Numerical Analysis of Micro Mixer based on Micro Robots

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***Abstract*—In this study, performances of a micromixer based on microfluids are estimated numerically. Faster and more efficient an active micromixer modeling that minimizes human contact is presented by making numerical calculations with basic microfluidic equations. In the model we created, two liquids of the same type were included in the micromixer environment in 0.005 second steps for the 3 second model. The density of the first liquid is 1 $mol.m^{-3}$, the density of the second liquid is 5 $mol.m^{-3}$. As a result of mixing, the new density of the two liquids is expected to be 3 $mol.m^{-3}$ at ideal conditions. According to the value calculated as a result of the simulation, the density of the model is 2.945 $mol.m^{-3}$. The efficiency obtained from the model examined in the study is 98.181%. In order to better interpret the efficiency of the presented model, it is compared with other active micromixers.**

***Index Terms*—Micro Robots, Micromixers, Numerical Analysis**

I. Introduction

Microfluidic devices have an increasing importance day by day as they are actively used in important fields such as biomedical diagnosis, food safety control, and environmental protection [1]. Microstirring has a significant impact on the efficiency and sensitivity of microfluidic devices. Micromixer are device that mechanical micro parts used to mix fluids. This devices can be used different fields as they can take advantages of the miniaturization of the fluids associated with mixing to reduce the amounts involved in chemical and/or biochemical processes. Micromixers are classified as active and passive micromixers. Passive micromixers do not operate using external energy except pressure head used to drive the fluid flow at a constant rate. Active micromixers function with external energy that generated either by moving components within the micromixer itself and control. Because of these features, micro mixers have important places in many areas [2].

The application of external energy can be within the micromixers, as in the case of magnets, or by the utilization of an external force field. Magnetic micromixers are able to execute the mixing of nanoparticles, which is the operation of mixing particles in the nanosize. Pressure field, acoustic field, magnetic field, electric field, and thermal field are examples of external energy used in active mixers. Pressure field driven micromixers use external pressure applied in various forms to achieve maximum mixing efficiency. Li and Kim's pressure driven micromixer uses pulsatile pressure as their mixing agent. The pulsatile pressure is created by the constant input of water head pressure. This study had 90% mixing efficiency. Their final analysis is based on various channel widths, frequencies, and flow rates; thus, the final result is accurate [3]. Acoustic field driven active mixers function due to the energization of bubbles by an acoustic field, and in general they do not have high mixing efficiency values; however, Orbay's multi-bubbled based active mixer is an exception to this generalization with a 93% mixing efficiency. Using a three-inlet PDMS microchannel, Orbay mixed two high viscosity polyethylene glycol (PEG) solutions. Due to a constant stream of nitrogen flowing through the center inlet of the three-inlet PDMS microchannel bubbles were formed in the device, which mixed the solutions homogeneously when energized by an acoustic field. Orbay managed to create an efficient active mixer which was also inexpensive and convenient [4]. Magnetic field driven micromixers could be activated by various forms of objects, which, create magnetic fields. Veldurthi's magnetic field driven micromixer has an approximately 90% mixing efficiency. The mixing occurs in a chamber which connects to two linear outlet and a linear outlet, which is an appreciable mechanism. The mixing is done by a micro-rotor consisting of three permanent magnets. In a general sense Veldurthi's micromixer had a good mechanism and high mixing efficiency. Electric field driven micromixers function by the exertion of electrohydrodynamic (EHD) disturbance and electrokinetic (EKI) instability [5]. Usefian and Bayareh's numerical study uses electrokinetic instability by electroosmosis to actuate their electric field driven micromixer. As a result of their study they concluded that mixing efficiency increases with the frequency, voltage value and angular velocity and decreases with the inlet velocity of fluids. Their mixing efficiency for their higher angular velocity is 97.67% and for their lower angular velocity is 71.02%. Thermal field driven active mixers utilize the increase of the diffusion coefficient, thermal bubbles or electrothermal effects to improve mixing performance [6]. Meng's electrothermal micromixer is a thermal energy driven active mixer, which has an experimentally confirmed 100% mixing efficiency. The micromixer had two straight inlets and a cylindrical mixing chamber [7].

