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Research Article

Design and Analysis of a Laminar Diffusion-Based Micromixer with Microfluidic Chip

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This study aims to perform optimizatione to achieve the best diffusion control between the channels by designing and analysing a microfluidic-based micromixer. The design and analysis of the micromixer were made with the COMSOL Multiphysics program. Some input and output parameters must be defined for diffusion control of the micromixer. Among these parameters, inputs are the diffusion coefficient and inlet flow rate, while outputs are velocity, pressure, and concentration. Each input parameter in the microfluidic chip affects the output of the system. To make the diffusion control in the most optimum way, the data were obtained by making much analysis. The data obtained from this program was also provided with the Fuzzy Logic method to optimize the microfluidic chip. The diffusion coefficient value (5E-11 m^2/s) should be given to the channels to achieve the optimum diffusion between the micromixer channels, if the inlet flow rate value (15E-15 m^3/s) is the output value of the system, the velocity is 0.09 mm/s. The pressure is 2 Pa, and the concentration is 0.45 mol/m^3. These values are the optimum values obtained from the analysis without damaging the liquid's microfluidic channels supplied to the micromixer's inlet.

1. Introduction

Microfluidic devices are the technology that allows us to manipulate and process small amounts of liquid using channels several micrometers long. The microfluidics field uses fabrication technologies developed by the microelectronics and microelectromechanical system (MEMS) industry [1, 2]. It provides outstanding advantages over macroscale instruments such as better sensitivity and higher resolution in separation and detection, batch production, faster analysis, and lower sample consumption. Thanks to these advantages, such devices are recognized as a promising option for miniaturization in the field of environmental and defense monitoring, chemical synthesis, and biomedical applications [3–5]. Stirring of samples in such applications is considered a significant part of microfluidic systems. In these systems, mixing becomes one of the critical points for the success of chemical reactions. Rapid mixing at microscale sizes has been a difficult problem in many applications. For this reason, micromixers have become an essential part of microfluidic systems.

Microfluidics integrates various subcomponents such as pumps, micromixers, reactors, and dilution chambers [6, 7]. Therefore, the study of microscale (i.e., microfluids) fluid flow has become central to the development of the respective devices. Micromixers are often vital components for microfluidic chip devices, as they are required for chemical applications, biological applications, and detection/analysis of chemical or biochemical content [8–10]. In the past, the importance of micromixers was poorly understood, and only a few research groups focused on this area [11, 12]. Recently, many new micromixer studies have been published [13–17]. Saygili et al. produced microfluidic molds using the 3D printing method. They observed mixing on different microplatforms with and without mixer geometry to understand the underlying diffusion mechanism that causes mixing in the microchannel [18]. Rasouli and Tabrizian proposed an energy-efficient acoustic platform based on the boundary-oriented acoustic flow that provides the rapid mixing required controlling nanoprecipitation [19]. The device encompasses vibrating bubbles and sharp edges in the microchannel to convert acoustic energy into powerful vortices fluid movements. Dehghani et al. sought to increase microfluidics' mixing using a micromixer with a passive method [20]. Du et al. used an AC field-effect flow control in induced charged electroosmotic (ICEO) to develop an electrokinetic micromixer with 3D electrode layouts [21]. Nan et al. have also dealt with micromixers in general reviews on micrototal analysis systems (microTAS) [22]. In this study, different from other studies, diffusion control of the micromixer designed and analyzed using COMSOL Multiphysics program was performed. The optimization of this control process was done using the fuzzy logic method. The necessary input parameters for this method, which works without mathematical modeling, were determined as a result of the analysis. The Fuzzy logic, which has been preferred in many fields for years [23–25], will be used for the first time to optimize the micromixer.

In microfluidic devices, the channel's size is microscale, and therefore the flow velocity is minimal. The Reynolds number, defined as the inertia force ratio to viscous force, indicates whether the fluid flow is turbulent or laminar [26]. When the dimensions are microscale, a Reynolds number of less than one indicates that the flow behavior is viscous. Because the flow's nature is laminar, the fluid flows in parallel layers without interruption between layers. The mixing of fluids is mainly dependent on diffusion with a very low mixing efficiency. For example, in a water-based microfluidic system ($2\,\mathrm{kg/m^3}$ liquid density and $0.001\,\mathrm{Ns/m^2}$ viscosity) with a channel width of $200\,\mu$m and a flow rate of $2\,\mu$L/s, the Reynolds number is 0.1 and the fluids spread is 2 s and 2 mm for $2\,\mu$m for 2000 seconds. Therefore, it is imperative to develop different micromixers to increase mixing efficiency in the development of microfluidic systems. There are different types of micromixers categorized as passive micromixer and active micromixer [27, 28]. An active micromixer is where mixing is provided by external input energy [29]. The passive micromixer has no external energy source or moving parts, and therefore mixing is achieved by the geometry of their structure [30, 31]. Most passive micromixers provide high mixing efficiency at a low flow rate [32, 33]. Because of this simple concept, passive micromixers are often preferred to integrate microfluidic devices [34, 35]. In this study, microfluidic modeling has been done by using a passive micromixer.

