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Robust Design of Electroosmosis Driven Self-Circulating Micromixer for Biological Applications

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Abstract—One of the issues that arises with microscale lab-on-a-chip technology is that the laminar flow within the microchannels limits the mixing of fluids. To combat this, micromixers have been introduced as a means to try and incorporate turbulence into the flow to better aid the mixing process. This study presents an electroosmotic micromixer that balances vortex generation and degeneration with the inlet flow velocity to greatly increase the mixing efficiency. A comprehensive parametric study was performed to evaluate the role of the relevant parameters on the mixing efficiency. It was observed that the suggested micromixer is perfectly suited for biological applications due to its low pressure drop (below 10 Pa) and low shear rate. The proposed micromixer with optimized working parameters is able to attain a mixing efficiency of 95% in a span of 0.5 seconds using a frequency of 10 Hz, a voltage of 0.7 V, and an inlet velocity of 0.366 mm/s.

Keywords—Microfluidics, active mixer, pulsed AC electroosmosis flow, micromixer.

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I. INTRODUCTION

THE implementation of microfluidics has gained increasing popularity, especially regarding lab-on-a-chip devices. These devices are comparatively inexpensive to produce, require a minimal amount of laboratory space, and provide the ability to precisely analyze and quantify samples of tiny volume [1], [2]. In certain situations, such as those seen in the biomedical industry, the homogenization of multiple liquids is required which is a task that microfluidics is naturally ill-suited for. Due to the presence of laminar flow within the microfluidic channels, these systems often rely on diffusion alone for mixing, resulting in very low mixing efficiency [3]. In order to increase the mixing efficiency within microfluidic devices, the mixing chambers are often adapted using either passive or active techniques to disturb the flow. Passive micromixers utilize a variety of channel shapes and obstructions to disorganize the flow whereas active micromixers use an external energy source such as pressure, electrical energy, or magnetic energy to alter the normal flow path [4].

Among the active micromixers, electroosmotic micromixers have been studied and used by many researchers [5]-[7] because of their high mixing efficiency with ionic solutions and lack of moving parts within the channel. Electroosmotic mixers work by applying AC voltage to a series of coupled electrodes that are in contact with the solution, resulting in fluid flow that is driven by the interaction of the solution with the generated electric field. In this study, we aim to investigate the mixing efficiency of an electroosmotic micromixer that also incorporates passive mixing techniques by using an altered microchannel shape. Throughout this paper, the effect of inlet velocity, voltage, and frequency on the mixing performance would be observed and elaborated, and the best optimum parameters are being reported.

II. NUMERICAL SIMULATIONS

A. Governing Equations

The complex flow model developed in this paper implements three physics interfaces for the flow field, electric field, and concentration field of the fluid domain. In each experiment the Reynold's number was found to remain below one, therefore, the fluid motion of the incompressible electroosmotic flow can be described by the continuity and Navier–Stokes equations in an unsteady–state flow condition as follows:

$$\nabla \cdot \vec{U} = 0, \tag{1}$$

$$\rho \left[\frac{\partial \vec{U}}{\partial t} + (\vec{U} \cdot \nabla)\vec{U}\right] = -\nabla P + \mu \nabla^2 \overrightarrow{U}, \tag{2}$$

where ρ, *U*, *P*, and μ denote the fluid density (*kg/m^3*), velocity vector (*m/s*), pressure (*Pa),* and dynamic viscosity (*Pa·s*), respectively.

Solid surfaces acquire a surface charge when they come in contact with an electrolyte. The electroosmosis phenomenon happens at the charged surfaces because of the creation of an electrical double layer (EDL). After the electric field is generated, the electroosmotic flow dislocates the charged fluid in the EDL in the direction of the electric field. The movement of ions in the diffuse EDL provides a velocity gradient perpendicular to the channel wall and gives rise to viscous transport. The slip velocity at the slipping wall is governed by the classical Helmholtz-Smoluchowski boundary condition:

$$U_{slip} = -\frac{\varepsilon \xi E_x}{\mu} \tag{3}$$

where ε is the permittivity of the medium, ξ is the zeta potential, and E_x is the tangential component of the electric field intensity.

