Numerical Simulation of Fluid Flow in Magnetohydrodynamic (MHD) Micropumps Using Hydrostatic Pressure Gradient

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ABSTRACT
In this paper the fluid flow of a particular type of micropumps, so-called Magnetohydrodynamic (MHD) micropump, has been simulated numerically. In this investigation, the governing equations of a fluid flow in MHD micropumps with the incompressible, steady state, laminar and fully developed assumptions, have been derived and solved. In the momentum equation associated with the considered flow model, the foregoing Lorentz force has been replaced by a uniform hydrostatic pressure gradient throughout the channel. The effects of channel geometry, electric and magnetic fields on the flow velocity produced by the micropump have been investigated. Finally, the comparison of numerical results with the experimental data issued by other researchers proved that the presented method simulates the fluid flow with a good agreement and the least amount of time and cost.

1. INTRODUCTION

With the advent of microelectromechanical systems (MEMS) technology, various micro-scale actuators, structures and sensors have been implemented on a tiny silicon chip employed for miniaturizing complex industrial components. From different types of microelectromechanical systems related to fluid, can imply to drug delivery and biomedical microfluidic devices. Today due to different applications of microfluidics, many investigations have been done in this field. For precise and effective regulation of small volume of fluids in micro-channels, micropumps are the most common employed components in the micro-fluidic devices.

In order of pumping mechanism, micropumps can be categorized to two types of mechanical and non-mechanical [1–3]. The most common types of mechanical micropumps are positive displacement pumps, which consist of a pump chamber with a flexible diaphragm. The fluid flows by the oscillatory movement of the actuator diaphragm which causes suction and discharge. Some of other mechanical micropumps are Piezoelectric [4], Electrostatic [5], Thermopneumatic [6], Bimetallic [7], etc. The flow of these types of pumps is intermittently pulsed rather than continuously pumped. In spite of mechanical micropumps, the non-mechanical micropumps are designed without any moving parts, so they do not endure adverse conditions like fatigue and wear and in addition the produced flow is continuous. In these types of micropumps, a kind of non-mechanical energy converts to a mechanical energy (such as kinetic head, potential head or pressure head).

Some types of non-mechanical micropumps are Electro-hydrodynamic (EHD) [8], Electro-osmotic (EO) [9] and Magnetohydrodynamic (MHD) [10–16]. EHD and EO micropumps are used for the fluids with low electrical conductivity, like organic solutions such as methanol and ethanol, while MHD micropumps are used for the fluids with electrical conductivity of more than 1 (S/m) such as sea water [11]. In the MHD type, the driving force of fluid is electromagnetic (Lorentz force) and is produced from two electric and magnetic fields which changing the direction of these fields can change the direction of fluid movement; hence these types of micropumps are bidirectional. If applied electric

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and magnetic fields are DC, the destructive phenomenon of bubble generation occurs but by applying AC fields it will decrease [13]. Bubble generation occurs with electrolysis of fluid near the electrodes because of electrical current passing [15].

2. ELECTROMAGNETIC THEORY

Figure 1 shows a schematic view of Magnetohydrodynamic micropumps. The required force for pumping the fluid in these pumps is a kind of electromagnetic force named as Lorentz force. The principle of the pump application is related to applying an electric field in the width of the channel which is filled with an electrical conductive liquid and a magnetic field produced by a permanent magnet or an electromagnet perpendicular on the electric field. The Lorentz force by the assumption of permanency of electric and magnetic fields and stability of magnetic properties of the fluid has been shown as Eq. (1):

$$\vec{F} = \vec{J} \times \vec{B} \tag{1}$$

where B is magnetic flux density vector, J being current density vector, and J is derived based upon the Ohm's Law.

$$\vec{J} = \sigma\vec{E} + \sigma\vec{V} \times \vec{B} \tag{2}$$

where E is the electric field intensity vector, σ is the electrical conductivity of the fluids, and V is the flow velocity vector. The direction of F force can be obtained from the right hand rule. The second term of above equation shows the induced current which is originated from electrically conductive fluid movement in the region of interaction of magnetic and electric fields. The force resulted from this induced current is opposite of the flow direction and is an interferer force in the pump.