Our study uses a magnetic field driven active micromixer. The substances are mixed in a chip which consists of two straight inlets, a cylindrical mixing chamber, and a straight outlet. Our main contribution is show that the efficiency of an active magnetic driven micromixer based on microrobots.The study has constant laminar flow of liquids flowing through both inlets. Since fully developed laminar flow does not change its characteristics with increasing length of flow, the flow of liquids will be uniform throughout the experiment.

II. Methodology

The microfluid dynamics is characterized by Reynolds number, Peclet number and due to our micromixer being a magnetic field driven active micromixer, the Strouhal number. Reynolds number represents ratio of inertial forces to viscous forces as shown in 1. Peclet number represents ratio of the convection rate over the diffusion rate as shown in 2. The Strouhal number represents the ratio of inertial forces due to the local acceleration of the flow to the inertial forces due to convective acceleration, can be represented as the ratio of residence time to of a species to the period of the disturbance as shown in 3.

$$Re = \frac{\rho U D_h}{\mu} \tag{1}$$

$$P_e = \frac{UL}{D} \tag{2}$$

$$S_{tr} = \frac{fL}{U} \tag{3}$$

where U is the average flow velocity, f is frequency (Hz) of the oscillations with dimensions $[T^{-1}]$, L is the length of the mixing plane and D_h is the hydraulic diameter of the channel.

Fluid flow in our study is laminar and fluids assumed as in-compressible Newtonian fluids. This can be described by continuity and Navier-Stokes equations **??**.

$$\nabla \vec{V} = 0 \tag{4}$$

$$(\vec{u}\nabla)\vec{u} = \frac{1}{\rho}\nabla p + v\nabla^2\vec{u} \tag{5}$$

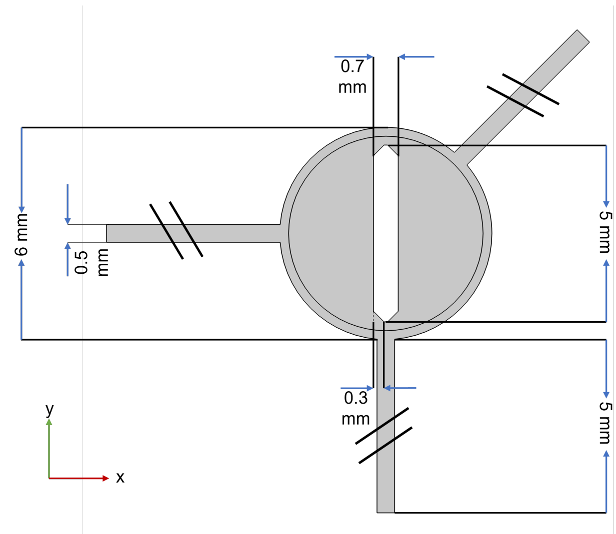

Fig. 1. Shows the micromixer environment and all the relevant dimensions. In the center of mixing chamber, a microrobot is placed with a sharp edge to improve mixing efficiency.

where p is the density of the fluid,$\vec{V}$ is the velocity vector and u is the kinematic viscosity pf the fluid.

The mixing efficiency of the micromixer can be calculated by the following 6.

$$(\eta) = (1 - \sqrt{\frac{\sigma^2}{\sigma^2_{max}}}) \times 100 \tag{6}$$

where is the standard deviation of the mass fraction of the species across the cross section of certain plane normal to flow path and σ_{max}, is the maximum variance from the mean value of the mass fraction of species across the cross section of certain plane normal to flow path. C_i is the concentration of the species at grid points i and $C_{\bar{m}}$ is the mean of the species calculated by

$$C_{\bar{m}} = \sum_{i=1}^{n} \frac{C_i}{n} \tag{7}$$

Micro robot is chamfered corners that has 0.3 mm distance from vertex. Its placed right in the middle of inner circle in micromixer channel which has two inlets and one output. Mixing chamber has a diameter of 3 mm. Inlets and output has a width of 0.5 mm, length of canals were not considered important due to mixing is not occurring without any outside help in a laminar flow. The length of channels is selected 5 mm for enough mixing. Micro robot was turning with 1500 rpm in the simulation.

