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Manipulation and control of the electrokinetic motion of a non-conductive micro-particle in microchannel by generating lateral temperature gradient

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ABSTRACT

In this article, the electrokinetic motion of a non-conductive particle immersed in an aqueous solution in a microchannel is studied; the particle is subjected to a lateral temperature gradient that is perpendicular to the direction of the applied electric field. Three-dimensional governing equations are solved numerically to simulate the motion of the particle. It is noticed that the particle undergoes lateral and rotational movements as well as a longitudinal motion. The lateral and rotational motions of the particle will be affected by a size of the particle, an applied external electric field and an initial magnitude of temperature gradient. The results show that the initial magnitude of the temperature gradient is the most significant factor. It was observed that by doubling the temperature difference, the particle travels 64 percent more in lateral direction. It also rotates 42 percent more while experiencing a doubled temperature difference. Another parameter that has been investigated is the magnitude of the electric field. By halving the magnitude of the applied electric field, the particle moves laterally 10 percent less for a constant longitudinal distance. Finally, it was discovered that the effect of size of the particle on its velocity is negligible.

1. Introduction

Based on the electric double layer theory, contact of aqueous solutions and solid surfaces causes a surface electric charge at the interface of these two media. As a result, the surface electric charge of the solid phase will attract the counter-ions existing in the solution and will cause the electric double layer (EDL) consisting of the compact and the diffuse layers. When the solution in the microchannel is under influence of an applied electric field, the counter-ions of the EDL start moving along the channel which tends to move the bulk of solution due to shear forces. This phenomenon is called electroosmosis and the generated flow field will be the electroosmotic flow. If a particle is suspended in the microchannel, the particle will also carry charge and the EDL will form around it. The motion of charged surfaces (e.g. micro-particles) under influence of the external electric field will be called electrophoretic motion of particle (electrophoresis). These two phenomena comprise a more general phenomenon called electrokinetics [1,2]. A correlation describing the electrophoresis velocity of a particle in microchannel will be presented later.

Electrophoresis has diverse applications in microfluidics. As an example, many experiments in microbiology require electrophoretic manipulation of proteins, nucleic acids, microbes, viruses, and other bio-molecules [3]. The electrophoretic effect in microfluidic systems has been widely investigated both in isolation, and in the context of other physical phenomena [4–16]. For instance, Ye and Li [4] theoretically investigated the motion of a particle in a gravitational field that runs perpendicular to the electric field. They observed that the motion of the particle could be divided into two phases. In the first phase, the particle will have both lateral and longitudinal motions, because of gravity and external electric field, respectively. In the second phase, it only moves forward since the forces in the vertical direction are balanced. Ye et al. [7] and Yariv and Brenner [17] investigated the motion of a particle eccentrically positioned in a cylindrical channel. They conclude that the particle has a rotational movement when it travels eccentrically in the channel. Ye and Li [5] discovered that the motion of a particle in a T-shaped junction can be controlled by changing the applied electric field, size of the particle and ratio of the zeta potential of the wall to that of the particle. They also studied motion of two spherical particles with different sizes inside the same rectangular microchannel [6]. Their results show that one particle placed beside another one will change both

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the electric field and the flow field, and consequently will change the motion of each particle. They claim that the smaller particle moves faster. If the smaller particle is located behind the larger one, it may reach, climb and overtake the larger particle. The motion of cylindrical particles throughout capillaries have also been analyzed by some researchers [18–20].

As we have pointed out above, the zeta potential plays a central role in the description of electrophoresis. Venditti et al. [21] investigated effects of temperature on the zeta potential for aqueous solutions including KCl-water. They report that for most solutions the zeta potential increases with temperature. Temperature gradients often cannot be fully prevented in the real-world devices, or they may even be intentionally applied to the system to enable enzymatic reactions. Since the electrophoretic motion directly relates to the temperature-sensitive parameters or zeta potential, viscosity and dielectric constant, it appears important to investigate how the electrophoretic motion is modified when temperature gradient within a microfluidic device.

In the current study, a spherical particle is placed at the junction of two flows with different temperature, and therefore fluid with a non-uniform temperature distribution will surround the particle. We expect that a non-uniform distribution of local fluid velocity will form on the surface of the particle under electrophoretic driving. This local velocity distribution will result in both lateral and rotational movements of the particle in addition to the axial, longitudinal movement along the mean direction of the electric field.

