Numerical Analysis of Micromixer based on Microrobots

Abdurrahim Yilmaz
Yildiz Technical University
Mechatronics Engineering
Istanbul, Turkey
a.rahim.yilmaz@gmail.com

Ali Anil Demircali
Imperial College London
The Hamlyn Centre
London, The United Kingdom
a.demircali@imperial.ac.uk

Beste Baban
The Koc School
Istanbul, Turkey
besteb2022@stu.koc.k12.tr

Serra Ozkasap
Dokuz Eylul University
Industrial Engineering
Izmir, Turkey
serraozkasap@gmail.com

Yegor Samoylenko
Yildiz Tehnical University
Mechatronics Engineering
Istanbul, Turkey
yegoraleksandr@gmail.com

Krishiv Chadha
MEF International Schools
Istanbul, Turkey
krishivchadha10@gmail.com

Huseyin Uvet
Yildiz Tehnical University
Mechatronics Engineering
Istanbul, Turkey
huvet@yildiz.edu.tr

***Abstract*—In this study, performances of a micromixer based on microfluidics are estimated numerically. Faster and more efficient an active micromixer model that minimizes human contact was presented by making numerical calculations with basic microfluidic equations. In the model that we created, two liquids of the same type were given to the micromixer environment based on microrobotic-shaped mixer with 0.005 second steps for the 3 seconds. The concentration of the first liquid was 1 mol/m3, and the concentration of the second liquid was 5 mol/m3. As a result of mixing, the new concentration of the mixed two liquids was expected to be 3 mol/m3 at ideal conditions. According to the value calculated as a result of the simulation, the concentration of the liquid was 2.945 mol/m3. The mixing efficiency obtained from the model examined in the study was 98.181%. In order to better interpret the efficiency of the presented model, it was compared with other active micromixer models.**

***Index Terms*—Microrobots, Micromixers, Numerical Analysis**

I. Introduction

Microfluidic devices have an increasing importance day after day as they are actively used in important fields such as biomedical diagnosis, food safety control, and environmental protection [1]. Micro stirring has a significant impact on the efficiency and sensitivity of microfluidic devices. As a microfluidic device capable of micro stirring, micromixers are designed to mix fluids and particles of the smallest scale while overcoming problems that come with size and laminar flow. These devices can be used in different fields as they can take advantage of the miniaturization of the fluids associated with mixing to reduce the amounts involved in chemical and/or biochemical processes. Micromixers are classified into two groups, active and passive micromixers. Passive micromixers do not operate using external energy except the pressure that comes from the pressure head. Active micromixers function with external energy that is generated by moving components within the micromixer itself and control. Because of these features, micromixers have an important place 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 that is 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 was based on various channel widths, frequencies, and flow rates; thus, the final result was accurate [3]. Acoustic field driven active mixers function due to the energization of bubbles by an acoustic field. In general, they do not have high mixing efficiency values. However, Orbay's multi-bubbled based active micromixer 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 micromixer 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 [5]. The mixing occurs in a chamber which connects to two linear inlets and one linear outlet, which is an appreciable mechanism. The mixing is done by a microrotor consisting of three permanent magnets. In a

978-1-6654-3663-2/21/$31.00 ©2021 IEEE

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. 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, but decreases with the inlet velocity of fluids. Their mixing efficiency were 97.67% and 71.02% for higher angular velocity and lower angular velocity, respectively. Thermal field driven active micromixers 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 one straight outlet. Our main contribution is to show the efficiency of an active magnetic driven micromixer based on a microrobotic-shaped mixer. 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 microfluidic dynamics is characterized by Reynolds number, Peclet number and due to our micromixer being a magnetic field driven active micromixer, the Strouhal number. The Reynolds number represents the ratio of inertial forces to viscous forces as shown in (1). Peclet number represents the 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 was laminar and fluids were assumed to be in-compressible Newtonian fluids. This can be described by continuity and Navier-Stokes equations as shown in (4) and (5).

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

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

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

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

The channels of micromixer has two inlets and one outlet. Mixing chamber has a diameter of 6 mm. Inlets and outlet have a width of 0.5 mm, length of the channels were not considered important due to mixing not occurring without any outside help in a laminar flow. The length of channels is selected 5 mm for enough mixing. Microrobot term is used for robots with dimensions smaller than one millimeter. Our microrobot itself consists of an microrobot has chamfered corners that are 0.3 mm away from the vertex. Microrobot was turning with 1500 rpm in the simulation. It was placed right in the middle of the inner circle in the micromixer channel,

COMSOL is one of the programs frequently used in micromixer 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 micromixer and microrobot designed in the COMSOL program are shown in Fig. 1.

