**Mixing in micro-analytical devices : Magnetohydrodynamic (MHD) mixing**

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# Introduction

Microfluidic technology has become an indispensable in today’s world, having widespread applications in healthcare industry, chemical industry, biomedical research, analysis and appliance production. Microfluidic devices find applications involving drug discovery, biomedical synthesis and analysis, diagnostics, Lab-on-chip devices etc. In such micro devices, fluid mixing often plays an crucial role in determining the performance of the devices. Devices solely dedicated for the purpose of mixing, be it multiple fluids, colloidal solutions, sample preparation etc are termed as ’micromixers’.

# Literature Survey

There are two broad categories of micromixers - passive and active micromixers. Passive micromixers rely on microchannel design features to enhance the process of mixing. Some of notable works on passive on the research and development of passive micromixers can be found in the works of . Active micromixers on the other hand rely on external energy input in the form of electric field, acoustic field, magnetic field, acoustic field and photothermal effect. Some important works on active micromixers can be found in the .

The flow manipulation employing electromagnetic fields is termed as magnetohydrodynamics. Ionic solution or electrolytes are composed of positive and negative ions. When such fluids are subjected to both electric and magnetic fields, their coupled effect induces Lorentz forces on the fluids . Applying different electrode combinations and magnets, complicated flow patterns can be generated, which in turn can be used to enhance the process of fluid mixing, species transport and reaction kinetics.

Jang and Lee conducted experimental studies on the potential function of an MHD device as a micropump. Yi *et al.* proposed a magnetohydrodynamic (MHD) device that generates chaotic advection and conducted experimental studies on it. Kang conducted numerical and experimental and developed an MHD device with both pumping and mixing functions. La *et al.* performed numerical simulations on MHD flow and their results gave crucial insights into the generation of complex flow patterns and their potential to promote homogeneous mixing of species. Chen *et al.* proposed a novel electromagnetic micromixer that can be used to mix two electrolytes. Other notable works on MHD devices can be found in the works of .

# Working Principle of MHD

Ionic solutions are often common base fluids in laboratory experiments and analysis. As we know these solutions are composed of charged ions (positive cations and negative anions). On subjecting these ionic solutions to an electric field, the ions mmigrate towards the opposite terminals, resulting in flow, commonly known as electroosmosis. Now, if we add a magnetic field to the picture, we observe something very interesting. When a magnetic field is applied, the coupled effect of the electric and magnetic field generates a transverse force, known as the Lorentz force. The direction of this depends on the charge of the ion, direction of the electric field and magnetic field. The working principle has been demonstrated in Fig. [1](#fig:1).

![](data:application/eps;base64,)

Working principle of magnetohydrodynamics.

# Problem Descrtiption

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Geometrical parameters of the proposed design.

In the present work, a numerical study is conducted on a proposed MHD device, that can intensify the process of fluid mixing or species transport and enhance the reaction kinetics of a chemical reaction. The bottom wall is lined with eleven electrodes. The side walls are lined with electrodes and a magnetic field is applied throughout the domain in the z-direction. For the species transport problem passive neutral tracer in an ionic solution is considered and for the reaction kinetics a binary reaction of the type is considered and the production of the product species C is tracked. The major geometrical parameters and schematics of the proposed design have been presented in Fig. [2](#fig:2) and Fig. [3](#fig:3). The chamber is of dimensions L W H, where L = W = 600 m and H = 50 m. The geometrical parameters of the elctrodes are : L = 35 m, W = 140 m and W = 200 m.

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Problem schematic of the proposed design.

# Mathematical Modeling

In this section, the required governing equations have deen discussed in the following subsections.

## Mass Conservation

The mass conservation is imposed by solving the continuity equation which is given as follows,

## Momentum Conservation

The momentum conservation governed by the Navier-Stokes equation for a incompressible, Newtonian fluid is given by,

The last term () on the right hand side of the Eq. [[eq:2]](#eq:2) is the Lorentz force vector and is given by,

Here, and are the current density and magnetic flux density.

For an ionic fluid with electrical conductivity , in the presence of both electric and magnetic field, the Ohm’s law for current density is given by,

In the present study, the effect of induced currents in the ionic solution are neglected and therefore the term is eliminated from Eq. [[eq:4]](#eq:4).

## Charge Conservation

We know, that the electric field can be defined in terms of the scalar field given by,

The charge conservation in the fluid domain is given by the Poisson’s equation for electric potential ,

where is the charge density and is the electric permittivity of the medium.

