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TECHNICAL BRIEF: NUMERICAL ANALYSIS OF MAGNETOHYDRODYNAMIC (MHD) FLOW IN MICRODEVICES

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Abstract- Over the past several years, magneto-hydrodynamics (MHD) fluid flow has been used to control fluid flow in micro devices without any mechanical components for various laboratory processes. In the presence of an external magnetic field, interaction of the applied electric with the magnetic fields results Lorentz forces in a microchannel that contains ionic fluid and with electrodes. Rectangular microchannels' geometries were designed, preprocessed, simulated and post processed in COMSOL, a commercially available finite element software to test the effectiveness of MHD flow. COMSOL Multiphysics software is used to model the coupled multiphysics effects in the ionic fluid flow by continuity, Navier-Stokes and chemical ion transport by Nernst-Planck principles. The study shows that the fluid flow rate through the exit port was observed higher with the application of external magnetic field than without any magnetic field. The study also suggests that an extensive study should be performed to find out the cross dependencies for fluid flow variables with and without the presence of external magnetic fields.
Keywords- Magneto-hydrodynamics, Lorentz forces, Ion transport, Numerical Simulation, Mathematical modeling, Numerical Solution, COMSOL Multiphysics.

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Introduction

In recent years, there has been a growing interest of research in Lab-on-a-chip (LOC) technology for varieties of laboratory applications for biochemical applications. Lab-on-a-chip is a minute chemical processing plant which integrates most common laboratory procedures such as filtration, mixing, separation and detection in a single chip. The interconnected networks of micro-/nano-channels and reservoirs for tiny volumes of samples are well matched with the demands for reducing demands of sample volume, low cost, rapid response, and massive parallel analyses. Many LOC devices need to propel the fluids and the contained samples to enhance mixing, and also control the fluid motion [1]. Over the last several years, several techniques for fluid propulsion in microchannels have been proposed. This paper presents the use of magnetic and electrostatic forces to generate magneto hydrodynamic effect for pumping fluids in micro-devices. Commonly known electrokinetically driven flow phenomena associated with the propulsion of fluids are: electro-osmosis, electrophoresis and di-electrophoresis [2]. Electro-osmotic phenomenon is due to the formation of a net electric charge on the electrode surface in contact with the electrolyte solution and the accumulation of mobile counter ions in a thin liquid (double electric or Debye) layer next to the surface. The electrolyte behaves neutral when it is away from the solid's surface. With an external electric field, the counter ions in Debye layer are attracted to the oppositely charged electrode and drag the liquid along. In other words, the electric field creates a body force through its effect on the counter ions, which, in turn, induces fluid motion. Electrophoresis refers to the movement of charged particles under external applied electric field used to separate large molecules (such as DNA fragments or proteins) from a mixture of similar molecules. Various molecules travel through the medium at different rates, depending on their electrical charge and size in the presence of electric fields. Due to the interactions between the electric dipole and the gradient of the electric field, the analyte species migrate in the solution. This phenomenon is commonly known as di-electrophoresis (DEP used to trap cells, beads, nano-tubes or other targets to be selectively manipulated or held in a place when washed [3-5]. One of the main advantages of using electrically induced flows is no need of the moving parts for transporting fluid in the system. Fluid flow rates induced from electrostatic forces is very low and consequently a very low Reynolds's number application and the usage of high electric fields are sometimes desired. Besides these, internal heat generation (commonly referred to as Joule heating) is created by the current flows through the buffer solution [6]. In contrast, Magnetohydrodynamics (MHD) (magneto fluid dynamics or hydromagnetics) includes the dynamics of electrically conducting fluids under the effect of magnetic field [7-11]. Examples include plasmas, liquid metals, and salt water or electrolytes. Governing equations which describe MHD are a combination of the continuity, Navier-Stokes equations of fluid dynamics and Maxwell's equations of electromagnetism. Besides these, the presence of electrically conducting ions in the fluid domain requires to couple the physics of fluid with the physics of ion transport in the fluid flow. These differential equations need to be solved simultaneously, either analytically or numerically. In microfluidic devices. In a recent review article, it has been reported that magnetohydrodynamics (MHD) offers an elegant means to control fluid flow in microdevices without a need for mechanical components such as fluid pumping, flow control in fluidic networks, fluid stirring and mixing, circular liquid chromatography, thermal reactors, and microcoolers [12]. Some unique advantages of MHD technique include no-moving parts, portable, economic, and versatile. This paper also incorporates a number of previous works done in the field of MHD and in microfluidics system [13-32].