III. Simulation Results

The purpose of this simulation is to provide maximum 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 the microrobot approach. We simulated mixing of the two liquids with different concentrations, one being 1 $mol.m^{-3}$ and the other one being 5 $mol.m^{-3}$. This setup with one liquid

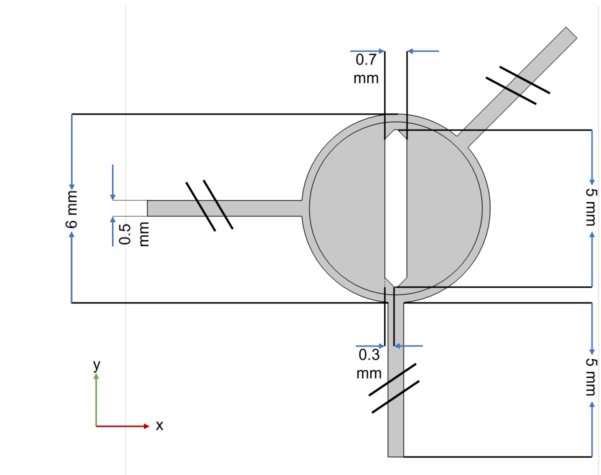

Fig. 1. Shows the micromixer environment and all the relevant dimensions. In the center of the mixing chamber, a microrobot was placed with a sharp edge to improve mixing efficiency.

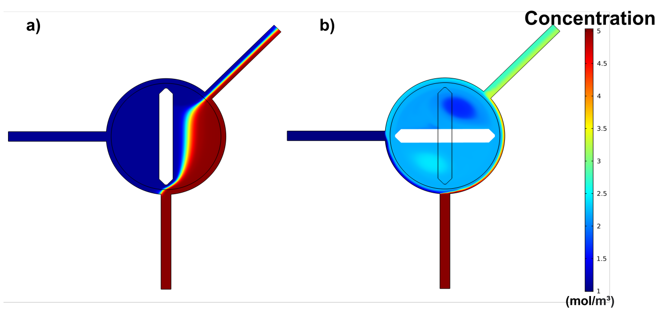

Fig. 2. Shows a) the initial concentration surface of the numerical analysis and b) the final concentration surface after 3 seconds of analysis.

of different concentrations made it also mix a little bit due to diffusion which possibly improved results.

The initial concentration of the model was at the extremes as observed from the scale. When the final concentration was examined, it was seen that the micromixer approaches the expected average concentration value. Samples of the same liquids with different concentrations values, one being $1 mol.m^{-3}$ and the other one being $5 mol.m^{-3}$, were sent from both channels of the micromixer. Liquids with 1000 kg/m^3 density mixed with the microrobot 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 seconds analysis with 0.005 second steps.

Simulation results were as shown in the Fig. 2. To calculate mixing efficiency, the value that was found as the average of 7 different points taken from this Fig. 3 was used to interpret the mixing efficiency. Table I shows the concentration value of each point. By using the seven concentration values, the average concentration value obtained from the model was

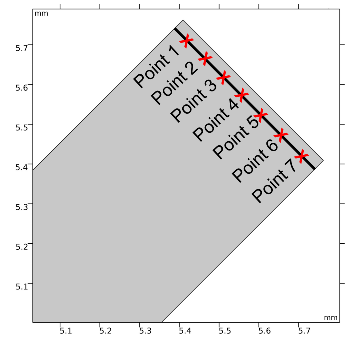

Fig. 3. Seven sample points taken from a graph of concentration variation over time to find mixing efficiency

calculated 2.945 ($p < 0.05$), which was very close to the expected average value of 3. As a result, the model with 98.181% ($p < 0.05$) efficiency was obtained. Table II shows summary of the numerical analysis.

IV. Discussion

The mixing efficiency is a key parameter for all 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 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. The reviews on active micromixers was presented by Liu et al. Micromixer was a 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

TABLE I
Concentration for Each Point that are Placed at the Outlet of Micromixer ($p < 0.05$)

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

TABLE II
Ideal Condition and Calculated Values

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

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 this study was calculated as 90% of the model. Unlike Veldurthi's work, in our system the mixer robot is not integrated into the motor rotor. It will be levitated and manipulated by another microrobot on the motor rotor. However, 2D analysis was performed in this study. Therefore, the only difference from the work of Veldurthi is the shape of the mixer in the chamber. 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 bubble [10]. Huang increased the mixing efficiency to 94% in 30 minutes using an AC signal [11]. Sue and Sie developed a pulsatile pressure driven micromixer with a varying T-type channel. 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]. Usefian et al. got the mixing efficiency of 96% by oscillating magnetic particles in a Newtonian fluid with a magnetic source mounted at the entrance of the micro-channel [14]. Mixing efficiency of %100 was achieved by Jeon et al. via utilizing magneto-hydrodynamics driven micromixer with the selected convenient electrode configuration [15]. 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 was the highest among the data found as a result of the research.