This study focuses on the electrokinetic motion of the spherical particle under the influence of lateral temperature gradient. Comprehensive parametric studies were performed to numerically investigate influences of the size of particles, the magnitude of temperature gradient, and the intensity of the electric field on the particle motion and its surrounding flow field. We will show that this effect exceeds the influence of thermophoretic force [22] in magnitude.

2. Governing equations

In this study, the electrokinetic motion of particle in the microchannel under influence of lateral temperature gradient will be studied numerically. The applied electric field along the microchannel gives rise to the electroosmotic flow in the microchannel (Fig. 1). The electroosmotic velocity of flow can be computed using Eq. (34), provided that the zeta potential of the walls (ζ_w) is used in this equation. The fluidic regions with higher and lower temperatures flow through the upper and the lower halves of the inlet face, respectively (Fig. 2). The particle and microchannel walls are electrically non-conductive and both translational and rotational motions of the particle are taken into account. The Navier–Stokes equations as well as the charge, liquid volume, and thermal energy continuity equations subjected to proper boundary conditions are solved to simulate and study the assumed model of the current study. In the following section, the governing equations will be briefly introduced.

2.1. Electric field

We assume that the solution is electrically neutral outside of the double layer. The equation of conservation of electric charges should be solved to find the electric potential in the system [2]:

$$\vec{\nabla} \cdot (\sigma(T)\vec{\nabla}\varphi) = 0 \tag{1}$$

In the above equation, φ is the electric potential, $\sigma(T) = \lambda(T)C$ is the electric conductivity, C is the molar concentration and $\lambda(T)$ is the molar conductivity [2]. In conventional problems in which the temperature and concentration are uniform within the domain, the above equation will turn to the Laplace equation ($\nabla^2\varphi = 0$). However, since we intend to perceive the effect of temperature gradient within the fluid on the particle motion in this study, the general form of the equation of conservation of electric charges (Eq. (1)) is solved.

Because the walls and particle are non-conductive, the boundary conditions for above equation will be

$$\vec{n} \cdot \vec{\nabla}\varphi = 0 \quad \text{at channel walls and particle surface} \tag{2a}$$

$$\varphi = \varphi_0 \quad \text{at channel inlet} \tag{2b}$$

$$\varphi = 0 \quad \text{at channel outlet} \tag{2c}$$

Here $\vec{n}$ is the unit normal vector of the surface pointing outwards.

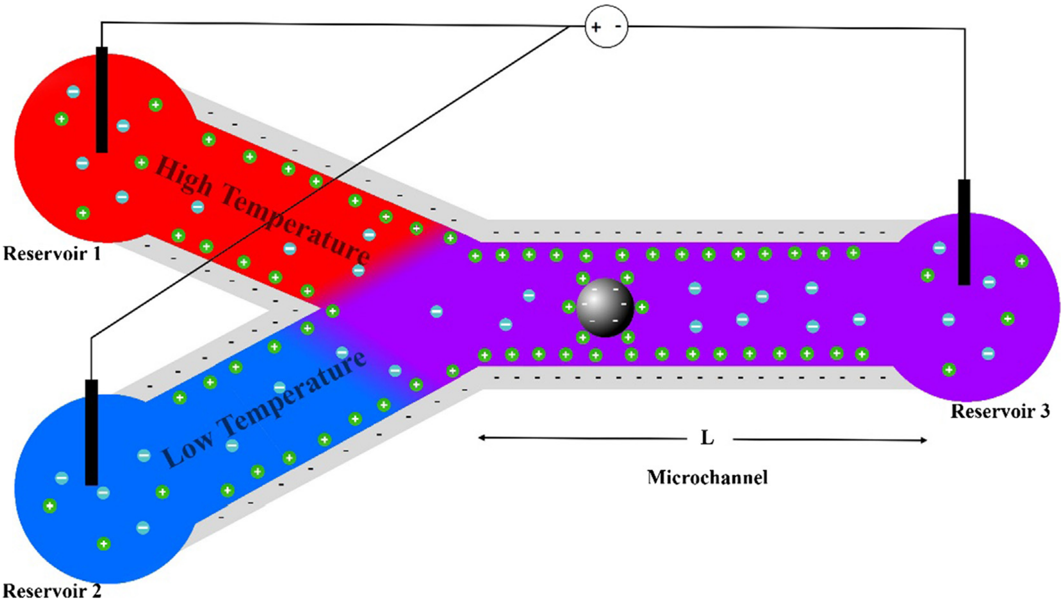

Fig. 1. Schematic diagram of the presumed microchannel of the current study.