In fluids with high electrical conductivity such as Gallium, by increasing the magnetic field this force increases which will cause to the flow rate reduction [11]. For the AC electric and magnetic fields Lorentz force (F) and current density vector (J) are formed as follow:

$$\vec{F} = \vec{J} \times \vec{B}\, \sin(\omega t) \tag{3}$$

$$\vec{J} = \sigma\vec{E}\sin(\omega t + \varphi) + \sigma\vec{V} \times \vec{B}\sin(\omega t) \tag{4}$$

where ω is the angular frequency of the electric and magnetic fields and φ is the phase angle between the electric and magnetic fields. By substituting Eq. (4) into Eq. (3), alternating Lorentz force obtains. In this case, the Alternating Lorentz force not only depends on the current amplitude and the magnetic field amplitude but also on the phase angle of the magnetic and electric fields.

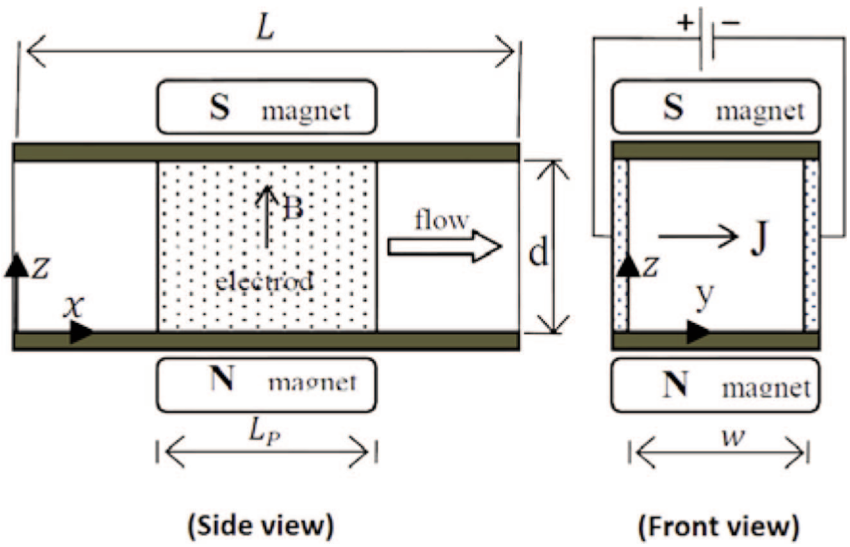

Figure 1. Schematic view of MHD micropump; w = width, d = depth, Lp = electrode length and L = channel length.

3. FLUID MECHANICS THEORY

The fluid flow in the microchannel is assumed steady state and fully developed. Furthermore the velocity components has been considered zero in y and z directions. By the mentioned assumptions the axial flow velocity in direction of the channel is fixed and only varies along the directions of y and z, so $u = u\,(y, z)$.

For the simplified flow field, the governing equations can be written as follows:

Continuity:
$$\frac{\partial u}{\partial x} = 0 \tag{5}$$

Momentum:
$$0 = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{6}$$

which μ, is the dynamic viscosity of the fluid.

In the microchannel under electromagnetic interactions, by temporary omission of electric and magnetic fields the Lorentz forces acting on the fluid particles can be considered as a linear pressure gradient throughout the channel which can be shown as follows:

$$-\frac{\partial p}{\partial x} = \frac{\Delta p}{L} \tag{7}$$

where Δp is the pressure head along the channel with length L given by the cross products of the current density vector and magnetic flux density vector.

$$\Delta p = (\vec{J} \times \vec{B}\sin(\omega t))L_P \tag{8}$$

where L_p is the length of electrode. The pressure gradient generated by the applied alternating electric and magnetic fields in the flow channel can be obtained from Eqs. (4), (7), (8). After the pressure gradient is substituted into Eq. (6) the momentum equation is rewritten as Eq. (9).

$$0 = \frac{\sigma B L_P}{L}\sin(\omega t)\left[E\sin(\omega t + \phi) - uB\sin(\omega t)\right] + \mu\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{9}$$

Despite the fact that obtained velocity distribution depends on time but average time of the flow rate could be considered uniform. As Alternating current frequency becomes larger the resulted flow rate would be more uniform. So the parts which include the time can be substituted by the amounts of time average. Therefore the obtained velocity is the average velocity of the flow. At last, by solving Eq. (9), by finite volume method, velocity distribution in cross section of channel would be obtainable.