This article proposes a simple model for controlled mixing by diffusion where two different laminar streams are in contact for a specific controlled time. The micromixer model was designed using the COMSOL Multiphysics program. The input parameters applied in this program's analysis process were the diffusion coefficient and inlet flow rate, while the output parameters were determined as velocity, pressure, and concentration. As a result of the analysis, diffusion control of fluids in the microchannel was performed using the fuzzy logic method. As a result, by controlling the inlet flow rate and the diffusion coefficient of the fluids, it has been observed that it is possible to control the concentration, pressure, and velocity of the species transported from one stream to another diffusion.

2. Materials and Methods

In this study, the design of the microfluidic-based micromixer was realized with COMSOL Multiphysics software. To apply diffusion control in the best way, attention has been paid to designing the channels in the micromixer. As a result of dozens of different analyses made with this software, the diffusion coefficient and flow rate of two different laminar flows entering the micromixer channels were determined as input data. Pressure, velocity, and concentration values were obtained by changing these data. The optimization of the data obtained from the analysis was done using the fuzzy logic method. In this section, the micromixer design, analysis, and optimization processes will be explained in detail.

2.1. Design of Micromixer. The geometry of the micromixer has a size in the order of microscale. The micromixer consists of a single microchannel with two inputs and two outputs. The width of the micromixer is determined as $150\,\mu$m and the height as $100\,\mu$m. The developed model is based on the controlled diffusion micromixer model, which is assumed to be the fluid creeping flow. Creeping flow refers to fluid flow dominated by viscosity with a low Reynolds number; therefore, inertial forces can be neglected. This makes the flow more suitable for micromixer simulation than the laminar flow assumption. The geometry of the device is shown in Figure 1. The device is divided into two parts due to its symmetrical geometry. The design is aimed at preserving a laminar flow area when two different fluids are combined, thus, preventing uncontrolled convective mixing. Transport of species between these fluids must be carried out solely by diffusion so that species with low diffusion coefficients remain in the respective streams. Both compounds diffuse into the water flow in different amounts depending on their diffusion coefficient.

The flow rate at the inlet is about 0.1 mm/s. The Reynolds number significant for characterizing the flow is given by:

$$\mathrm{Re} = \frac{\rho U L}{\mu} = 0.001. \tag{1}$$

ρ is the liquid density ($\mathrm{kg/m^3}$), U is the characteristic velocity of the flow, μ is the liquid viscosity (1 mPa.s), and L is a characteristic dimension of the device ($150\,\mu$m). When the Reynolds number is significantly less than 1 in this model, the creeping flow interface can be used. The convective term in the Navier-Stokes equations can be removed by dropping the incompressible Stokes equations:

$$\begin{gathered}\nabla\left(-pI + \mu\left(\nabla u + (\nabla u)^T\right)\right) = 0,\\ \nabla . u = 0.\end{gathered} \tag{2}$$

U is the local velocity (m/s), and p is the pressure (Pa).

Mixing in the instrument is performed with relatively low concentrations of the species compared to the solvent. In this case, the mixture should contain water. This means that solute molecules only interact with water molecules, and Fick's law can describe diffusive transport. The mass balance equation for dissolved matter is as follows:

$$-\nabla.(-D\nabla c + cu) = 0. \tag{3}$$

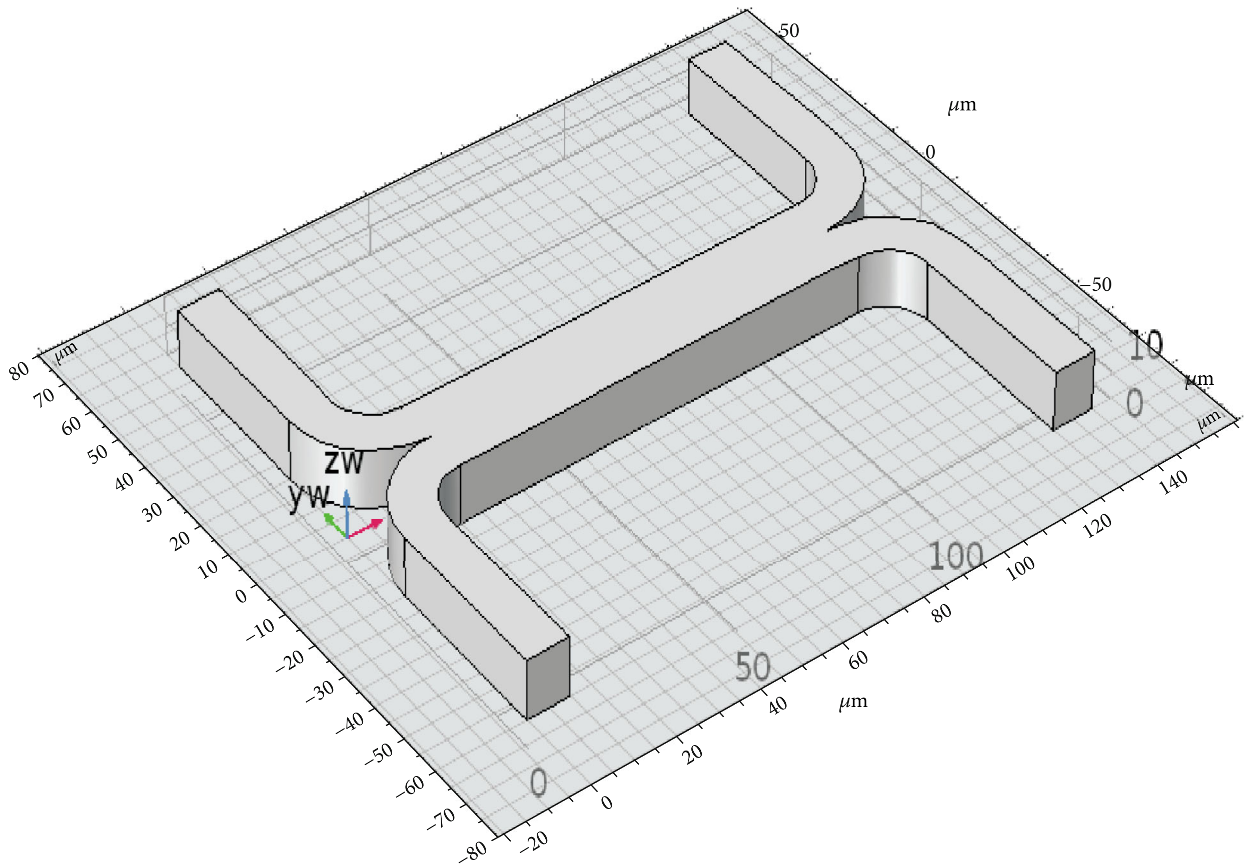

Figure 1: Micromixer model geometry.

In this equation, D is the diffusion coefficient of the solute (m^2/s), and c is the concentration (mol/m^3). Another dimensionless number can characterize standard streams: The Peclet number is given as:

$$\mathrm{Pe} = \frac{LU}{D} \tag{4}$$

In this model, the parametric solver is used to solve Equation (1) for three different types, each with different D values: D: $1 \times 10 - 11\,m^2/s$ and $1 \times 10 - 10\,m^2/s$. These D values correspond to the Peclet numbers of 100, 20, and 10, respectively. Since these Peclet numbers are all greater than 1, numerical stabilization is required when solving the Fick equation, as a cell significantly more extensive than 1 expresses the Peclet number.

Two versions of the model have been solved:

(i) In the first version, it is assumed that a change in solute concentration does not affect the liquid's density and viscosity. This means that it is possible to solve the Navier-Stokes equations and then solve the mass balance equation

(ii) In the second version, viscosity is quadratically dependent on concentration:

$$\mu = \mu_0 \left(1 + ac^2\right). \tag{5}$$

In this equation, a is the constant of the size m^3/mol^2, and μ_0 is the viscosity at zero concentration. Such a relationship between concentration and viscosity is often observed in solutions of larger molecules.

2.2. Analysis of Micromixer. The micromixer model processes an H-shaped microfluidic device for controlled mixing by diffusion. The device brings two different laminar streams into contact for a controlled time. The contact surface is well defined, and by controlling the flow rate, it is possible to control the number of species transferred from one stream to another by diffusion. The diagram of the microfluidic-based micromixer two input and two output devices to be analyzed is shown in Figure 2.

The purpose of the design is to avoid convective mixing by preserving the laminar flow area when two flows converge along with inlet A and inlet B, respectively, and the fluid flow is defined as creeping flow due to Reynolds number. The different species concentrations will be injected into the micromixer from inlet A and inlet B. The transport of the species between streams A and B must be done by diffusion so that the low diffusion coefficient species remain in their respective streams. The analysis process of the micromixer

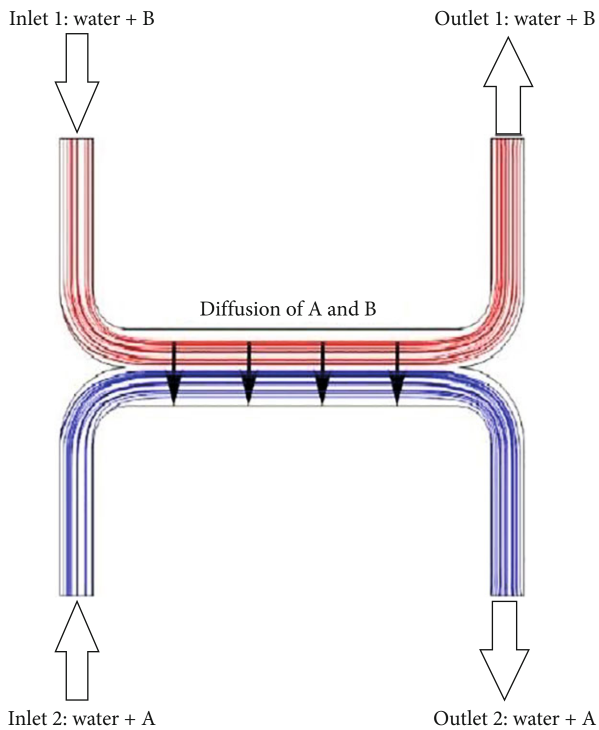

Figure 2: Diagram of the micromixer device.

using COMSOL Multiphysics will be explained in this section.