The balance equation for the current field in the channel can be obtained by Ohm's law shown as:

$$\nabla \cdot (-\sigma \nabla V) = 0, \tag{4}$$

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where σ corresponds to the conductivity of the solution (*S/m*). The electric potentials on the selected electrode pairs were set to be time-varying sinusoidal functions with the same maximum voltage and frequency, but with opposite polarities. In addition, the convection-diffusion equation governs the concentration field of the dissolved substances in the domain as:

$$\frac{\partial c}{\partial t} + \nabla \cdot (-D\nabla c) = R - u \cdot \nabla c \tag{5}$$

where *c* denotes the concentration, *D* represents the diffusion coefficient, and *R* is the reaction rate. As there are no reactions that occur within this study, the reaction rate is considered to be zero.

The evaluation of the mixing quality is obtained by:

$$Mixing\ index = 1 - \sqrt{\frac{\sigma_{mean}^2}{\sigma_{max}^2}} \tag{6}$$

$$\sigma_{mean}^2 = \int (C_i - C_{mean})^2 dy \tag{7}$$

The integral is applied to the nodal points of the outlet domain where C_i corresponds to the concentration at point *i*. A mixing index (MI) value of 0% indicates that no mixing has occurred, whereas a MI value of 100% represents full mixing at the outlet.

B. Numerical Model

The schematic of the proposed micromixer is illustrated in Fig. 1. It consists of a straight channel followed by an expansion unit with four electrodes located at the chamber's corner walls. The mounted electrodes produce a time-dependent sinusoidal electric field inside the chamber which leads to the circulation of flow and consequently better mixing efficiency. The electrolyte used in this study has the same material properties of water with an ionic solution conductivity of $\sigma = 0.11845\ S/m$, a relative electric fluid permittivity of $\varepsilon_r = 80.2$, and a diffusion coefficient of $D = 1 \times 10^{-11}\ m^2/s$.

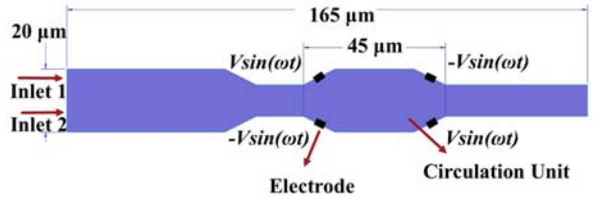

Fig. 1 Geometry of proposed micromixer

C. Model Validation

The discretization of the numerical simulation domain was performed by using 24590 unstructured triangular elements with the highest element density in the electrode region walls (Fig. 2). The present model's accuracy was assessed by comparing the results of the numerical simulations obtained in this study with the study's results done by Chen et al. [5] (Fig. 3). The agreement between the previously reported mixing qualities and the mixing qualities obtained in this study implies that the numerical methods used in this study are reasonable.

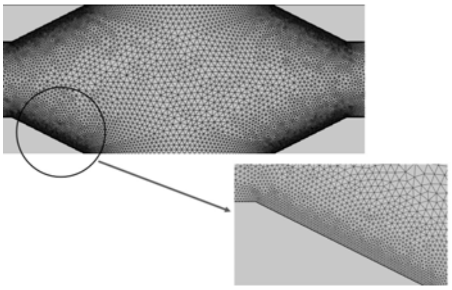

Fig. 2 Triangular meshing structure of the domain.

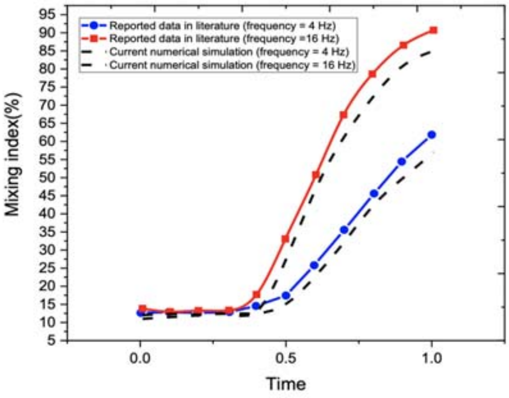

Fig. 3 MI validation [5]

III. Results and Discussion

The electroosmotic mixer's working principle is to rotate the flow inside of the microchamber with the help of two pairs of electrodes on the tilted channel walls of the expansion chamber. The four microelectrodes placed on the channel wall produce a sinusoidal electric field with respect to the applied AC current, leading to the formation of four vortices in the fluid flow domain. As seen from Fig. 4, two of these vortexes are located at the chamber entrance and exit, and the other two are located in the middle of the chamber. The vortices contribute to the folding and stretching of the two reagents and facilitate the process of mixing. The first rotational vorticity sends thin layers of the two reagents inside the expansion chamber. Without this eddy the reagents would enter the circulation region of the expansion unit in bulk form, causing a significant drop in mixing performance. This layer-by-layer entrance expands the contact area of the two reagents and forces mixing to happen between smaller volumes, allowing for shorter mixing times with higher quality. In this study, the effects that various inlet velocities, voltages, and frequencies have on the mixing quality has been studied by conducting 64 sets of experiments, observing the mixing quality at 0.5 seconds.

