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Flow Characteristics in a Magnetohydrodynamic Micropump

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Abstract

A mathematical study of the flow characteristics is presented for a micropump of which pumping mechanism is based upon magnetohydrodynamic (MHD) principles. MHD is the study of flow of electrically conducting liquids in electric and magnetic fields. Lorentz force is the pumping source of conductive, aqueous solutions in the MHD micropump. It may have potential applications in medicine delivery, biological and biomedical studies. Conducting fluid in the microchannel of the MHD micropump is driven by Lorentz force in the direction perpendicular to both magnetic and electric fields. This micropump has no moving parts and produces a continuous (not pulsatile) flow. The performance of the MHD micropump obtained theoretically is compared with a pervious experimental results obtained by another different authors.

Keywords: magnetohydrodynamic (MHD), micropump, Lorentz force, simulation.

1. Introduction

Conductive fluids can be propelled using the Lorentz force, in a process called magnetohydrodynamic (MHD) pumping. Jang and Lee were the first to fabricate a MHD micropump employing a permanent magnet and applying dc current [1,2]. Heng et al. [3] proposed to solve this problem by employing an ac current and a permanent magnetic field, and shaping the channel in a diffuser/nozzle structure to obtain a net flow of solution in one direction. Lemoff and Lee were the first to construct a practicle MHD pump by combining both alternating current and alternating magnetic field in their ac MHD pump [4-6]. The MHD principle has been widely used in nuclear power plant cooling systems, but has not seen widespread application in conventional pumps.

Compared with other types of nonmechanical micropumps, the MHD micropump has several advantages, such as simple fabrication process, bidirectional pumping ability, and the usability of medium conducting liquid. The voltage requirement of the AC MHD micropump is lower than most of the other micropumps compatible with biological systems. Moreover, the design of the AC MHD micropump allows for multiple, independently controlled pumps to be integrated on a single chip, thus enabling complex microfluidic systems. It is believed that the MHD micropump can be used in biomedical devices such as a drug delivery system or microfluidic propulsion application. Fig. (1) shows the principle of the MHD micropump, where Lorentz force is generated in the direction perpendicular to both magnetic and electric fields.

The Lorentz force can be produced using a DC or an AC current. In a DC configuration, a DC current is applied across the channel in the presence of a uniform magnetic field from a permanent magnet. This type has been used for some time to pump liquid metals [7] in nuclear reactors. In aqueous solutions, the practical application of this type is quite limited since the same electrolytic reaction that enables current conduction also produces gas bubbles that impede fluid flow [8] and causes electrode degradation. Using an AC current avoids electrolysis.

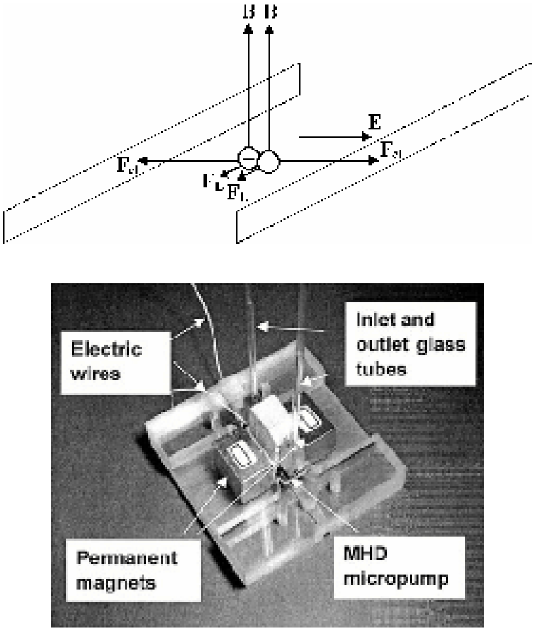

Fig. (1): The principle of the MHD micropump.

Hosokawa et al. reported MHD micropump with the working fluid of mercury [9]. Homsy et al. [10] studied the DC MHD in microchannels made in glass. Gas bubbles formation due to DC operation did not influence the performance of the pump since the bubbles were generated outside the pumping channel.

In this paper, the flow characteristics in MHD micropump using Lorentz force as pumping source of the medium conducting fluid or aqueous solution which is available in biological applications will be presented.