After the design process is completed, some parameters and definitions should be made to the system. The diffusion coefficients and inlet flow rate ratio of A and B fluids entering the channels are significant for diffusion control. These parameters must be defined as variable input during the analysis process.

In this study, the designed micromixer was loaded into the COMSOL program, and the necessary parameters were defined in the program. We use the program's fluid flow and chemical type transport module to simulate the geometric model. Some of the parameters specified in the system are fixed, and some are variable. The system's input and output parameters are variable since optimization will be made with the fuzzy logic method. While the input parameters used in the analysis process were diffusion coefficient and inlet flow rate, the output parameters were determined as concentration, pressure, and velocity.

The Reynolds number was determined as 0.001 to provide the laminar flow area of the A and B fluids, which are given as input to the micromixer channel. This number is vital to prevent convective interference. Another critical parameter is the diffusion coefficient. Choosing these coefficients low is essential for successful diffusion control. In this study, the diffusion coefficient for A and B was entered between 5E-11 m^2/s. The inlet flow rate has been entered as 10E-15 m^3/s.

Analysis of the microfluidic-based micromixer is required for the optimization process. The problem of the system must be well understood to perform analysis operations. Data will be obtained according to the analysis results made on the specified input and output parameters. The optimization process will be carried out with the help of these data. The analysis process took much time because the input and output parameters were not fixed numbers in the system. Dozens of different analyses were performed in the COMSOL program, and optimum values were obtained for the micromixer model.

2.3. Optimization with Fuzzy Logic. The claim that classical logic is insufficient to meet both right and wrong and neither right nor wrong at the same time because it is based on a two-valued system that is thought to see everything as right or wrong has led to the development of precious and fuzzy logic systems [36, 37]. Fuzzy logic is the extraction of result values with the help of certain mathematical functions, depending on each rule that it will create, by processing the values obtained with specific algorithms using the result of experiences and data of people. Fuzzy logic is not based on Aristotelian (classical) logic but uses functions expressing fuzzy sets. There is a binary value (0-1) logic in classical logic [38]. Fuzzy logic derives results by considering binary values and expresses them with verbal variables such as less, less, more, medium, long, and regular. It allows processing with intermediate values (such as 0.3 and 0.92) instead of 0-1 values. It adds the ability to generalize by carrying two valuable memberships to multipreciousness. In this method, uncertainties in the system can be expressed. It is also a suitable method for systems whose mathematical model is complex and challenging [39].

The fundamental elements that make up the fuzzy logic method are inputs, outputs, fuzzification, rules, and defuzzification (Figure 3). The fuzzification unit maps measured inputs, which can be net values, to ambiguous linguistic values using the fuzzy reasoning mechanism. The step after fuzzification consists of two parts. These are fuzzy rule base and fuzzy interference. The fuzzy rule base provides the necessary definitions to describe linguistic control rules and fuzzy data manipulation in a fuzzy logic method. The Fuzzy Inference unit is the fuzzy reasoning mechanism that performs various fuzzy logic operations to understand the control action for a given fuzzy input. Based on fuzzy concepts, humans can simulate decision making and derive fuzzy control actions using inference rules in fuzzy logic. Defuzzification is a scale mapping that converts output variables into discourse universes corresponding to the value range. A unit provides a blur-free control action from an uncertain control action. As a result, fuzzy outputs are made available in real-time systems [40, 41].

The first step of system modeling with the fuzzy logic method is determining the input and output variables to be applied. The most important task of the microfluidic-based micromixer modeled in this study is to perform diffusion control of A and B fluids in the channels. To achieve this, attention must be paid to the diffusion-related fuzzy logic method's output parameters, and the rules should be written clearly. In this study, optimization processes are made according to input and output parameters using the Matlab-Fuzzy Logic program. The system's input parameters are defined as the diffusion coefficient and inlet flow rate of A and B fluids entering the micromixer. The output parameters of the system are determined as velocity, pressure, and concentration of the liquids. Diffusion coefficient values allow the diffusion of A

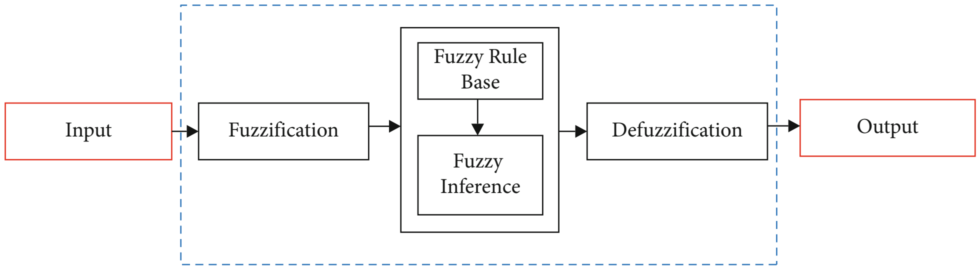

Figure 3: The basic structure of the fuzzy logic controller.