## Transport of Species

### Non-reactive Species

The advection-diffusion equation is solved to find the concentration () field of a passive, neutral species in the domain with a diffusion coefficient of .

$$\label{eq:7}
\frac{\partial c}{\partial t} + \nabla \cdot \left(\mathnormal{c}\vec{v}\right) = \mathnormal{D\_c}\nabla^2 \mathnormal{c}$$

### Reactive Species

The reaction kinetics is analyzed by solving the advection-diffusion equation for reactive species A and B. Here, we consider a binary reaction, with reaction rate constant . The concentrations of species and are given by . We assume that the diffusion coefficients of the species is same and equal to .

$$\label{eq:8}
\begin{equation}\label{eq:8a}
\frac{\partial c\_A}{\partial t} + \nabla \cdot \left(\mathnormal{c\_A}\vec{v}\right) = \mathnormal{D\_c}\nabla^2 \mathnormal{c\_A} - k\_r\mathnormal{c\_A}\mathnormal{c\_B}
\end{equation}
\begin{equation}\label{eq:8b}
\frac{\partial c\_B}{\partial t} + \nabla \cdot \left(\mathnormal{c\_B}\vec{v}\right) = \mathnormal{D\_c}\nabla^2 \mathnormal{c\_B} - k\_r\mathnormal{c\_A}\mathnormal{c\_B}
\end{equation}
\begin{equation}\label{eq:8c}
\frac{\partial c\_B}{\partial t} + \nabla \cdot \left(\mathnormal{c\_B}\vec{v}\right) = \mathnormal{D\_c}\nabla^2 \mathnormal{c\_B} - k\_r\mathnormal{c\_A}\mathnormal{c\_B}
\end{equation}$$

The quality of mixing is quantified by calculating the mixing index (), which is given by ,

where $\mathnormal{c^\*}$ represents the fully mixed state and is fixed at 0.5 for the present study.

# Numerical Modeling

We use the finite element framework of COMSOL Multiphysics for numerical analysis. The Electric Currents Interface is used to solve for electric potential in the computational domain. The solution is used to evaluate the electric field (). The Laminar Flow Interface is used to solve for the flow field. The Lorentz force () is added as a body force term in the domain. Finally, the species transport is analyzed using the Transport of Diluted Species Interface. The Transport of Diluted Species Interface is used to study transport of both non-reactive and reactive species. After many tests we have chosen a very fine mesh setting for the computational domain. The bulk of the domain has a maximum mesh size of 15 m, the microchamber walls have a maximum size of 12 m. The bottom wall electrodes have a maximum mesh size of 7.5 m. This mesh setting gives a total of 2.28 10 elements and it was found to be sufficient to achieve convergence. The computational domain with the final mesh setting has been presented in Fig. [4](#fig:4)

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Computational domain

# Experimental Analysis

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3D printed MHD prototype

A protoype MHD mixer with dimensions 4.5 cm 4.5 cm 1.2 cm is 3D printed using SLA (Stereolithography). The printer used was Creality LD-002H and the resin used was Anycubic UV (405 nm) sensitive resin (clear). The mixing chamber (cavity) has dimensions 3 cm 3 cm 0.5 cm. The wires have nominal diameter of 1 mm and the dimensions of the square Neodymium magnet was 10 mm 10 mm 1 mm. The final version of the prototype with four electrodes attached to the bottom wall has been presented in Fig. [5](#fig:5).

A 10 (by weight) was prepared to be used as the base solution for the mixing analysis blue and red dyes were used. The experimental setup has been presented in Fig. [6](#fig:6). At first the electrodes were connected to the function generator, keeping the signal output OFF. The chamber was filled with KCl solution to approximately 3/4 the depth. Then, a blob of dye was introduced at the central position and the signal output was turned ON. A square wave signal with peak-to-peak voltage of 2.5 V, offset voltage of 5 V, frequency of 8 kHz and 50 duty cylce, generated by the function generator was applied to the top and bottom electrodes only. The left and right electrodes were not used in the present study. The time lapse of the entire advecion and difusion of the dye was captured. The observations have been presented in Section 8.3.

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Experimental setup

# Results and Discussions

In this section, the numeircal and experimental results have been presented and discussed.

## Electric Potential and Velocity Field

For the current study we have used the following combination of electrode potentials. The side wall (W1 - W4) or bottom wall (B1-B8 and C1-C3) were set at : V = 0 V, V = 7.5 V, V = 0 V, V = 8.5 V; V = 7.5 V, V = V = 2.5 V, V = 1.5 V, V = 0.5 V, V = 5 V, V = 10 V, V = 0 V, V = 10.5 V, V = 0.75 V, V = 10 V, V = 5 V. Magnetic flux density of 20 mT was was considered only in the z - direction.

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Distribution of electric potential () throughout the computational domain.

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Velocity field in the xy plane at a height of z = H/3.