2. Theory

The pumping mechanism for a MHD micropump results from the Lorentz force. This force is produced when an electric current is applied across a channel filled with conducting solution in the presence of a perpendicular magnetic field. The Lorentz force is both perpendicular to the current in the channel and the magnetic field, and is given by

$$F = I \times Bw, \tag{1}$$

where I is electric current across the channel measured in amperes, B the magnetic field measured in Tesla and w the distance between the electrodes. This results in a pressure given by

$$P = IB / h, \tag{2}$$

where h is the height of the electrode. In microchannels, flow is governed by Poiseuille's law,

$$P = QR, \tag{3}$$

where Q is the volumetric flow rate and R is the fluidic resistance, which is dependent on the geometry of the channels [11] and is given by

$$R = \frac{2\mu L(perimeter)^2}{(cross-sectional \quad area)^3}, \tag{4}$$

where L is the total length of the channel and μ is the viscosity of the fluid. For the case of a rectangular channel, the fluidic resistance is given by

$$R = \frac{8\mu L(w+h)^2}{w^3 h^3}. \tag{5}$$

Substituting (5) into (3) and then equating with (2) gives the flow rate for a rectangular cross-section as

$$Q = \frac{IBw^3 h^2}{8\mu L(w+h)^2}. \tag{6}$$

In the MHD micropump, electric current is carried between the electrodes across the channel by both positive and negative ions which have opposite transverse velocities. The transverse velocity, v_t is defined as the component of velocity perpendicular to the channel. The Lorentz force acting on each ion is given by

$$F = qv \times B, \tag{7}$$

where q is the charge of the ion measured in coulombs. The component of the force along the direction of the channel is given by

$$F = qv_t B. \tag{8}$$

Since the positive and negative ions have opposite charge and opposite v_t , the Lorentz force on both types of ions is in the same direction. Since the mean free path of ions in a liquid is extremely small, collisions rapidly transfer momentum from the ions to the solvent molecules. Thus, the sum of the Lorentz forces on all of the ions is just the net force felt by the bulk fluid.

The pressure head difference of the MHD micropump can be obtained with the following relation:

$$\Delta p = JBL_e \tag{9}$$

where J is the current density and L_e is the electrode length. (Note that L_e generally does not equal L, the total length of the channel.)

3. Numerical Simulation Results and Discussions

The performance of the MHD micropump is obtained by calculating the pressure head difference and volumetric flow rate as the current changes. Fig. (2) shows the comparison between Jang et al [2] experimental (bubble) results of pressure difference between inlet and outlet due to applied current at the magnetic flux density of 0.44 T and the present theoretical results for a channel of 0.4 mm height, 1 mm wide and 40 mm long. The working fluid in these results was seawater (Table 1).

Table 1: seawater properties (20° C, 1 atm).

Electric conductivity	4 S/m
Density	1025 kg/m^3
Viscosity	1.09 E-3 kg/m.s
Relative permeability	1
Relative permittivity	72

The pressure difference of the bubble generation experimental data [2] is larger than the present theoretical results as shown in Fig. (2). This can be explained in the two-phase flow in the presence of electric field. Few bubbles generated in the lower current, where experimental data [2] are closer to the theoretical values than the case of more bubbles and higher currents.

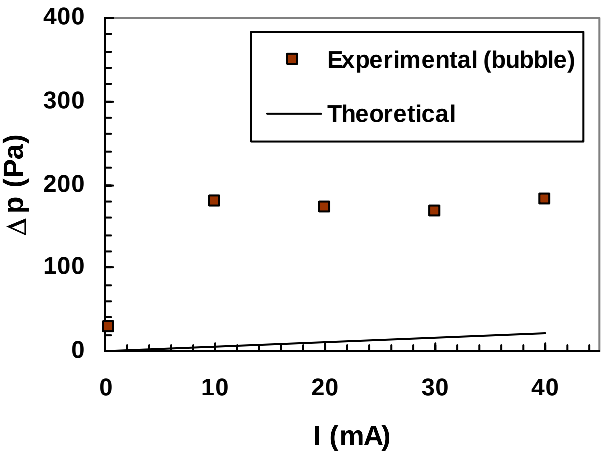

Fig. (2): Comparison between Jang et al [2] experimental (bubble) results of pressure difference between inlet and outlet due to applied current and the present theoretical results.