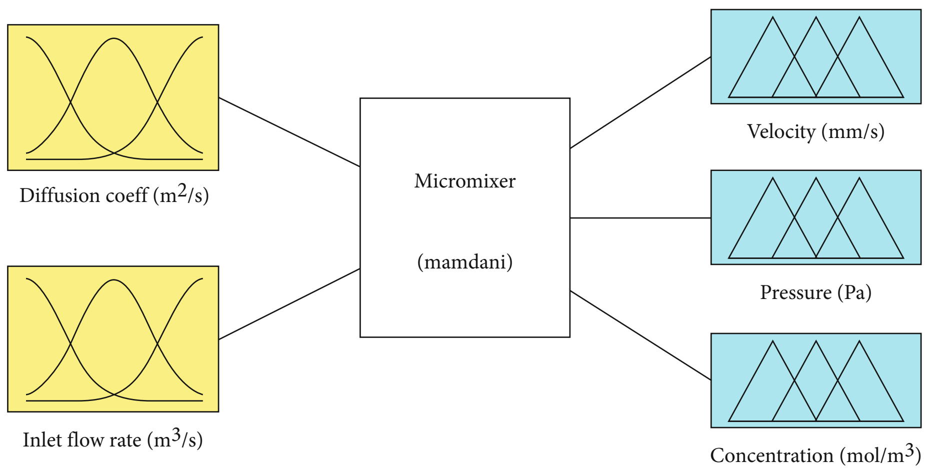

Figure 4: Fuzzy logic model of the micromixer.

and B liquids to occur. The inlet flow rate ratio of liquids also affects the fluids' pressure and outlet velocity in the micromixer channel. The inputs and outputs of the fuzzy logic system are shown in Figure 4.

In the fuzzy logic method, the membership function values written for each input and output value are adjusted according to the values of the upper and lower limits of the input and output parameters. Dozens of different analysis processes were carried out with the COMSOL Multiphysics program. Rules and parameter values were determined according to the analysis results. After selecting the upper and lower limits for modeling the necessary parameters with the membership function, a total of 9 rules were created to define the relationship between these parameters. This rule table is shown below (Table 1).

Table 1: Fuzzy logic rules.

	Inputs			Outputs		
	Diffusion coeff	Inlet flow rate		Velocity	Pressure	Concentration
1	L	L	THEN	L	L	BD-1
2	L	MD	THEN	MD	MD	BD-1
3	L	HG	THEN	HG	HG	BD-1
4	MD	L	THEN	L	L	GOOD
5	MD	MD	THEN	MD	MD	GOOD
6	MD	HG	THEN	HG	HG	GOOD
7	HG	L	THEN	L	L	BD-2
8	HG	MD	THEN	MD	MD	BD-2
9	HG	HG	THEN	HG	HG	BD-2

L: LOW, MD: MIDDLE, HG: HIGH, BD-1: BAD, GD: GOOD, BD-2: BAD.

In the triangular membership function used for diffusion coefficient input, "LOW" for values in the range [1–3], "MIDDLE" for values in the range [3–7], and "HIGH" for values in the range of [7–10] were used. In the triangle membership function used for inlet flow rate input, "LOW" for values in the range of [1-10 m^3/s], "MIDDLE" for values in the range of [10-20 m^3/s], and "HIGH" for values in the range of [20-30 m^3/s] were used. In the triangle membership function used for velocity output, "LOW" for values in the range of [0-0.06 mm/s], "MIDDLE" for values in the range of [0.06-0.12 mm/s], and "HIGH" for values in the range of [0.12-0.2 mm/s] were used. In the triangle membership function used for pressure output, "LOW" for values in the range of [0-1 Pa], "MIDDLE" for values in the range of [1-3 Pa], and "HIGH" for values in the range of [3-4 Pa] were used. In the triangular membership function used for concentration output, "BD-1" for values in the range [0-0.3], "GOOD" for values in the range [0.3-0.6], and "BD-2" for values in the range [0.6-1] were used.