COMSOL is one of the programs frequently used in micro mixer analysis. It provides the opportunity to make high-accuracy analysis with many types of physics it contains. In this study, numerical analysis of a 2D micromixer that mimics the shape of a microrobot was performed. For this, Transport of Diluted Species and Laminar Flow physics of COMSOL program were used. The COMSOL Multiphysics feature was used to combine these two physics. Shapes and dimensions of the micro mixer and micro robot designed in the COMSOL program are shown in Fig. 1.

III. Simulation Results

The purpose of this simulation is to provide maxiumum efficiency by minimizing human interaction on the micromixer systems. Thus, faster measurements were made with a lower margin of error. Simulation was needed to test the efficiency of micro robot approach. We simulated mixing of the two liquids with different concentration, one being 1 $mol.m^{-3}$ and the other one being 5 $mol.m^{-3}$. This setup with one liquid of different concentration made it also mix a little bit due to diffusion which possibly improved results.

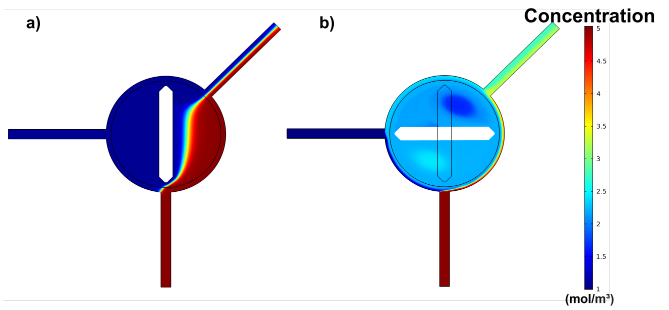

Fig. 2. Shows a) the initial concentration surface of the numerical analysis and b) the final concentration surface after 3 seconds of analysis.

The initial concentration of the model is at the extremes as observed from the scale. When the final concentration is examined, it is seen that the micromixer approaches the expected average concentration value. Samples of the same liquids with different density values were sent from both arms of the micromixer. Liquids of different densities mixed with the micro robot inside were expected to come out with an average value. The speed and duration of the mixing process are important factors for the experiment. In the simulation made for the new micromixer model examined in this study, a time-dependent concentration graph was observed as a result of the 3 second analysis, each step being 0.005 seconds.

Simulation results are as shown in the Fig. 2. To calculate mixing efficiency, the value found as the average of 7 different points taken from this Fig. 3 was used to interpret the mixing efficiency. Table I is shown the concentration value of each point. By using the seven concentration valuess, the average concentration value obtained from the model is 2.945, which is very close to the expected average value of 3. As a result, the model with 98.181% efficiency was obtained. Table II shows summary of the numerical analysis.

IV. Discussion

The mixing efficiency is a key parameter for a micromixers. Some methods have been proposed to evaluate the mixing efficiency. A commonly used method is based on the intensity of segregation. Micromixers are magnetically actuated by permanent magnet, electromagnet, microstirrer and integrated electrodes. The efficiency of micromixers for liquids of different densities was investigated by performing operations on the Reynolds number, Peclet number and Strouhal number which are characteristic numbers affecting the operating

