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Some practical applications of magnetohydrodynamic pumping

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ABSTRACT

Magnetohydrodynamic pumping provides a unique opportunity to mobilize fluids inside a channel using very low power and without employing any external moving parts. In this paper, we illustrate certain unique applications of these pumps such as sample injection, fluid flow in packed bed, and on-chip assay development, all of which are relevant to point-of-care diagnostic device design and fabrication. A linear flow velocity of 5 cm/min was obtained using four on-board pumps in a closed loop of circumferential track length of 10 cm (channel cross section of 0.5 mm × 0.5 mm), whereas it dropped to 1.8 mm/min in a packed bed column operated by a single pump. Finally, these pumps were integrated with silicon immunoassay chips to evaluate the feasibility of transporting electro active species with these pumps from source to electrochemical detection site.

1. Introduction

Micropumps [1] are inevitable components of labs-on-chip and micro-total analysis systems, as basic processes like filtration [2], mixing [3], separation [4] and detection involve manipulation of fluid motion at microscales. Though there has been significant progress in micropump research [1], developing a truly microscale pump with considerable stroke volume (requirement is variable depending on application, but 0.5–1 ml stroke volume should suffice most microscale applications) that can deliver fluids at precise flow rates, especially in the sub-microliter range, is still challenging. Magnetohydrodynamic (MHD) pumping [5] is a promising technique, ideally suited for microfluidic applications because of its simple design (no moving parts) and low power requirement [5–11]. Because MHD micropumps are integrated in situ within the fluidic channels, they enable an elegant way to manipulate fluid flow along programmable pathways [5,7,8,12]. In contrast with other pumping methods, it is a simple matter for MHD to pump within a closed loop and within a sealed system, without using any valves. In this paper, we demonstrate some unique applications of MHD in microfluidics like pumping in a packed bed, movement of bubbles using MHD, sample injection and on-chip assay development, which are among the essential constituent elements of a total microanalysis system.

2. MHD pumping

Flow rate and stroke volume are paramount micropump performance characteristics. However MHD pumps are in-line and hence no-issue of stroke volume. The optimum flow velocity for both open channel and packed bed MHD pumping depends on a number of parameters like channel dimensions, particle size, porosity, redox concentration, magnetic and electric field strength, pump size and channel geometry. Let us first consider the open channel (without packing) characteristics of MHD. For a rectangular cross section, the Lorentz force (F) obtained due to the interaction of orthogonal magnetic field (B) and electric field density (J) is given by [13]:

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

Fig. 1 shows the schematic of MHD pumping action in a channel. The electric field generated by electrodes on the vertical wall of the microchannel interacts with the orthogonal magnetic field to create a body force parallel to the channel length. This body force generated on the fluid is responsible for a net forward movement of the fluid. This is an elegant and unique way to generate fluid movement in a closed loop without using any moving components inside the channel.

Accurate prediction of flow due to MHD in microchannels [14] can only be obtained by sophisticated simulation using Computational Fluid Dyanamic-Multiphysics packages. However, a simple expression for volumetric flow rate may be obtained from Hagen–Poiseuille equation [15]:

$$Vhw = \frac{iBh^2w^3}{8\,\mu l(h+w)^2} \tag{2}$$

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Q = flowrate (m^3/s)
V = velocity(m/s)
i = current(A), 3 - 4 mA
B = Magnetic field(T), 0.2 - 0.6 T
h = Depthofchannel(m), 5 - 9 e - 4 m
w = widthofchannel(m),5 - 9 e - 4 m
l = length(m), 0.1m
μ = viscosity($N.s/m^2$)

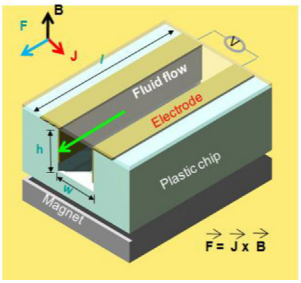

Fig. 1. Schematic of MHD pump. The variables for MHD pumps are listed on the left. We have used microchannels with gold electrodes deposited on vertical wall.

$$V \propto F, \text{ where } F = \frac{iBhw^2}{8\,\mu l(h+w)^2} \quad (3)$$

Variables are shown in Fig. 1 along with range used for this paper. '*F*' is the lumped parameter and has same unit as the flow velocity. Eq. (2) shows that the flow rate is directly proportional to current (i), magnetic field (B) and width (w), and inversely to the length (l) of the channel.

The above equation also indicates that the MHD force increases with increase in channel size (depth and width), and therefore is not favorable for very small channels.

3. Experimental

3.1. Setup

While it is easy to set up a magnetic field across the channel by placing either a permanent magnet or an electromagnet at the bottom of the chip, achieving constant current (thereby attaining constant flow) in the electrolyte solution has met with several difficulties. These include generation of bubbles at the electrodes at higher applied voltage, corrosion of electrode and depletion of electrolyte during continuous operation [6]. The use of redox chemistry has solved both corrosion of electrode and elimination of electrolysis of water to a great extent [16–18]. We have chosen the redox chemistry involving equimolar solution of Potassium ferri/ferrocyanide [$K_3Fe(CN)_6/K_4Fe(CN)_6$] for most of the experiments included in this paper.