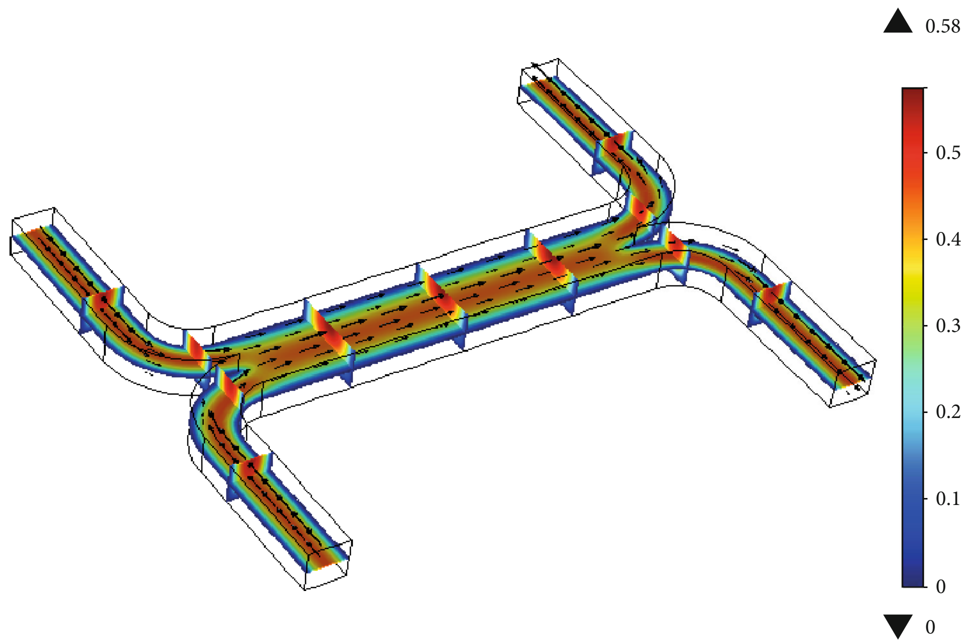

FIGURE 5: Velocity magnitude on the channel.

3. Results and Discussions

3.1. COMSOL Analysis Results. Analyses of the microfluidic-based micromixer device were performed using the COMSOL Multiphysics program. Fifty different analyses were performed to achieve optimum results for the device. The system's input variables are the diffusion coefficient and inlet flow rate, while the outputs are velocity, pressure, and concentration. According to the analysis results, the liquid type's diffusion coefficient used in the micromixer for diffusion control should be optimum 5E-11 m^2/s, and the inlet flow rate of the liquid should be 15E-15 m^3/s. When these input parameters are applied to the micromixer device, it is understood that the velocity in the output channel is 0.09 mm/s, the pressure is 2 Pa, and the concentration is 0.45 mol/m^3.

The velocity field is shown in Figure 5 for the case where viscosity is independent of concentration. The flow is symmetrical and is not affected by the concentration area. The arrow volume plot is used to visualize the flow direction. The color in the figure shows the respective values. The highest velocity value measured along the channel is 0.58 mm/s.

Figure 6 shows the corresponding pressure distribution in the channel walls resulting from the flow. It indicates that the pressure at the inlets is very high compared to the outlets required to drive the fluid through the system. As the liquid passes through the guided channel of the micromixer, the pressure decreases. The highest pressure measured in micromixer channels is 8.03 Pa.

The effect of the diffusion coefficient on species concentration is shown in Figure 7. Mixing for A and B liquid types is almost perfect for the diffusion coefficient chosen. The concentration ratio is equal to 0.45 mol/m^3 for these species. As a result of the analysis, it clearly shows that the micromixer device can be used to separate lighter molecules from heavier ones. By placing some of these devices in series, a high degree of separation can be achieved.

It has been observed that the species with the smallest diffusion coefficient do not undergo any significant mixing between both streams, and the mixture is almost perfect as the species with the largest diffusion coefficient. Therefore, it can be concluded that the concentration of the species depends on the diffusion coefficient of the molecule. Therefore, this micromixer can be used to separate types with different diffusion coefficients, i.e., lighter molecules from heavier ones, if multiple stages of this device are arranged in series.

3.2. Fuzzy Logic Results. As a result of the COMSOL Multiphysics program analysis, a large amount of data was obtained. Using these data, the optimization of the microfluidic-based micromixer has been made. The optimization process was carried out with the method of fuzzy logic using the Matlab program. Input and output parameters used for this method are described in Section 2.3. The micromixer device is designed to have two input and three output variables. After determining the lower-upper values for each variable parameter with the membership function, a total of 9 rules were created to define the relationship between the parameters. These rules determined by applying the Min-Max operator are shown in 3-dimensional graphs in Figure 8. These figures show the relationship between input and output parameters.

The inlet flow rate affects the micromixer's velocity and pressure in direct proportion (Figures 8(a) and 8(b)). The diffusion coefficient input value has less effect on the velocity and pressure of the mixer. After about 20 m^3/s, inlet flow rate, pressure, and velocity values have increased significantly. While the maximum pressure acting along the channel in the micromixer is 3 Pa, the maximum velocity has been determined as 0.15 mm/s. The result of the fuzzy logic model