The chosen combination of electrodes result in the potential distribution as demonstrated in Fig. [7](#fig:7). Under the coupled effect of electric and magnetic field, the flow profile at a height of z = H/3 has been presented in Fig. [8](#fig:8). In Fig. [8](#fig:8), we observe that multiple vortices were generated in the xy plane, causing strong transverse flow throughout the domain. Such a complex flow pattern is extremely suitable to enhance the advection and diffusion of any test species.

## Fluid mixing and Chemical kinetics

In this study we have studied mixing behavior of non-reactive species and reaction kinetics of two reactive species. The corresponding simulation results have been presented in the following sections.

### Non-reactive Species

A passive, neutrally bouyant species in supplied through Inlet 2 (see Fig. [3](#fig:3) for reference), the species gets advected throughtout the domain by the micro-vortices. This dstribution of the species results in bands of high and low concentrations of the test species, resulting in steep concentration gradients, which in turn result in enhanced diffusion rates. In Fig. [9](#fig:9), we observe that it took a mere 10 seconds to produce a high quality mixture at the outlet.

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Time lapse of a non-reactive species subjected to MHD flow.

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Time evolution of mixing index at the outlet.

The mixing quality is quantified by evaluating the mixing index (given by Eq. [[eq:9]](#eq:9)) at the outlet. The variation of the mixing index has ben presented in Fig,. [10](#fig:10), where we observe that reaches a value of 0.8 between 4 to 5s and thereafter, a steady value of is achieved.

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Effect of magnetic flux density () on at the outlet.

For the present study we have kept the electrode potentials fixed at a aforementioned combination. In Fig. [11](#fig:11), we present how the magnetic field strength affects the overall mixing performance of the device. We note that on increasing B, the value exhibits a linear drop. This decline in can be attributed to the Lorentz forces. Higher magnetic field strength will increase the Lorentz forces (while keeping the electric potential constant), which ultimately results in stronger velocity fields. Strong fluid velocities cause higher advection, thereby augmenting the advective transport of the species, while reducing the diffusion, as there is no suffient time to diffuse. This results in the drop of the mixture quality at the outlet. Thus, it is advisable to use magnets with low field strengths.

### Reactive Species

As discussed earlier, for the study of reaction kinetics we consider a binary reaction (), where we track the production of species C. For this purpose, reactant A is supplied throught Inlet 2 and reactant B is supplied through Inlet 1 and 3 (see Fig. [3](#fig:3) for reference). The production of species C over time has been presented in Fig. [12](#fig:12).

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Time lapse of production of product species C as a result of chemical reaction between species A and B.

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Time evolution of average species C concentration at the outlet.

The average concentration of the new species C is evaluated at the outlet using Eq. [[eq:10]](#eq:10) and the results have been presented in Figs. [13](#fig:13) and [14](#fig:14).

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Effect of magnetic flux density () on at the outlet.

In Fig. [13](#fig:13), we observe the average concentration of species C shows a step rise between 3 to 5 seconds and beyond the production rate gradually drops. The effect of magnetic field strength on the reaction kinetics have been presented in Fig. [14](#fig:14), where we see a linear decline in the concentration at the outlet. Thus, just like non-reactive, magnets with low field strengths are preferable in order to enhance the reaction kinetics.

## Experimental Observations

Once the function generator is turned on, the dye blob, once introduced in the central region of the mixing chamber, gets stretched by a pair of counter rotating vortices (at the top and bottom electrodes), as demonstrated in Fig. [15](#fig:15). This results in bands of high and low concentrations, which in turn raises the diffusion rates.

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Counter rotating vortices generated by Lorentz forces stretch and fold the dye blobs resulting in bands of high and low concentrations.

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Time lapse of red dye under the influence of counter rotating vortices.

Higher advection and diffusion brought about by the MHD flow, results in rapid mixing of the dye as demonstrated in Figs. [16](#fig:16) and [17](#fig:17). The time lapse images of the blob dyes (red in Fig. [16](#fig:16) and blue in Fig. [17](#fig:17)) demonstrate that effect of micro-vortices generated by the Lorentz forces.

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Time lapse of blue dye under the influence of counter rotating vortices.

# Conclusions

We have successfully demonstrated the potential of MHD devices as micro- mixers and reactors through our numerical and experimental studies. It is concluded that MHD offers better flow control and MHD principle gives superior results even for simple geometries. The fabrication effort and cost of MHD micro devices is quite low. Further numerical and investigations have potential applications in reagent mixing and chemical kinetics.

# Future Work

* Further numerical studies need to be conducted for design and parameter optimization.
* The current prototype will be miniatured and converted into an closed system
* Experiments of MHD in different types of electrolytes need to be conducted to gain better insights into the MHD phenomenon in terms of mixing.

# Citations

Li2018 Wen2017 Qian 2002 Qian 2005 Qian 2009 Chen 2018 Warner 2019 Yuan 2017 Patel 2006 Bayareh 2019 Mahapatra 2024