Fig. (3) presents a comparison between Jang et al [2] experimental (bubble) results of flow rate due to applied current and the present theoretical solution that follows Equation (6). The experimental flow rate data is also larger than the theoretical solution with the bubbles that is caused by the electrolysis of the conducting liquid. The flow rate in this comparison is 63 μl/min at 1.8 mA and B = 0.44 T.

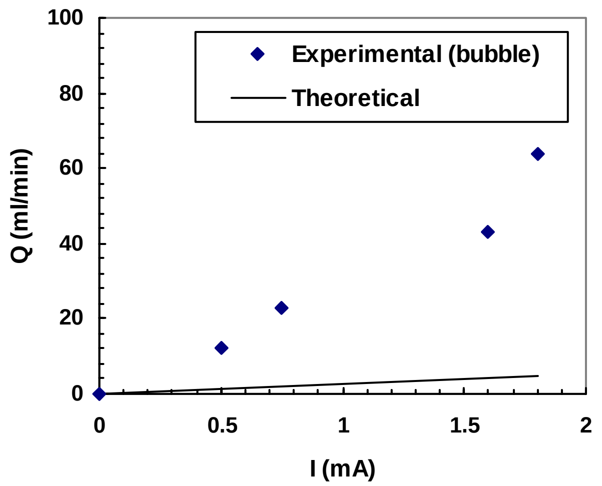

Fig. (3): Comparison between Jang et al [2] experimental (bubble) results of flow rate due to applied current and the present theoretical results.

Gas bubbles formation due to DC operation did not influence the performance of the pump since the bubbles were generated outside the pumping channel. This can explain the good agreement of the presented theoretical results with the DC MHD micropump experimental results of Homsy et al [10] as shown in Fig. (4).

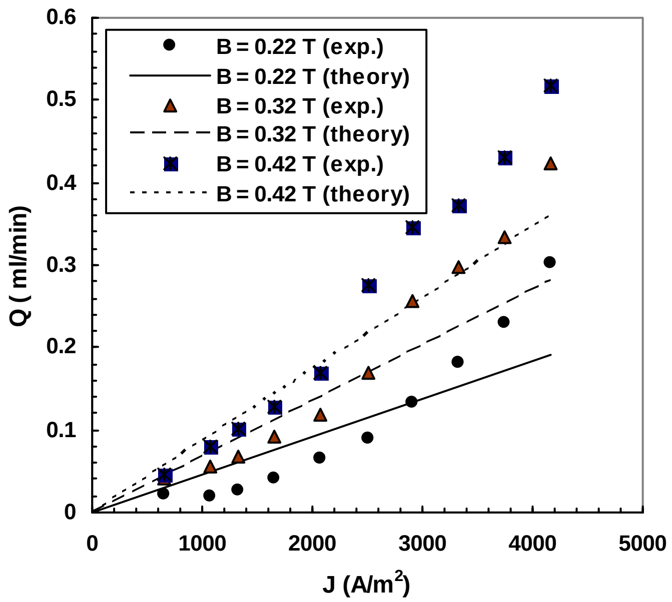

Fig. (4): Comparison between Homsy et al [10] experimental results of flow rate vs. current density and the present theoretical results.

Fig. (4) shows that the volumetric flow rate increases with the current density. The experimental results of Homsy et al [10] were on the same order of magnitude as the theoretical results. However, experimental values were less than expected from theory for low current density values, while in the higher current density range, volumetric flow rate exhibited values higher than the theoretical. The main sources for these deviations are believed to come from the back flow induced by hydrostatic pressure at low current density, and Joule heating at high current density.

4. Conclusions

A mathematical study of the flow characteristics is presented for a micropump of which pumping mechanism is based upon magnetohydrodynamic (MHD) principles. Conducting fluid in the microchannel of the MHD micropump is driven by Lorentz force in the direction perpendicular to both magnetic and electric fields. The performance of the MHD micropump obtained theoretically is compared with a pervious experimental results obtained by another different authors. Gas bubbles formation due to DC operation did not influence the performance of the pump since the bubbles were generated outside the pumping channel. This can explain the good agreement of the presented theoretical results with the DC MHD micropump experimental results. In the comparisons with AC MHD micropump few bubbles were generated in the lower current, where experimental data were closer to the theoretical values than the case of more bubbles at higher currents.

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