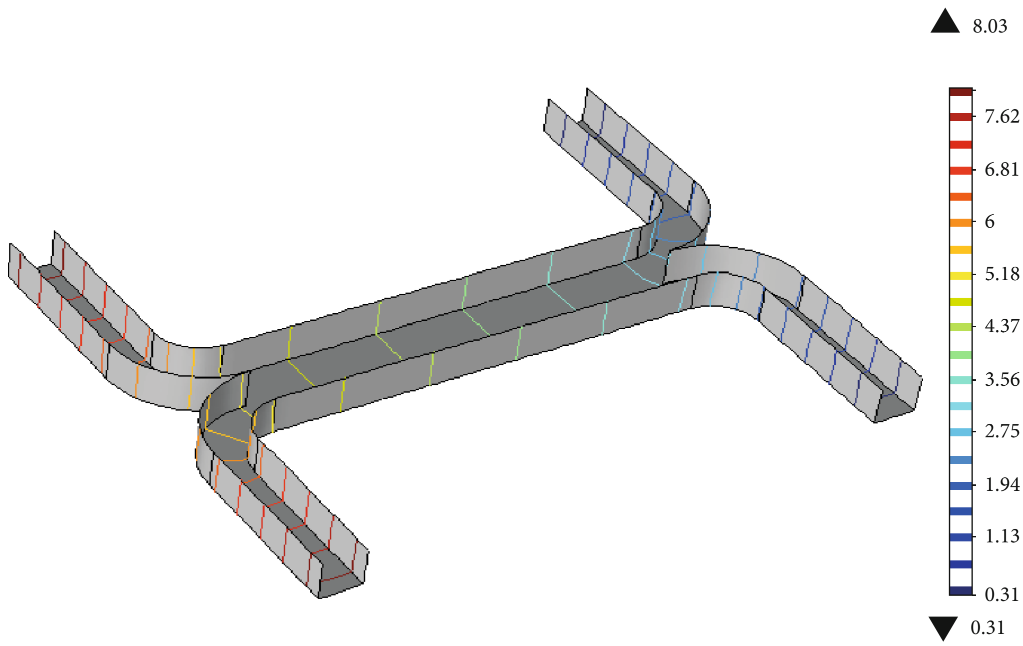

Figure 6: Pressure distribution on the channel walls.

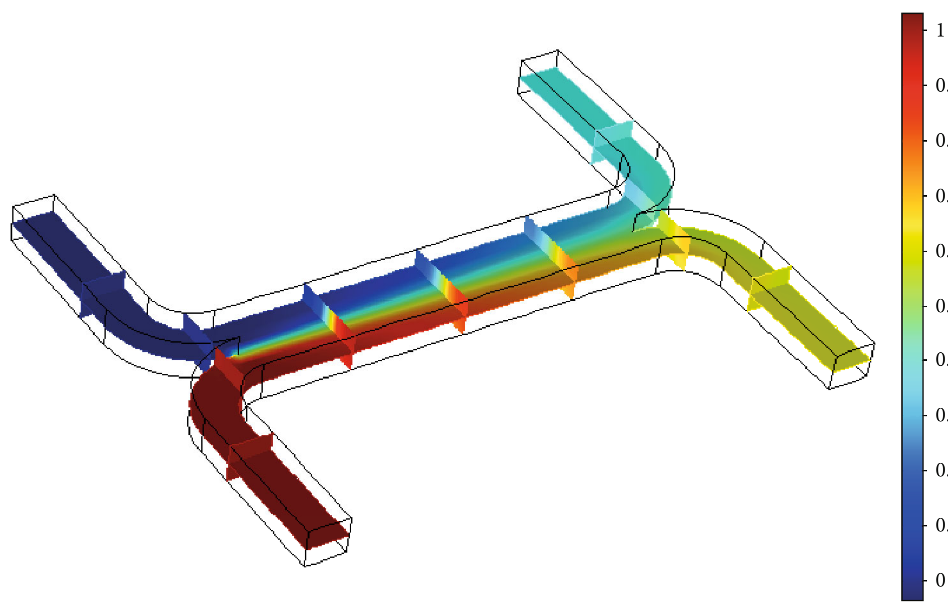

Figure 7: Concentration distribution for a species with diffusivity.

developed to perform diffusion control of two different types of liquid in the micromixer channels is shown in Figure 8(c). In this model, the effect of the liquid species' diffusion coefficient in the concentration process is high. The success rate in the concentration process increased after the 5E-11 m^2/s coefficient value. The change in the inlet flow rate was less significant. If liquids with a very low diffusion coefficient are supplied to the micromixer device, the concentration does not occur, and diffusion control cannot be achieved. The change in the output parameters obtained in response to the input variables applied to the liquids entering the micromixer channel is shown in Table 2.

4. Conclusions

In this study, the design and analysis of a microfluidic-based micromixer device has been designed and optimized to achieve the best diffusion control between the channels. The data obtained from the analysis were classified in Fuzzy Logic, and optimization processes were made. The system's