Geometrical Modeling

A micro-conduit having micro scale dimensions for its height and width was used to study MHD fluid flow by both three dimensional and two dimensional analysis [13]. A rectangular cross sectioned microchannel with length L=18mm, width W=330μm, and height H=670μm was created in Solid Works, a geometrical modeling software. In order to compare the pumping efficiency of straight microchannel, two other micro-conduits with converging and diverging geometries were created.

A rectangular cross sectioned microchannel with inlet cross sectional area; width W=330μm × height H=670μm and outlet cross sectional area; width W=330μm × height H=335μm were created. Also, a rectangular cross sectioned microchannel with inlet cross sectional area; width W=330μm × height H=670μm and outlet cross sectional area; width W=330μm × height H=was created. Due to the MHD effects, ionic fluid is pushed forward from the inlet to the outlet developing the velocity profiles in the conduit. It should be noted that the height to the width (H/W) ratio of the straight, diverging and converging channels from the inlet reservoir to the outlet reservoir are, respectively, 1 to 1, 1 to 2, and 1 to 1/2. Two different approaches are considered to determine the effectiveness of the MHD effects in straight, diverging and converging microchannels and the models are as shown in [Fig-1].

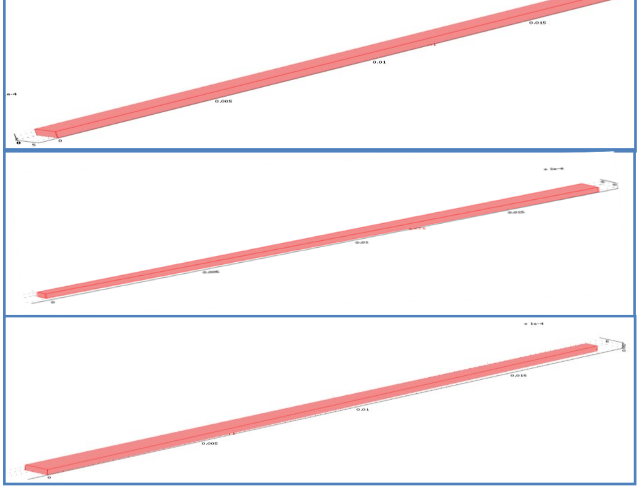

Fig. 1- Geometrical Modeling of (a) Straight (b) Converging, and (c) Diverging Microchannels

Mathematical Modeling

Physics of Fluid Flow

The mathematical models consist of a set of governing equations that are used for a closed-form solution and are also embedded within COMSOL 3.5a to analyze and describe the physical phenomena in a given fluid domain. There exist multiple governing equations that each has their own given characteristics to solve for certain values that are based upon the user's interest. The purpose is to introduce and describe the governing equations of the fluid domain.

The three equations used are the continuity, momentum, and later developed as the generalized Navier-Stokes equations.

- Incompressible flow
- Steady flow
- Newtonian fluid

Continuity Equation:

$$\nabla \cdot \mathbf{u} = 0 \qquad (1)$$

Navier-Stokes Equations:

$$\rho \mathbf{u} \cdot \nabla u = -\nabla \rho + \mu \nabla^2 u + F_L \qquad (2)$$

Where ∇ ρ is the fluid density, p is pressure gradient, F_L (= J×B) is induced Lorentz force in the RedOx ionic solution and μ is viscosity of the fluid [Fig-2]. Fluid velocity u is defined as **u**=ue_x+ue_y+ue_z, in which u, v, and w represent, respectively, the velocity components in the x-, y- and z- directions. Simultaneously solving these two equations with appropriate initial and boundary conditions, general characteristics of fluid flow can be identified.