3.2. Materials

Methanol, sodium borohydride ($NaBH_4$), potassium thiocyanate (KSCN), sodium sulfite and formaldehyde were bought from EMD Chemicals. Additional chemicals purchased include HPLC grade water from Baker scientific, 1-ethyl-3-(3-dimethyl amino propyl) carbodiimide hydrochloride EDC from TCI America, hydrogen tetrachloroaurate ($HAuCl_4$) from Alfa Aeser, TG-25 from Technic, and gold from Surepure Chemicals. Masks for MHD pump fabrication were obtained from thin metal parts. All other chemicals were reagent grade and used as received from VWR. Permanent magnets used for MHD pumping were bought from KJ magnetics. Single channel potentiostat from CH Instrument, Model 600C was used for cyclic voltammetry experiments on gold electrodes. The electrical field and associated electronics were controlled by program written in Labview from National Instruments. The optical measurements were done by means of a CCD camera (Nikon Coolpix).

3.3. Chip design and fabrication

The LC chip was fabricated from polymeric substrates (polycarbonate, cyclic olefinic polymer, or cyclic olefinic copolymers). Initial prototype chips were fabricated using computerized numerical control (CNC) machining methods. The channel cross sectional sizes ranged from 0.5 mm × 0.5 mm to 0.9 mm × 0.9 mm. The electrodes required for the MHD propulsion was directly deposited on the wall of the channel using thermal vapor deposition of gold. However, getting a uniform thickness of gold on the vertical wall using the above method on the channel vertical wall was difficult. The process was also quite time consuming and leads to heating of plastic chips causing deformation. An electroless deposition of gold [13] was therefore adopted for better adhesion of gold layer which gave a more reliable performance of MHD pumps. Briefly, the electroless deposition of gold involved exposing the selective part of the chip with UV light for 3 h. Then the chip was submerged in 50 ml 0.36 M ethylene diamine solution containing 50 mM EDC for 3 h at room temperature. The chip was then cleaned with de-ionized (DI) water and submerged in $HAuCl_4$ for 2.5 h. It was then cleaned with DI water and further submerged in $NaBH_4$ followed by another 20 min in 50 ml 0.5 M KSCN solution. Thereafter, it was cleaned thoroughly with DI water and put into 50 ml gold plating solution. The solution was kept at 42 °C for 1 h. The gold deposited on the chip surface only where exposed to UV light. Once the final deposition of gold electrodes were obtained and tested for conductivity, the rest of the chip was thoroughly sanded to remove the nonspecific gold deposition on the chip surface. The gold electrodes were further tested by running a cyclic voltammetry with equimolar (0.25 M) concentration of potassium Ferri/Ferro cyanide solution in water (inside the fluidic channel). A maximum current of ~2.4 mA indicated good deposition of gold on the vertical channel wall (electrode area ~5 mm × 0.5 mm, channel width 0.5 mm). The electrical connection lines and pads on the cover film (same plastic material) were created by depositing thermally evaporated gold in an Edward Auto 306 vacuum coating machine. Briefly, the cover film was covered with a custom fabricated mask and placed inside the vacuum coating machine. The gold was thermally evaporated onto the masked cover film. The mask was then removed and the cover film was subsequently used for bonding the chip thermally [19] using a press (at 2000 psi and 2 °C lower than glass transition temperature of chip material). Fig. 2A shows a fully fabricated chip with channels filled with food dye for easy visualization.

4. Results and discussion

4.1. Evaluation of flow speed

As different lab-on-chip devices will contain different designs of fluidic path and hence different flow resistances, it is important to understand the MHD flow characteristics in different channel geometries.

While actual flow field calculation of MHD needs sophisticated simulation, simple parametric evaluation of main variables in the flow helps in the initial design of experiments with MHD. Accordingly, the first step in verifying the chip functionality was to study the effects of various parameters in Eq. (2) with a simple geometry as shown in Fig. 2B. Test tracks of different cross sectional areas were designed and fabricated to conduct these initial flow rate studies. The circumferential length of test track was 10 cm and the channel height and width were varied from 0.5 to 0.9 mm. Gold MHD pumping electrodes were fabricated as discussed earlier in Section 3.2. In this test track configuration shown in Fig. 2B, there are four pairs of electrodes, with each pair acting as an independent MHD pump. The test track was filled with a redox pumping solution (equimolar-0.25 M solution of potassium ferri/ferrocyanide) and a plug of red dye mixed with a higher concentration (1 M) of redox solution was injected at one corner of test track. Flow velocity was measured by tracking the movement of red dye by time-lapse images obtained from the CCD camera. The flow velocity