Contours of the vorticity magnitudes have been plotted for different voltage amplitudes as shown in Fig. 5. It can be seen that the voltage has a positive relationship with the amplitude of the vorticities in the fluid domain. The higher circulation power that results due to increased voltage leads to the generation of a static region in the center of the expansion unit as well as two static microvortices at the entrance and exit of the chamber. These static regions cause the flow to be undesirably trapped in the microfluidic system, deteriorating the mixing quality.

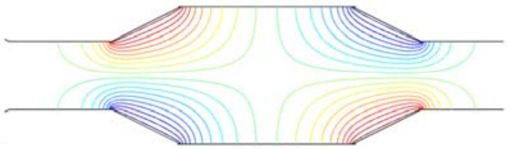

Fig. 4 Electrical potential lines at peak voltage

While the polarity of the voltage changes, there are no vorticities in the fluid domain for that moment in time and the vorticities have to gradually reform. At higher frequencies this process happens very quickly, offering little time for previously trapped flow to progress through the channel prior to vorticity regeneration. This can cause a fairly significant drop in mixing efficiency between 0.7 V and 1.0 V, as shown in Fig. 6. This phenomenon happens slower for lower frequencies (below 10), causing only a slight drop in performance between voltages of 0.7 V to 1.0 V, as shown in Fig. 7. It can also be noted that increasing the inlet velocity reduces the impact of the drop in mixing performance. This is because higher inlet velocities aid in releasing fluid from the trapped areas, decreasing the drop in mixing efficiency from 30% to 0.4% when high frequencies are used.

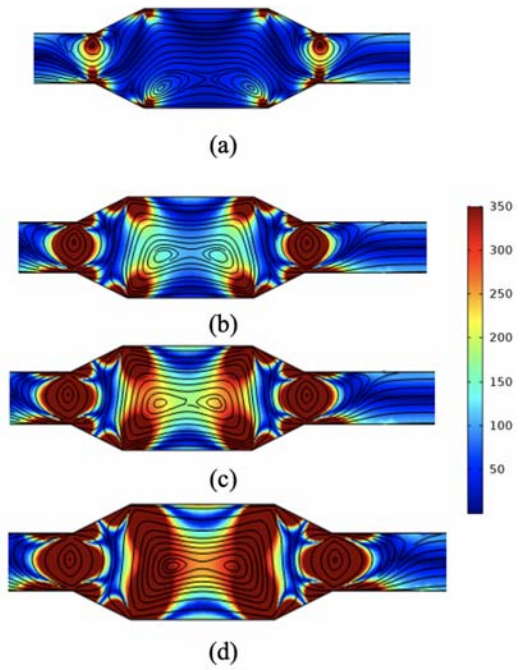

Fig. 5 Vorticity magnitude (1/s) for different voltage amplitude: (a) V = 0.1, (b) V = 0.4, (c) V = 0.7, and (d) V = 1.0 V

The results from these tests suggest that voltage has a larger influence on mixing quality when lower frequencies are used. It can also be observed that higher frequencies can generate better mixing efficiencies than lower frequencies if low voltages are required. Out of the 64 experiments, the highest performance achieved (a mixing quality of 95%) occurs at an inlet velocity of 0.366 mm/s, a frequency of 10 Hz and a voltage of 0.7 V. The surface concentration for the micromixer with these parameters is shown at different time intervals in Fig. 8.