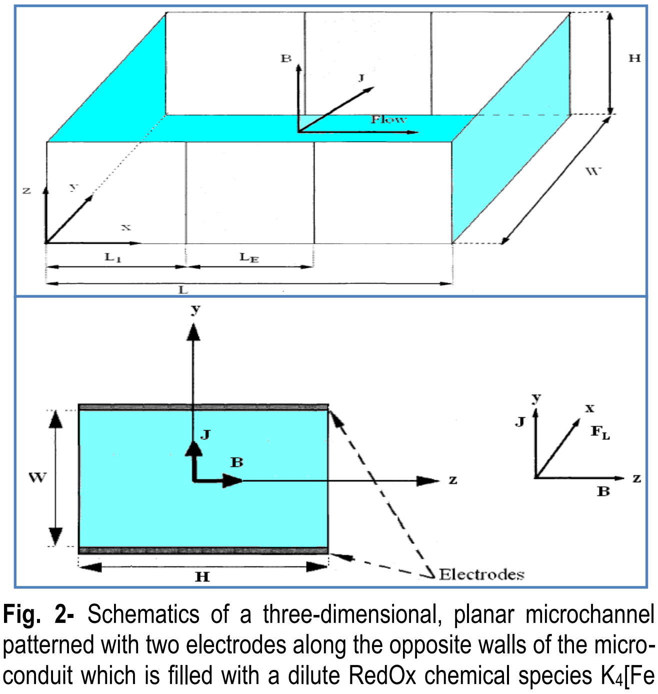

Fig. 2- Schematics of a three-dimensional, planar microchannel patterned with two electrodes along the opposite walls of the micro-conduit which is filled with a dilute RedOx chemical species K_4[Fe (CN)$_6$]) and K_3[Fe(CN)$_6$] that is subjected to a uniform magnetic field of flux density B. A potential difference ΔV is imposed across the electrodes resulting in a current density J which then oriented orthogonally with the magnetic field to induce the Lorentz forces. The Lorentz forces pump the ionic fluid from the inlet reservoir to the outlet reservoir through the conduit.

Physics of Multi-Ionic Mass Transport

We present a multi-ion mass transport model by Nernst-Planck equation for the concentration of each species. It is assumed that there are K dissolved ionic species(here we have three ionic species involved) in the solution.

The flux density due to convection, diffusion, and migration is given by:

$$N_k = u c_k - D_k \nabla C_k - z_k m_k F c_k \nabla, \qquad k = 1..., k. \tag{3}$$

Where c_k is the molar concentration, D_k is the diffusion coefficient, z_k is the valence of each ionic species, and m_k is the mobility of the k^{th} ionic species. F is Faraday's constant (F=96484.6 C/mol) and V is the electric potential in the solution.

According to Nernst-Einstein expression, the relationship between migration coefficient (m_k) and diffusion coefficient (D_k) is given by:

$$m_k = \frac{D_k}{RT}, k = 1..., K \tag{4}$$

Where R is the universal gas constant and T is the absolute temperature of the electrolyte solution.

According to Nernst-Planck expression, the concentration of each ionic species under steady state is governed by:

$$\nabla \bullet N_k = \frac{\partial N_{kx}}{\partial x} + \frac{\partial N_{ky}}{\partial y} + \frac{\partial N_{kz}}{\partial z} = 0, \qquad k = 1,..., K. \tag{5}$$

Where, N_{kx}, N_{ky}, and N_{kz} represent, respectively, the x-, y-, and z-components of the k^{th} species' flux densities.

The local electro-neutrality condition for K ionic species in the solution is given by:

$$\sum_{K=1}^{K} Z_k C_k = 0 \tag{6}$$

Since the width of the microchannel is sufficiently larger than the thickness of the electric double layers formed around the electrode surface walls, electric double layers are not considered in the mathematical modeling of the multi-ion mass transport.

The current density J in the RedOx ionic solution due to convection, diffusion, and migration is expressed as:

$$J = F \sum_{k=1}^{k} z_k N_k \tag{7}$$

The current density J induces due to the interaction between the magnetic field B and the applied electric potential V across the electrodes. The constitution of the Nernst-Planck equations and the local electroneutrality condition defines an accepted approximation of electrochemical mass transport phenomenon.

