex flow pattern in the flow path. The flow pattern is responsible to make the diffusion quickly between the two layers. So, if flow pattern changes, the rate of diffusion increases. In the straight microchannel, flow does not change. The mixing in this situation only occurs due to natural diffusion. The flow pattern only changes when there is a bend presents in the flow path. Total 10 bends (figure 11) were designed in this micromixer to change the flow path.

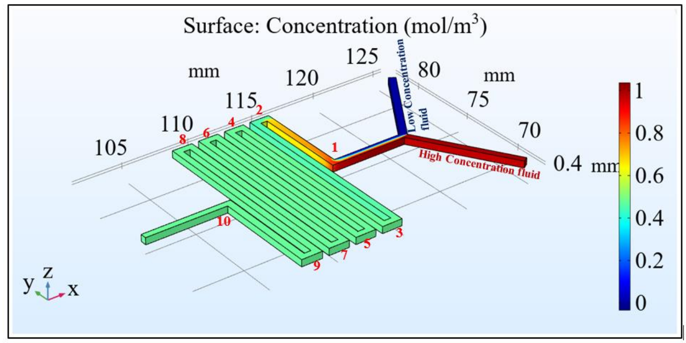

FIGURE 12: CONCENTRATION DISTRIBUTION INSIDE THE 3D MICROMIXER.

When two different concentration fluid meets with each other at Y-junction, they tend to flow separately alongside with each other. It is illustrated in figure 13(b). Fluid streamlines coming from low concentration side remain in this side until bend 1. High concentration fluid lines also remain in the high concentration up to bend 1. Fluid lines from low concentration side moves to the high concentration in the bend 1. It is illustrated by red dotted line in figure 13(c). This is where the mixing begins. This also explains the concentration change in figure 52 immediately after the bend 1. Similar changes also observed in the subsequent bend. In figure 13(d), it is observed that both low concentration and high concentration fluid lines changes the sides repeatedly. This increases the diffusion rate. Ultimately, two different concentration fluid mixes with each other at the mixer outlet.

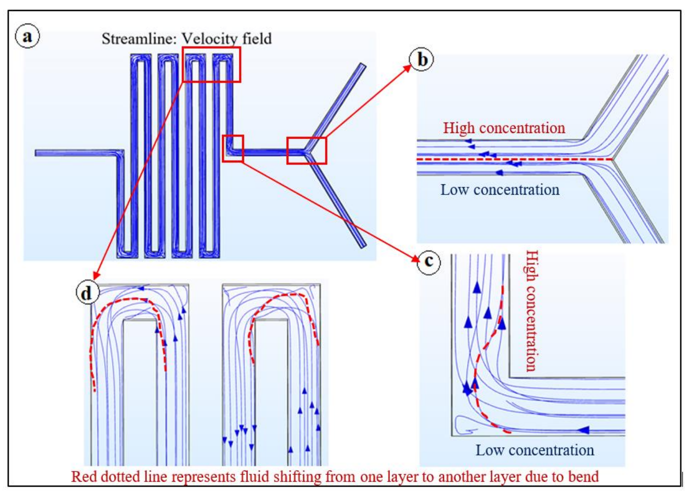

FIGURE 13: SIMULATED FLOW PATTERN INSIDE THE 3D MICROMIXER.

Numerical results were compared with experimental results as the dimensions and geometry were same. It was found that flow pattern is similar in the Y-junction of the micromixer. Fluid layer does not move direction in the straight part of the micromixer as like the laminar flow pattern. The fluid layer changes direction in the bend for both numerical and experimental results. So, the experimental and numerical results are analogous for the micromixer. The flow pattern comparison is illustrated in figure 14.

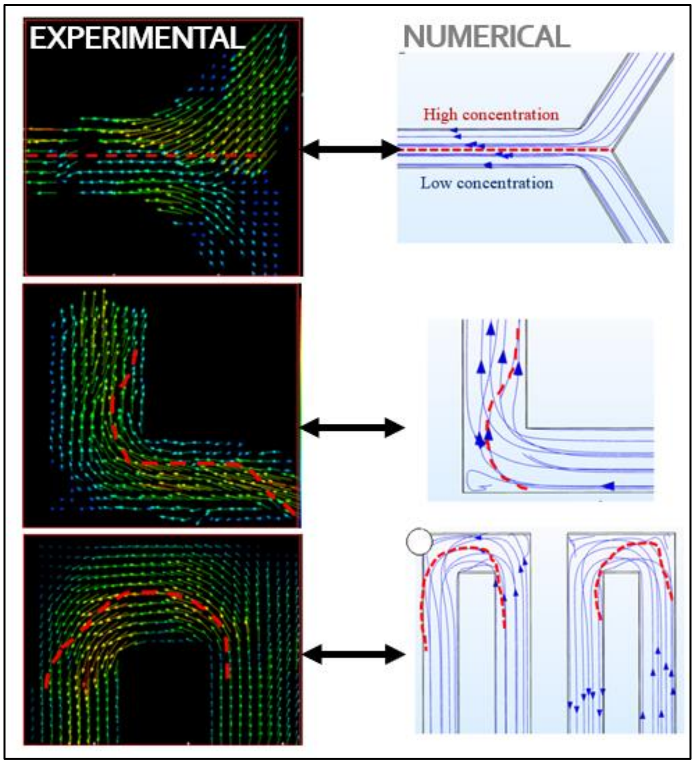

FIGURE 14: COMPARISON BETWEEN SIMULATED AND EXPERIMENTAL FLOW PATTERN INSIDE THE MICROMIXER.

5. CONCLUSION

A micromixer is a crucial part of a lab-on-a-chip device. This lab-on-a-chip device is a game changer for the future health care system in the world. So, the development of micromixer technology can contribute a lot to the future medical diagnostic system by making mixing easier in the microscale for different types of the reagent with the test sample in a lab-on-a-chip device. In this work, two well established micromixer fabrication process were discussed. They are soft lithography and 3D printing microfabrication techniques. Although, the 3D printing technique has some advantages over the soft lithography technique as a microfabrication process. But it still has some limitations. Achieving lower dimensions is still a challenge in the 3D printing technique. For the current work, the lowest dimension achieved using the 3D printing technique is 500 microns. Besides, the 3D printing materials is not transparent compared to PDMS. So, it requires a PDMS layer to observe the flow inside the microfluidic device. These challenges should be explored in the future to use the 3D printing process as a competitive option for microfluidic device fabrication. COMSOL Multiphysics was used to simulate fluid flow inside the passive micromixer to understand the dynamics better inside the mixing zone. Fluid layers inside the micromixer changes direction after passing every bend section. The fluid layers from the lower region move toward the upper region of the channel. This intensified the diffusion process inside the micromixer. These direction changes of the fluid layers occurred repeatedly in the subsequent bend of the passive micromixer. These direction changes contribute to the mixing in the micromixer. The results observed in the numerical simulation for passive micromixers are analogous to experimental results.

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