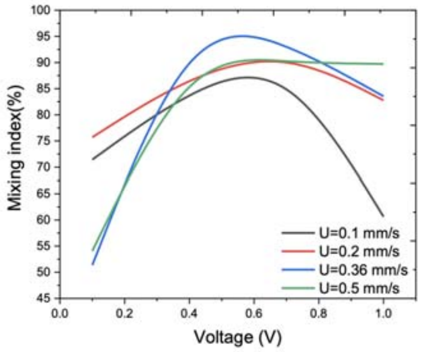

Fig. 6 Mixing quality versus voltage for different inlet velocities at a frequency of 20 Hz

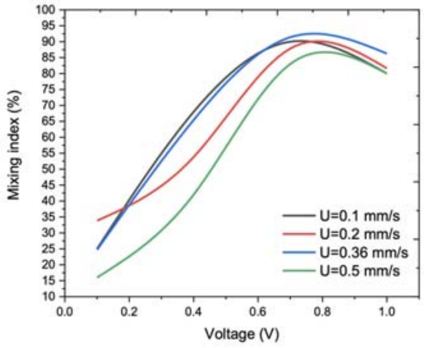

Fig. 7 Mixing quality versus voltage for different inlet velocities at a frequency of 5 Hz

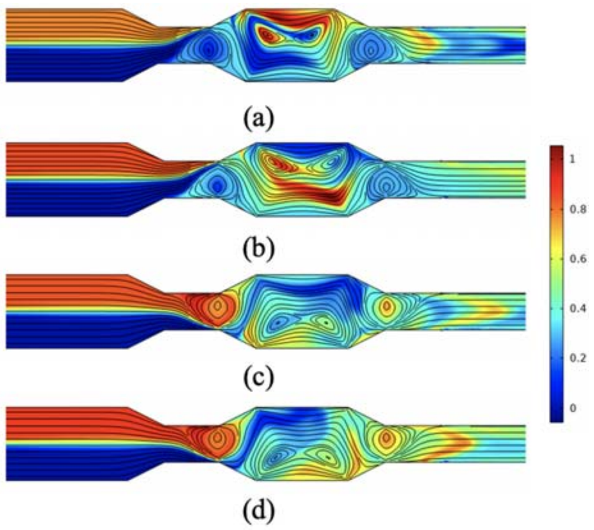

Fig. 8 Surface concentration contour for the micromixer with the highest performance: (a) t = 0.15 s, (b) t = 0.18s, (c) t = 0.23, and (d) t = 0.43s

One of the advantages of the proposed micromixer is the low-pressure drop and low shear rate along the channel, making it an ideal candidate for circumstances that require low surface tension due to the use of biological specimens. The pressure drop is dependent on the inlet velocity used and varies from 2 Pa to 10 Pa between inlet velocities of 0.1 mm/s and 0.5 mm/s (Fig. 9), respectively. The shear rate has a proportional relationship with the shear stress imposed on the particles inside the domain. As shown in Fig. 10, high shear rate is only generated at the corners of the micromixer and the maximum shear rate of 3000 s^{-1} is an acceptable range for biological setups.

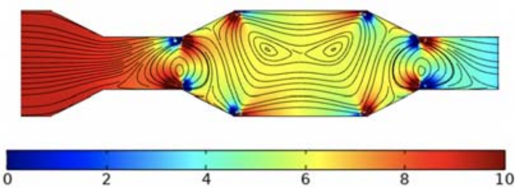

Fig. 9 Pressure drop along the micromixer with an inlet velocity of 0.5 mm/s

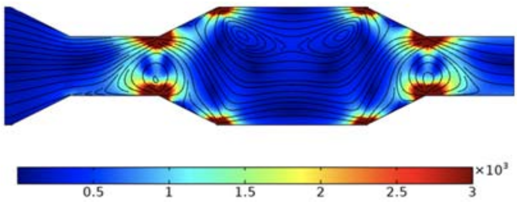

Fig. 10 Shear rate (s^{-1}) contour within the expansion unit

IV. CONCLUSIONS

In this study, a micromixer was developed to achieve a mixing efficiency of 95% in an extremely short time span of 0.5 seconds with extremely low measures of pressure drop and shear rate. This was made possible by incorporating both active and passive mixing techniques into the microfluidic system, including electroosmosis as well as using specified channel geometries. The specific locations of the electrodes on the channel wall allow for four vortices to be developed within the flow that aid in the folding and stretching of the fluids. An interesting relationship was discovered between the frequency and voltage of the electrodes with the inlet velocity of the flow. It was found that at lower frequencies the voltage has the most prominent effect on mixing efficiency, whereas at higher frequencies the mixing efficiency is mainly altered by the inlet velocity of the flow. Computational analysis on the micromixer outlined that the combination of a frequency of 10 Hz, a voltage of 0.7 V, and an inlet velocity of 0.366 mm/s allowed for ideal mixing.

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