Numerical Modeling

Numerical analysis involves modeling fluid flow in the micro-conduits through the use of an algorithm for the mathematical modeling. Numerical simulation and modeling allows for these mathematical equations to be solved. Software that combines numerical techniques with the intricacies of fluid flow is utilized. COMSOL 3.5a couples the equations of flow theory with mathematical models in order to solve highly complex fluid flows. COMSOL Multiphysics includes a number of different solvers for PDE-based problems.

Results and Discussion

Simulation results for three rectangular microchannels, namely; straight, converging and diverging, as discussed earlier were simulated using COMSOL Multiphysics, finite element software. Simulation results have demonstrated the MHD pumping in a rectangular straight microchannel with and without RedOx chemical species. These results were then compared and analyzed with converging and diverging microchannels.

In order to visualize and analyze MHD effects in fluid pumping, the fluid velocities were observed at inlet (x » 0), mid-section(x » 9 mm) and outlet (x » 18 mm) of each micro-conduit. The results show the progression of the fluid pumping from the inlet to the outlet due to the MHD effects as shown in the [Fig-3]. Parametric studies of straight, converging and diverging microchannels comparing 3D and 2D simulation results are under investigation and will be reported in our forthcoming publications.

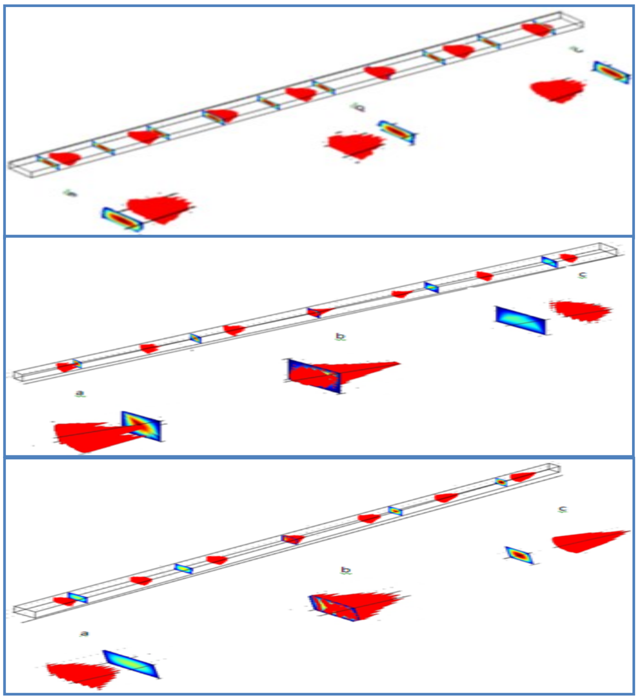

Fig. 3- Fluid Velocity Distributions of MHD Fluid Flow in I. Straight Microchannel, II. Converging Microchannel, and III. Diverging Microchannel with the velocity vectors showing the velocity contours at (a) inlet (b) mid-section and (c) outlet respectively. The concentration of the RedOx species (K4[Fe(CN)6]) /K3[Fe(CN)6]) C0=0.25 M when the magnetic flux density, B =0.44 T and the dimensions of the conduit are L=18 mm, W=330 μm and H=670 μm.

Conclusions

Microfluidic devices with MHD effects brings a novel technique of fluid manipulation that can be used for lab-on-a -chip devices for a wide range of applications. In several micro conduits, main issue is how to propel, manipulate, and control the fluid. This research studied the computational analysis of fluid manipulation by an interaction between electric and magnetic. Mathematical modeling consists Nernst-Planck equation (concentration of the ionic species) and Navier-Stokes equation (fluid flow performance) coupled together with various operating conditions including external magnetic field was presented. Simulation results prove the effectiveness of MHD for fluid propulsion in microchannels including straight, converging and diverging microchannels. The microfluidic conduit models based on RedOx-based MHD driven flow also gives the deeper understanding of multiphysics flow dynamics.

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