Chemical Engineering Science 134 (2015) 12–22

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Transient rotating electromagnetohydrodynamic micropumps between two infinite microparallel plates

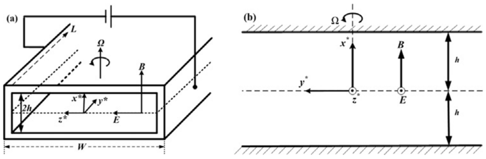
Yongjun Jian [a],*, Dongqing Si [a], Long Chang [b], Quansheng Liu [a]

[a] *School of Mathematical Science, Inner Mongolia University, Hohhot, Inner Mongolia 010021, PR China*
[b] *School of Mathematics and Statistics, Inner Mongolia University of Finance and Economics, Hohhot, Inner Mongolia 010051, PR China*

HIGHLIGHTS

- Analytical solution of transient rotating EMHD flow through a parallel microchannel is presented.
- Three different cases for both DC and AC electric and magnetic fields are studied analytically.
- The influences of involved parameters of Re_Ω and Ha on rotating EMHD velocity and flow rates are studied.
- A comparison of theoretical results with related experimental data is performed when rotation effect is lack.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form
22 March 2015
Accepted 16 April 2015
Available online 2 May 2015

Keywords:
Electromagnetohydrodynamic (EMHD)
Micropump
Hartmann number
Rotating Reynolds number
Method of separation of variables

ABSTRACT

By using the method of separation of variables, analytical investigations are performed for combined transient rotating electromagnetohydrodynamic (EMHD) flow of an electrically conducting, incompressible and viscous fluid between two slit microparallel plates. The flow relies on the rotating effect and the Lorentz force produced by the interaction between an externally imposed electrical current and a transverse magnetic field. Three different cases associated with electric and magnetic fields are discussed respectively, i.e., uniform electric and magnetic fields (case I); AC electric field and uniform magnetic field (case II); AC electric and magnetic fields (case III). The variations of velocity profiles and volume flow rates with time and their dependence on the rotating Reynolds number Re_Ω and the Hartmann number Ha are explained graphically. The results show that the magnitude of rotating EMHD velocity increases with Ha within a range when $Ha < 3$ in our present analysis. With the increase of the rotating Reynolds number, the magnitude of rotating EMHD velocity decreases in axial direction and increases in lateral direction. For small rotating Reynolds number Re_Ω, an interesting phenomenon for case I is that the maximum is not shifted and the maximum of the velocity in axial direction is the minimum of the velocity in lateral direction, and vice versa. However, there is a shift of the maximum for large rotating Reynolds number Re_Ω. Under the case II and the case III, the periodic oscillating phenomenon of the rotating EMHD velocity occurs. In addition, for three cases, the flow rate in y^* direction increases with Hartmann number and decreases with rotating Reynolds number. The amplitude of EMHD velocity is larger under the case II than that of steady solution under case I, but smaller than that under case III for prescribed Hartmann number Ha and rotating Reynolds number Re_Ω. Interestingly, there is a giant augmentation of the flow rates both in axial and in lateral directions for case III due to the aiding part of Lorentz force being greatly larger than retarding one in certain parameter ranges of phase of the magnetic field relative to the electrical field. By comparing our theoretical results in the limit case without rotation effect with related experimental data, the analytical

---

* Corresponding author.
E-mail address: jianyj@imu.edu.cn (Y. Jian).

http://dx.doi.org/10.1016/j.ces.2015.04.036

results coincide qualitatively with the fitted curve obtained in experiments.

1. Introduction

Microfluidic transport based lab-on-a-chip plays an important role in many areas of biochemical and biomedical process, fuel cells, physical particle separation and heat exchanger (Stone et al., 2004; Laster and Santiago, 2004; Karniadakis et al., 2005). The fluid flow in these applications is effectively actuated by employing pressure gradients (van Lintel et al., 1998; Abhari et al., 2012), electrical fields (Ghosal, 2002; Sadr et al., 2004; Chakraborty, 2007; Jian et al., 2010, 2011, 2014), electromagnetic fields (Pamme, 2006), laser (Weinert et al., 2009), capillarity (Hardt and Schönfeld, 2007), surface acoustic wave (Yeo and Friend, 2014), bubbles (Hua et al., 2002; Marmottant and Hilgenfeldt, 2004), etc. Among these different pumping principles, magnetohydrodynamic (MHD) micropumps have attracted the attention of many researchers due to several advantages such as simple fabrication process, the absence of moving parts, bidirectional pumping ability, continuous flow corresponding to a conduction pump type using a permanent magnet and the possibility to achieve relatively high flow rates (West et al., 2002; Yi et al., 2002; Weston et al., 2010). The driving force in MHD micropumps is originated from the Lorentz force generated as a result of an interaction between an externally imposed electrical current across a channel filled with electrically conducting liquids and a transverse magnetic field orthogonal to the currents (Nguyen, 2012). In a general way, the magnetic field can be produced by a permanent magnet or electromagnet. The feasibility of MHD micropumps has been demonstrated by using both direct current (DC) and alternating current (AC) electric and magnetic fields (Nguyen and Kassegne, 2008).