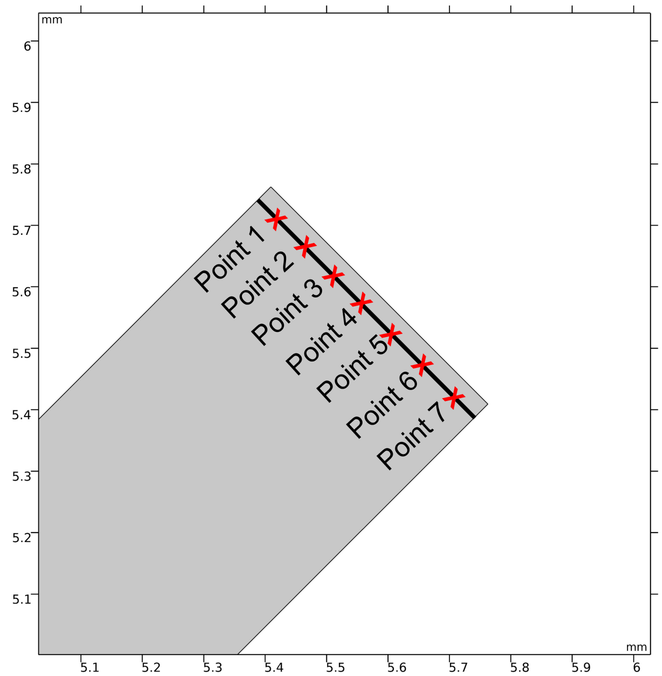

Fig. 3. Seven sample points taken from a graph of concentration variation over time to find mixing efficiency

TABLE I

Concentration for Each Point that is Placed at the Outlet of Mixer

Points	Values
1	2.785
2	2.778
3	2.834
4	2.893
5	3.080
6	3.149
7	3.099

TABLE II

Ideal Condition and Calculated Values

Points	Values
Ideal Condition	3
$C_{\bar{m}}$	2.945
Efficiency	98.181%

conditions for active micromixers. These calculations are of great importance for numerical simulations. This is because the mixing performance of the micromixers helps to validate the experimental results.

TABLE III
COMPARE DIFFERENT ACTIVE MICROMIXERS MIXING EFFICIENCY

Active Micromixers	Percent Efficiency Values
Liu's Method	80%
Chen's Method	86%
Veldurthi's Method	90%
Ozcelik's Method	92%
Huang's Method	94%
Sue and Sie's Method	95%
Cao's Method	97%
Our Method	**98.181%**

The reviews on active micromixer was presented by Liu et al. micromixer that flexible artificial ciliary based micromixer composed of Fe doped Polydimethylsiloxane(PDMS). For this active micromixer, 80% mixing efficiency was observed under 200 G magnetic force [8]. Chen used artificial eyelashes with embedded magnetic particles that are driven by a homogeneous magnetic field in a T-shaped channel. In this micromixer, a high mixing efficiency of 86% was achieved when the magnetic coils orbited eight shapes [9]. Veldurthi's model placed a micro-rotor in a chamber to obtain maximum mixing quality [5]. The result of the study was calculated as 90% of the model. Ozcelik et al. calculated the mixing efficiency of 92% for high viscosity liquids in less than 100 ms, using the surface roughness of the side walls of the PDMS microchannel to cavitate the bubbl [10]. Huang increased the mixing efficiency to 94% in 30 minutes using an AC signal [11]. Another active micromixers are examined Sue and Sie developed a pulsatile pressure driven micromixer with a varying T-type chanel. When examined in different phases, it was observed that the mixing efficiency was 95% [12]. A ferrofluid-based microfluidic magnetic micromixer developed by Cao et al. achieves 97% mixing efficiency in 8 seconds with a hybrid magnetic field created by some micromagnets and an external AC to exert periodic magnetic forces on the ferrofluid [13]. In this study, when the time-dependent concentration change was examined it was seen that the efficiency of the model was approximately 98.181%. It has been determined that the efficiency of the model studied is the highest among the data found as a result of the research.

V. CONCLUSION

In this study, numerical analysis of a mixer-based micro mixer that mimics the shape of a micro robot rotating at 1500 rpm in the mixing chamber was performed. With 98.181% mixing efficiency, it has a higher mixing effect than many mixers in the literature. In addition, micro-robots have the ability to levitate and stir as they are magnetically manipulated. Therefore, high performance of a micro mixer to be realized with this method has been demonstrated. If it is experimentally verified, an effective mixing mechanism will be revealed when the advantages of micro-robots are added in addition to the advantages of manipulating with a magnetic field. In future studies, this numerical analysis will be verified experimentally.

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