4. RESULTS AND DISCUSSIONS

The geometrical properties of the simulated micropump are shown in Table 1. The fluid is sodium chloride solution with conductivity of 1.5 S/m and dynamic viscosity of 6×10^{-8} Pa.s. The phase angle has been considered zero.

Figure 2 shows the effect of magnetic field variation on the fluid flow velocity in a constant electrical current of 140 mA. It is observable that by increasing the magnetic flux density, the fluid velocity increases. It's due to the Lorentz force in the fluid flow equation. As the Eqs. (1), (3) show, this force has a direct relation with the magnetic flux density. By increasing magnetic flux density, the Lorentz body force and the flow velocity increase.

Figure 3 shows the effect of variation of passing electrical current from the fluid in the channel on the flow velocity in a fixed magnetic flux density. It is observable that by increasing electrical current,

Table 1. Dimensions of simulated MHD micropump

Parameter	Value	Unit
Channel length (L)	20	*mm*
Electrode length (L_P)	4	*mm*
Channel width (w)	800	μm
Channel depth (d)	380	μm

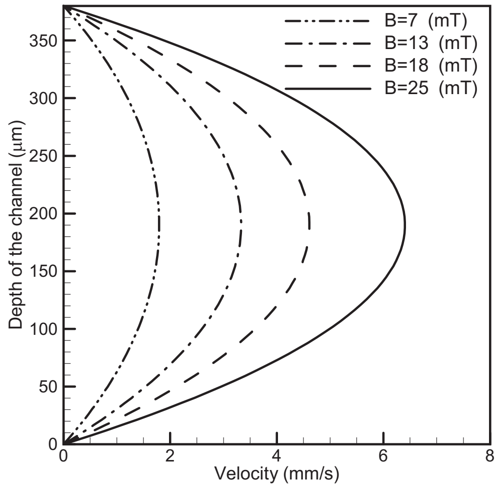

Figure 2. Variation of the mid width velocity profiles at different magnetic flux density values.

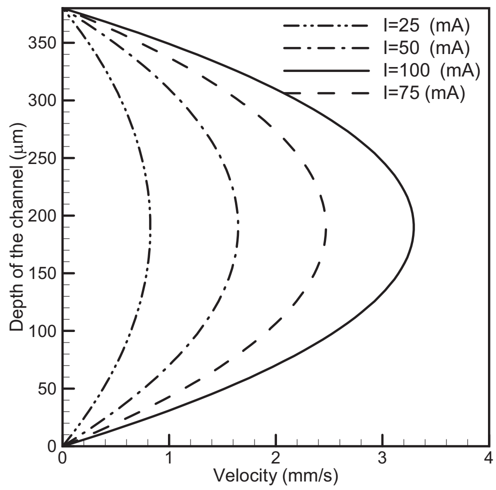

Figure 3. Variation of the mid width velocity profiles at different current values.

the flow velocity increases. Increasing in electrical current which leads to increase in electrical current density as it is shown in Eqs. (1) and (3) will lead to increase in Lorentz body force on fluid and will increase flow velocity.

Geometry of the channel section has a direct effect on fluid flow governing equations so it seems necessary to investigate the influence of channel dimension variation on the average flow velocity in the circumstance of a fixed electrical current.

Figure 4 shows the fluid average velocity $\left(\bar{u} = \frac{1}{A}\iint u\,dA\right)$ change which is because of variation in channel depth and magnetic flux density for a fixed electrical current. It is observable that by increasing channel depth the average velocity of fluid increases but this direct relationship is not permanent and from a specific point by increasing channel depth the average velocity of fluid would decrease. By increasing the channel depth, the effect of friction on upper and lower walls decreases which leads to the fluid velocity increase, but also the electrodes area will increase and in a fixed electrical current, electrical current density decreases to the point which neutralizes the effect of friction force decrease and even would lead to decrease in velocity in a higher depth.

Figure 5 shows effect of the channel width change on the average velocity of fluid in a fixed electrical current. It is observable that increase in channel width would lead to increase in flow velocity. By more increase in the width of channel, the trend of average velocity variation would not

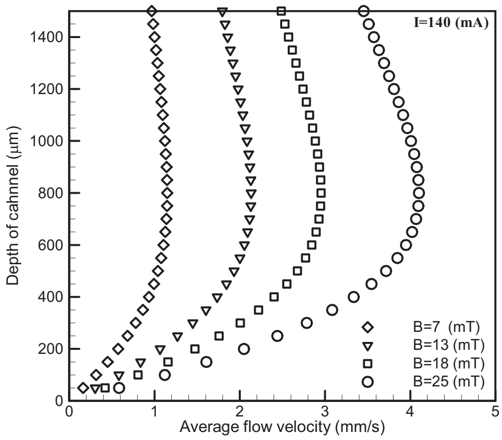

Figure 4. Variation of the flow velocity average versus channel depth at fixed current.