Many theoretical and experimental researches have been reported in the literature to study the flow behavior of MHD micropumps. Jang and Lee (2000) have experimentally shown that the average flow rates in micropumps can be substantially augmented by employing low-magnitude magnetic fields. A simple theoretical analysis of the 1D problem was also performed. However, an obvious deviation between theoretical and experimental results could be found. Lemoff and Lee (2000) presented theory, fabrication method and experimental results of a novel AC MHD micropump. Also, a simple theoretical express of time-averaged Lorentz force was given not from the point view of hydrodynamic model. Verardi et al. (2001) simulated the MHD duct flow employing finite element method and validated that axial velocity profiles were distorted into M-shape, which is a remarkable feature of MHD flow due to the strongly decrease of the axial velocity in the region near the center of the duct. By using the explicit finite difference method, Wang et al. (2004) conducted the numerical simulations of two-dimensional fully developed laminar flow for a MHD micropump. They found that the channel dimensions and the induced Lorentz forces have significant influences on the flow velocity profile, which was extensively explained by Moreau (1990). Ho (2007) obtained analytical solution of MHD micropump in rectangular ducts and compared the analytical results of flow rate and average flow velocity with those of experiments. Kabbani et al. (2008) proposed the closed-form solutions of flow field in a rectangular MHD micropump under both DC and AC electric and magnetic fields. Recently, Moghaddam (2012) reported an unsteady analytical solution for both DC and AC MHD micropump in a circular microchannel. Rivero and Cuevas (2012) studied the influence of slip condition on MHD micropumps based on both one- and two-dimensional flow models. The effect on slip length on the flow rate was analyzed and the comparison with previous experiments was performed. Based upon finite difference method, Moghaddam (2013) numerically investigated MHD micropumps of power-law fluids in a 2D rectangular microchannel. Very recently, by using the perturbation method, Buren et al. (2014) studied EMHD flow through a microparallel channel with corrugated walls. The corrugations of the two walls are periodic sinusoidal waves with small amplitude either in phase or half-period out of phase. Si and Jian (2015) extended the results of Buren et al. (2014) to take the influence of viscoelastic Jeffrey fluids into account. Kim et al. (2014) presented a theoretical and experimental investigation of the performance of a DC MHD micropump fabricated on photosensitive glass for circulating liquid metal. In addition, heat transfer characteristics and entropy generation analysis of MHD micropump were performed (Duwairi and Abdullah, 2007; Ibáňez and Cuevas, 2010; Shojaeian and Shojaee, 2013).

The importance of the flows in the rotating frame of reference has attracted the attention of many scholars. In practice, the microfluidic actuation system may be located in a rotating environment, such as in centrifuges for flow control or mass separation. A good advantage of using a centrifuge is that the centrifugal pump can dispel bubbles of gas in the microfluidic network. Duffy et al. (1999) experimentally studied electrokinetic control of liquid flow in multiple enzymatic assays in the rotating microfluidic systems. They found that such centrifugation may relieve Joule heating problem. In addition, there are several literatures associated with the effect of uniform rotation on the electrohydrodynamic instability (Takashima, 1976; Othman, 2004; Ruo et al., 2010). Chang and Wang (2011) developed a steady rotating electro-osmotic flow through microparallel plates. They obtained analytical solutions of rotating electroosmotic velocity field and volume flow rate. The above theory of rotating electro-osmotic flow of Newtonian fluids was extended by Xie and Jian (2014) to study power law fluids and by Li et al. (2015) to study third grade fluids.

However, no one seems to have discussed, to the authors' knowledge, the steady or unsteady rotating MHD micropump in a microchannel. The purpose of the present article is to investigate the MHD micropump between two infinite microparallel plates when the entire system rotates about an axis perpendicular to the planes of the plates. The analytical solutions are provided for both DC and AC electric and magnetic fields. Additionally, a comparison of our present analytical results with those in related experimental data is performed. Good agreement is obtained between the experimental data and those from our present theoretical considerations in limit case when rotating angular velocity is lack.

2. Formulation

2.1. Uniform electric and magnetic fields (case I)

The transient rotating EMHD micropump flow of an incompressible viscous electrically conducting fluid is considered. The physical modeling is sketched in Fig. 1. The flow is driven by Lorentz force along y^* direction which is produced by the interaction of DC electrical fields of intensity E_0 in z^* direction and homogeneous magnetic field of strength B_0 in x^* direction. The length of the channel is L, the width is W and the height is $2h$, and