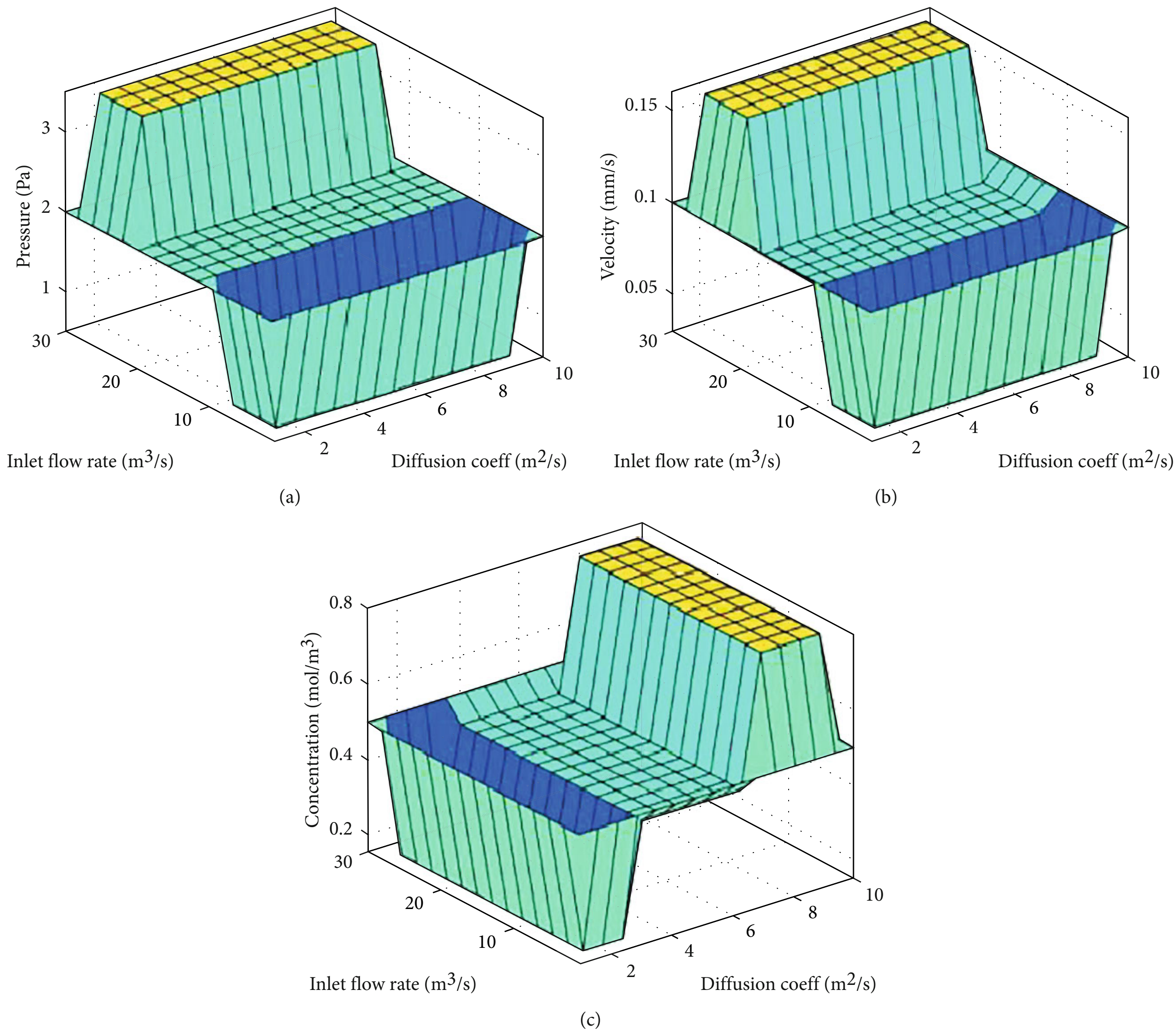

Figure 8: (a) Inlet flow rate and diffusion coefficient affect the pressure. (b) Inlet flow rate and diffusion coefficient affect the velocity. (c) Inlet flow rate and diffusion coefficient affect the concentration.

Table 2: Fuzzy logic outputs in response to the inputs.

Inputs		Outputs		
Diffusion coeff [m^2/s]	Inlet flow rate [m^3/s]	Velocity [mm/s]	Pressure [Pa]	Concentration [mol/m^3]
2	5	0.03	0.5	0.15
2	15	0.09	2	0.15
2	25	0.16	3.5	0.15
5	5	0.03	0.5	0.45
5	15	0.09	2	0.45
5	25	0.16	3.5	0.45
8	5	0.03	0.5	0.8
8	15	0.09	2	0.8
8	25	0.16	3.5	0.8

input parameters are the diffusion coefficient and inlet flow rate, while the output parameters are speed, pressure, and concentration. The output data obtained in the optimization processes were obtained by changing the input variables.

As a result of analysis and optimization processes, the liquids' diffusion coefficient should be higher than 5E-11 m^2/s. The inlet flow rate value should be higher than 15E-15 m^3/s to perform diffusion control of two different liquids types. Suppose the input variables are applied to the micromixing device in these value ranges. In that case, it is understood that the pressure in the outlet duct is in the range of 2-6 Pa, the velocity is in the range of 0.09-0.5 mm/s, and the concentration is in the range of 0-1 mol/m^3. These values are the optimum values obtained for the analysis without damaging the microfluidic channels of the liquid supplied to the micromixer's inlet.

With this study, the diffusion control of two different liquids was successfully carried out in the microfluidic-based micromixing device. The analysis and optimization processes showed that the separation between liquids depends on the diffusion coefficients of the species. The larger the difference in diffusion coefficients results in more efficient separation. This device can be used for diffusion control at the microlevel in many biomedical applications such as drug delivery, tumor cells, and blood analogs. In our next study, different sizes of micromixers will be designed, and their effect on the diffusion of liquids will be investigated.

Data Availability

Data deposited in a repository We prefer authors to deposit their data in a public repository that meets appropriate standards of archiving, citation, and curation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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