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A numerical investigation of a novel micro-pump based on the induced charged electrokinetic phenomenon in the presence of a conducting circular obstacle

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ABSTRACT

A new micro-pump based on the electrokinetic phenomenon is numerically studied using a conducting circular obstacle placed in a junction of three micro-channels. The induced-charge electrokinetic flow over the conducting obstacle generates vortices and provides a pressure gradient, resulting in pumping the solution towards the micro-pump outlet. A theoretical model based on the thin electric double layer (EDL) is developed to simulate the influence of the applied electric field on the flow field. The numerical results indicate that the induced pressure and the mass flow rate in the pump outlet are affected by the electric field magnitude, micro-channel walls zeta potential, circular obstacle size and its position.

1. Introduction

Electrokinetics are extensively used in biomedical [1–3] and colloidal sciences. It can generate flow field (electroosmosis) [4,5], move ions, particles and cells (electrophoresis) [6,7] and separate them by size (dielectrophoresis) [8,9]. The functionality of many microfluidic and lab-on-a-Chip devices are affected by the fluid flow in their microchannels. Disadvantages of the pumps with moving parts, such as vibration and fatigue, has prompted the researchers to develop the pumps with non-moving parts. For instance, thermal gradient can generate fluid flow in micro scale devices [10]. However, large temperature gradients can negatively affect the biomedical functionalities of these microscale devices. Other means of fluid pumping may be achieved by employing piezoelectricity [11], electrochemical reactions [12] or electric field [13,14]. Using DC and AC electric fields as an actuator, the bulk fluid can be pumped either due to the electroosmosis effect [15] or the thermal gradient [10].

Electrokinetic based micro-pumps are widely used in microfluidic lab-on-a-chip devices to generate fluid flow in micro and nano-channels [16–18]. This can be carried out by applying an external electric field in the channels through electroosmosis effect. Many studies have been conducted to design different electrokinetic based micro-pumps in microfluidic devices [19,20].

For the first time, in 1962, Levich [21] used a conducting particle in a microfluidic system that was filled with aqueous solution and theoretically predicted that vortices were induced around the conductive surface in the presence of the external electric field. Three decades later, Gamayunov [22] visualized the vortices around a conducting spherical particle. The study by Herr et al. [23] took into account the electroosmotic flow in the cylindrical capillaries with non-uniform zeta potential and showed that the axial variation of the wall zeta potential induces pressure gradients through the micro-channel. The control of the electroosmotic flow on a capillary micro-device using an applied external voltage were experimentally investigated by Nolan et al. [24]. In 2002, Dutta [25] simulated the electroosmosis and electroosmosis-pressure driven flow in a micro-channel and demonstrated that the electroosmotic flow have linear dependence on the magnitude of the externally applied electric field. In 2004, Bazant and Squires [26] provided a physical description of the induced-charge electroosmosis phenomenon and found that the nonlinear electrokinetic slip at a polarizable surface can be used to make a new micro-pump or micro-mixer. In 2005, Yariv [27] analyzed the motion of a fully conductive particle driven by an induced-charge mechanism.

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Nomenclatures

D_s	Micro-chamber diameter
$\vec{E}$	External applied electric field
L	Distance between two electrodes (length of the micro-pump)
L_1	Micro-channels length
$\hat{n}$	Unit normal vector pointing into the liquid phase
$\dot{m}$	Mass flow rate
P	Pressure
r_p	Radius of the conducting circular obstacle
S	Conducting circular obstacle surface
t	Time
$\vec{U}$	Velocity field
W	Micro-channels width

Greek symbols

ε	Dielectric constant in the medium
ε_0	Permittivity of vacuum
$\zeta_{induced}$	Induced zeta potential on the conducting circular obstacle surface
ζ_w	Constant zeta potential on the micro-channel walls
θ	angular coordinate
μ	Viscosity
ρ	Solution density
ρ_e	Free charge density
φ_e	Applied electric potential

Jamaati et al. [28] presented an analytical solution for pressure-driven electrokinetic flows in planar micro-channels with velocity slip at walls and proposed an analytical expression for the velocity profile without considering the Debye-Hückel approximation. A similar study for rectangular micro-channels was performed by Min et al. [29]. A new micro-valve and micro-mixer based on the induced-charge electrokinetic motion of a particle were introduced by Daghighi et al. [30,31]. The local vortices which are generated near an electrically conducting surface can be used to control the liquid flow rate [15] or separate particles [32]. These vortices were experimentally shown by Daghighi et al. [33].