TABLE III
MIXING EFFICIENCY OF OTHER ACTIVE MICROMIXERS

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%
Usefian's Method	96%
Jeon's Method	100%
Microrobotic Mixer	**98.181%**

V. CONCLUSION

In this study, numerical analysis of a mixer-based micromixer that mimics the shape of a microrobot rotating at 1500 rpm in the mixing chamber was performed. With 98.181% mixing efficiency, it had 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 micromixer 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 microrobots are added in addition to the advantages of manipulating with a magnetic field. In future studies, this numerical analysis will be verified experimentally.

ACKNOWLEDGMENT

This work was supported by TUBITAK (The Scientific and Technological Research Council of Turkey) Support Program for Priority Research Projects Grant, 116E743.

REFERENCES

[1] Y. Yang, Y. Chen, H. Tang, N. Zong, and X. Jiang, "Microfluidics for biomedical analysis," *Small Methods*, vol. 4, no. 4, p. 1900451, 2020.
[2] M. Bayareh, M. N. Ashani, and A. Usefian, "Active and passive micromixers: A comprehensive review," *Chemical Engineering and Processing-Process Intensification*, vol. 147, p. 107771, 2020.
[3] Z. Li and S.-J. Kim, "Pulsatile micromixing using water-head-driven microfluidic oscillators," *Chemical Engineering Journal*, vol. 313, pp. 1364–1369, 2017.
[4] S. Orbay, A. Ozcelik, J. Lata, M. Kaynak, M. Wu, and T. J. Huang, "Mixing high-viscosity fluids via acoustically driven bubbles," *Journal of Micromechanics and Microengineering*, vol. 27, no. 1, p. 015008, 2016.
[5] N. Veldurthi, S. Chandel, T. Bhave, and D. Bodas, "Computational fluid dynamic analysis of poly (dimethyl siloxane) magnetic actuator based micromixer," *Sensors and Actuators B: Chemical*, vol. 212, pp. 419–424, 2015.
[6] A. Usefian and M. Bayareh, "Numerical and experimental study on mixing performance of a novel electro-osmotic micro-mixer," *Meccanica*, vol. 54, no. 8, pp. 1149–1162, 2019.
[7] J. Meng, S. Li, J. Li, C. Yu, C. Wei, and S. Dai, "Ac electrothermal mixing for high conductive biofluids by arc-electrodes," *Journal of Micromechanics and Microengineering*, vol. 28, no. 6, p. 065004, 2018.
[8] F. Liu, J. Zhang, G. Alici, S. Yan, R. Mutlu, W. Li, and T. Yan, "An inverted micro-mixer based on a magnetically-actuated cilium made of fe doped pdms," *Smart Materials and Structures*, vol. 25, no. 9, p. 095049, 2016.
[9] C.-Y. Chen, C.-Y. Chen, C.-Y. Lin, and Y.-T. Hu, "Magnetically actuated artificial cilia for optimum mixing performance in microfluidics," *Lab on a Chip*, vol. 13, no. 14, pp. 2834–2839, 2013.
[10] A. Ozcelik, D. Ahmed, Y. Xie, N. Nama, Z. Qu, A. A. Nawaz, and T. J. Huang, "An acoustofluidic micromixer via bubble inception and cavitation from microchannel sidewalls," *Analytical chemistry*, vol. 86, no. 10, pp. 5083–5088, 2014.
[11] J. Huang, Y. Lo, C. Hsieh, U. Lei, C. Li, and C. Huang, "An electro-thermal micro mixer," in *2011 6th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, pp. 919–922, IEEE, 2011.
[12] C.-L. Sun and J.-Y. Sie, "Active mixing in diverging microchannels," *Microfluidics and Nanofluidics*, vol. 8, no. 4, pp. 485–495, 2010.
[13] Q. Cao, X. Han, and L. Li, "An active microfluidic mixer utilizing a hybrid gradient magnetic field," *International Journal of Applied Electromagnetics and Mechanics*, vol. 47, no. 3, pp. 583–592, 2015.
[14] M. Bayareh, A. Usefian, and A. Ahmadi Nadooshan, "Rapid mixing of newtonian and non-newtonian fluids in a three-dimensional micro-mixer using non-uniform magnetic field," *Journal of Heat and Mass Transfer Research*, vol. 6, no. 1, pp. 55–61, 2019.
[15] H. Jeon, M. Massoudi, and J. Kim, "Magneto-hydrodynamics-driven mixing of a reagent and a phosphate-buffered solution: A computational study," *Applied Mathematics and Computation*, vol. 298, pp. 261–271, 2017.