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# Electromagnetohydrodynamic flow in a rectangular microchannel

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ABSTRACT

Recently, electromagnetohydrodynamic (EMHD) flow has often been exploited for fluid transport in narrow confinements through combined electrokinetic and electromagnetic actuation mechanisms. This study aims to theoretically investigate the EMHD flow through a rectangular microchannel. Analytical solutions expressed in the form of eigenfunction expansions are derived, which are determined by the Debye parameter, the Hartmann number, the aspect ratio of the channel, the deviation angle between the channel and the imposed electric field, and the distribution of zeta potentials on channel walls. The influences of these factors on primary and secondary flows are critically examined. Compared with the flow through two-infinite-plate channel, the lateral walls of the rectangular channel have significant effects on both primary and secondary flows. It is also revealed that, by horizontally placing the channel along a direction that deviates from the imposed electric field by an angle, a remarkable increment of the primary flow rate can be achieved without improving the strength of the electric field. The findings in the present study may help one to look for a suitable configuration for the optimum performance of EMHD-based micropumps.

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## 1. Introduction

Over the last decades, microfluidics based lab-on-a-chip device finds its importance in a wide spectrum of emerging technological processes and applications. A wide variety of functions and operations can be effectively and conveniently performed in these devices, including reaction, detection, actuation, drug delivery, synthesis, physical particle separation, and preparation, transport and analysis of chemical and biological samples, among many others [1–3]. To realize desired functions, of particular interest is the pumping of fluids which is required to be suitable for the microfluidic system to transport fluids within different parts of the device. Several mechanisms for fluid actuation in extreme narrow passages and confinements have been proposed in the existing literature, such as the micropumps by applying pressure gradients, capillarity, electromagnetic fields, and electric fields, to name a few [2–5].

Among these various actuation mechanisms, electrokinetics-based micropumps [6] have attracted one of the most attention. For certain reasons like the ionization of surface groups, most solid substances acquire a surface electric charge when brought into contact with an electrolyte solution [6]. In return, the charged substance redistributes free ions in the surrounding electrolyte solution, forming a double-layer structure of ions in the vicinity of the surface of substance, which is referred to as the electric double layer (EDL). The so-called EDL is composed by a Stern layer formed by immobile counterions absorbed on the solid surface, and a diffuse layer which develops under the influence of random thermal motion and electric attraction. In the bulk region outside the EDL, the electrolyte solution is almost electrically neutral. If this system is immersed in an electric field, the near-wall solution where the EDL forms will move through Lorentz forces exerting on free ions and the bulk solution will be driven into motion as well through viscous drags. The resultant flow is known as the electroosmotic (EO) flow, which is characterized by a plug-like velocity profile. Moreover, the flow velocity is independent of the dimensions of confinements which makes it better option for fluid transport at microscale. The electrokinetic pumping may also offer the advantages such as easy control and fabrication, an absence of mechanical moving parts and low sample dispersion.

In EO flows, the strength of the externally applied electric field determines the volumetric flux. The stronger the electric field is, the larger the volumetric flux (and hence the better transport performance) can be attained in electrokinetics-based microfluidic devices. Due

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to practical constraints, the field strength, however, should be limited, so as to avoid the Joule heating effect which is undesirable and harmful to many test samples, especially for those thermally labile chemical analytes and biological macromolecules [7,8]. Additionally, the electrokinetic pumping suffers from mixing deficiency and its performance highly depends on the physicochemical properties of aqueous solutions such as pH, ionic strength, or chemical composition of solutions. In this regard, a demand for more versatile alternative fluid propulsion mechanism arises, which may provide a way for better control and manipulation of fluid transport in microfluidic devices.