In this paper, we propose an innovative micro-pump for the first time using the induced-charged electrokinetic effect, which induces a pressure driven flow. Since the flow field in a biological systems are mainly caused by the pressure gradient, this type of flow field will be preferred in the microfluidic LOC devices. However, the pressure gradient micro-pumps are mainly more complex, bulky and expensive comparing to the electrokinetic micro-pumps. Since the proposed microfluidic device of the current study utilizes the electroosmotic effect to induce the pressure gradient and fluid flow, it will be very compact, vibration free and inexpensive, and the generated flow field will also be more similar to the flow field of the real biological systems. Here we use the OpenFoam software based on the finite volume method to numerically solve the governing equations, and evaluate the proposed micro-pump performance considering various physical parameters involved.

2. Model description

The proposed micro-pump of the current study consists of three micro-channels. Two incoming channels as micro-pump inlets are connected to the reservoirs, and a vertical micro-channel contains the pump outlet. The length and width of the three micro-channels are considered as equal and assumed that all the branches are open to the atmosphere, indicating the lack of an external pressure gradient in the system. A circular chamber is placed at the junction of the channels, and a fully electrically conducting circular obstacle is fixed at the center of the chamber. The channels and reservoirs are filled with the homogeneous electrolyte solution. Dimensions and other details are shown in Fig. 1.

DC electric field (x-axis direction) is applied along the micro-channels by two electrodes. The planar electrodes are fixed inside the reservoirs in front of the inlets 1 and 2. As illustrated in Fig. 1, negative and positive electrodes are embedded on left and right sides of the micro-pump, respectively. Furthermore, it is assumed that the micro-channels walls are non-conductive and carry uniform negative surface charge (constant zeta potential).

3. Theory and governing equations

When the micro-channel is filled with aqueous solutions, the electric double layer (EDL) will be formed near non-conducting micro-channel walls (Fig. 2). If an external electric field is applied through the channel, movement of ions in the EDL will drag the adjacent liquid molecules and will generate fluid flow in the micro-channel. This flow is known as electroosmotic flow (EOF) [34]. According to the classical electrokinetics, the EOF velocity has a linear relationship with the applied electric field and wall zeta potential [34]. As shown in Fig. 2, when a conducting circular obstacle is put into the solution, the external electric field will lead to migration of the negative and positive charges to the two sides of the circular obstacle and form a non-uniform charge distribution. In this situation, the circular obstacle will be electrically isolated, and consequently, ionic concentrations and their charge types in the EDL will be varied around the circular obstacle. As a result, under the effect of the electric field, the slip velocity on the circular obstacle surface will be in opposite directions. According to this fact, the generation of vortices around the conducting circular obstacle is predictable.

In 2004, Squires and Bazant [26] derived an exact steady-state analytical solution for the induced zeta potential on the surface of a 2D circular cylinder.

$$\zeta_{induced}(\theta) = 2r_pE\cos(\theta) \tag{1}$$

where, θ is the angular coordinate, r_p the radius of the cylinder and E is the external applied electric field. It should be noted that this solution is valid only for relatively simple and regular geometries. For a surface with irregular shape or complex geometry, there is no simple analytical solution for the induced zeta potential on the conducting surface. This constraint prompted us to employ a numerical method to obtain the distribution of zeta potential on the circular obstacle surface.

The system of equations for simulating the electric filed and the flow field are described below.

3.1. Electric field

According to the electrostatics theory, the Poisson equation can be used to calculate the applied electric potential at any point as [34].