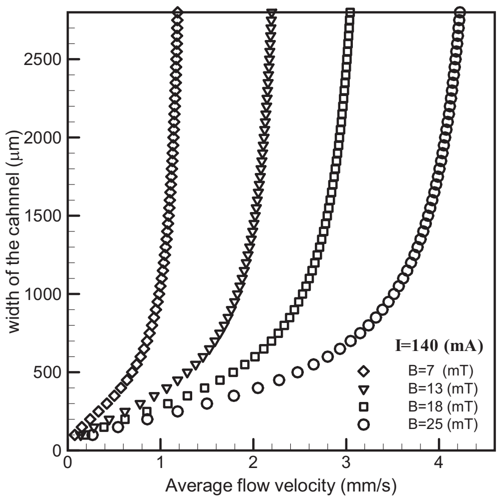

Figure 5. Variation of the flow velocity average versus channel width.

reverse like before and by more increase in width of channel the variation in average flow velocity lowers to the point which increase in channel width would not make a sensible effect on flow velocity. This is because of fixed electrical current density which results in fixed Lorentz force. In other words, by increasing width of channel the effect of wall friction on average velocity decreases while Lorenz force remains fixed.

5. COMPARISON WITH EXPERIMENTAL RESULTS

For evaluation of presented numerical solution, the numerical results have been compared with the experimental results which have been issued by Lemoff and Lee [13]. The dimensions of AC MHD micropump made by Lemoff and Lee have been shown in Table 1. The solutions used in the experiments are respectively, 1M, 0.1M and 0.01M NaCl, 0.01M NaOH, Phosphate Buffered Saline (PBS, pH 7.2), and Lambda DNA in 5 mM NaCl. The viscosities of these solutions are deduced from the calculated flow rate for each of the six solutions listed by Lemoff and Lee, and they are 7 × 10-4Pa.s, 14 × 10-4Pa.s, 8 × 10-4Pa.s, 6 × 10-4Pa.s, 5 × 10-4Pa.s and 6 × 10-4Pa.s in the order mentioned above. Fig. 6 shows the experimental results for the average velocity of the fluid in order of different solutions which electrical current has been regulated on 10, 12, 24, 36, 100 and 140 (mA) and the average AC magnetic flux density is 13 (mT). In addition the results of numerical simulations in this article have been presented in the figure. It is observed that there is a good agreement between the numerical and the experimental results.

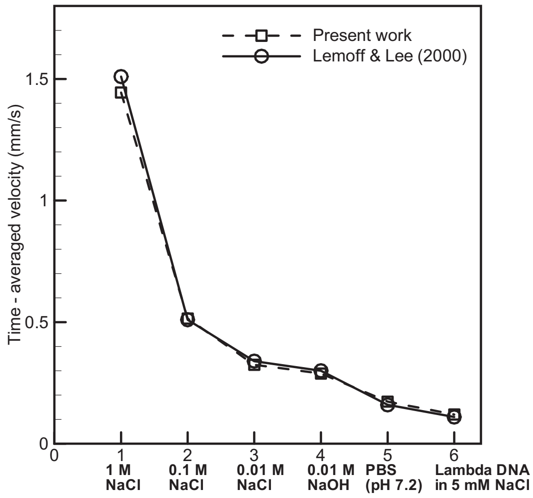

Figure 6. Comparisons between the present simulation and experimental results.

6. CONCLUSION

The equations of fluid flow in these micropumps with the mentioned assumptions such as two dimensional, laminar and fully developed has been derived and has been simulated by the finite volume method. The results show the effect of different parameters such as geometrical dimensions of the channel and the intensity of applied magnetic and electric fields on flow velocity. The results show that the best factor for increasing the flow velocity is optimum design of the channel section dimensions. Moreover by variation in magnetic flux density, electric current and phase angle can control the flow velocity.

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