Recently, the application of magnetic fields has been recognized as a suitable flow actuation mechanism [9–20]. When an electrically conductive fluid flows over a transverse magnetic field, an electric current is produced because of charge separation. The applied magnetic field interacts with the injected electric current, giving rise to a net Lorentz body force which is raised in the direction perpendicular to both of the magnetic and electric fields. The pump that makes use of this electromagnetic force as a driving source in narrow confinements is termed the magnetohydrodynamic (MHD) micropump. Jang and Lee put forward a novel micropump based on the MHD principle, which has a variety of advantages such as bidirectional pumping ability, simple fabrication process, and the ability to drive the conducting fluid which is difficult to be transported in electrokinetics-based micropumps [9]. In their study, it was experimentally established that the average flow rates in micropumps can be substantially augmented by employing low-magnitude magnetic fields. As the driving source in MHD micropumps, the Lorentz force can be produced either by a DC or an AC electric current. Huang et al. [10] studied the performance of DC type MHD micropumps fabricated by LIGA method. Their experiments testing on several aqueous solutions showed that the average flow rate was proportional to the magnitude of the applied electric current. The generated flow rate, however, was not stable and finally decreased to zero for all tested solutions after the pump ran for hundreds of seconds, which was attributed to bubble generation due to the electrolysis of pumping solutions. When aqueous solutions are actuated by a DC voltage source, bubble generation around electrodes, which are immersed in the solutions, is inevitable. In order to prevent introducing gas bubbles into pumping channel, Homsy et al. [11] designed two microchanneled frit-like structures which connected the pumping channel to adjacent side reservoirs, where the electrodes were located. This configuration insures the separation of the electrodes from the main channel where flow is pumped such that bubbles generated around the electrodes do not enter the main channel [11]. Based on this concept, Nguyen and Kassegne [12] further designed a MHD micropump with bubble isolation and release system, which helped to collect bubbles and release them to outside environment. In their design, the electrodes were placed along the pumping length in supplementary channels, which were peripherally located in left- and right-side of the main pumping channel. With the aid of guiding track, bubbles generated in the side channels are easy to escape to an air chamber avoiding entering into the pumping channel. To circumvent the bubble generation, Lemoff and Lee [13] designed an inventive AC type MHD micropump, which used a transverse sinusoidal electric current together with a perpendicular, synchronous AC magnetic field. In their study, experiments were conducted to determine the maximum applied current allowed in microchannels before gas bubbles were observed. The results showed that the electrolysis phenomenon was remarkably reduced when the frequency of the applied current was sufficiently high [13]. The AC type MHD pumping, however, may result in low volumetric flow rate due to low intensity of AC magnets. This is because the operation of electromagnets under high frequency and current conditions is limited by induction heating in electrode materials [14]. To alleviate bubble formation (due to electrolysis of aqueous solution) and electrode corrosion, the so-called redox-MHD microfluidics has been proposed through addition of electroactive species which undergo Faradaic processes at electrodes [15]. However, the addition of redox species to solution brings undesirable interferences with detection, sample, and reagents for lab-on-a-chip applications. More recently, a new method was implemented by Nash and Fritsch [16] to use the poly(3,4-ethylenedioxythiophene)-modified electrodes, which eliminated the need to add chemicals to a sample in traditional redox-MHD microfluidics. For these polymer-modified systems, a much lower frequency of AC is needed in comparison to prior AC type MHD studies [17]. Thus, the induction heating can be considerably reduced.

In an attempt to incorporate both electrokinetic and MHD effects in a micropump, Chakraborty and Paul [21] obtained closed form expressions for the electromagnetohydrodynamic (EMHD) flow through a one-dimensional two-parallel-plate microchannel. Compared with the flow driven by the electrokinetic force only, the authors found that with the aid of a relatively low-magnitude magnetic field, the same volumetric flux can be obtained with a much reduced electric field strength [21]. Therefore, the Joule heating effect, which depends on the square of the imposed electric field, can be circumvented. In this regard, the magnetic field may offer an additional degree of freedom, so that the system can be operated at a lower strength of the imposed electric field without sacrificing the overall throughput rate [21]. To this date, EMHD flow in microchannels has been widely studied. Efforts have been made by Das et al. [19], Paul and Chakraborty [22], Munshi and Chakraborty [23], Reddy et al. [24], Buren et al. [25], Escandon et al. [26], Buren and Jian [27], Jian et al. [28], Si and Jian [29], Sinha and Shit [30], Sarkar et al. [31–33], Wang et al. [34], Xie et al. [35] and Vargas et al. [36], among others.

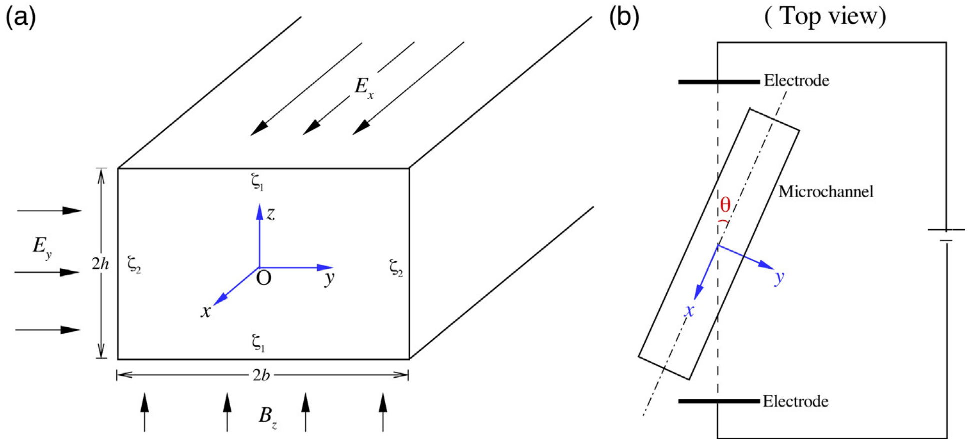

**Fig. 1.** Definition sketch of the problem.

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