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Dielectrophoretic motions of a single particle in the vicinity of a planar wall under a direct-current electric field

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A R T I C L E I N F O

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A B S T R A C T

We have numerically investigated two-dimensional dielectrophoretic motions of one particle induced due to interactions with a nearby planar wall under uniform electric field. Results show that the motions depend strongly on the gap between the particle and wall and their conductivity combination while the motion direction is determined uniquely by the wall conductivity. The particle is repelled to move farther away from the wall less conductive than the fluid, and vice versa. The motions become strengthened as either conductivity of the particle or wall deviates further from that of the fluid. Finally, the mechanism for the wall-induced DEP motions is examined.

1. Introduction

When subjected to a spatially nonuniform electric field, a conducting or nonconducting particle experiences a certain degree of electric force regardless of electric charge on the surface and thus is forced to move. Such a phenomenon is called the dielectrophoretic (DEP) motion or the dielectrophoresis. Since the DEP forces depend strongly on the electrical properties of particles and fluid, the shape and size of particles, and the frequency of electric field (in case of AC), the particles can be easily manipulated and separated by utilizing DEP. In recent years, therefore, the DEP motion has become one of the most promising tools to be used for separation of biological cells or orientation and manipulation of particles in micro- and nanofluidics [1–4].

Consider a single spherical particle suspended freely in an unbound viscous fluid under an external uniform electric field. Here, the presence of the particle makes the electric field around it spatially nonuniform, inducing nonzero DEP force density along the particle-fluid interface. Due to the symmetry, however, the particle experiences zero integrated DEP force and thus no motion, implying that the particle motion can be generated through symmetry breaking [5,6]. Provided that a planar solid wall is situated near the particle, the symmetry becomes broken and thus nonzero DEP force is induced, resulting into a DEP motion of the particle. Since most of the real applications involve microfluidic devices or channels bounded by solid walls, rigorous understanding of the wall-induced DEP motions or the DEP particle-wall interactions is very crucial.

Because of their promising feasibility in potential applications, quite a few studies have been performed so far on the wall-induced DEP motions. Liu and Bau [7] analytically studied DEP motions of cylindrical and spherical particles (more conductive than the fluid) submerged in a viscous fluid confined in shells and, as a limiting case, in semi-infinite walls, where plausible electric-potential distributions were artificially prescribed along the wall–fluid interfaces. In the study, they predicted that the particle is always attracted to move toward the wall. As the particle approaches the wall, the DEP force monotonically increases and the particle velocity increases, achieves a maximum, and then decays to zero. Subsequently, Young and Li [8] analytically studied on determination of the small gap separating a (nonconducting or insulating) spherical particle in electrophoresis from a (nonconducting) planar wall required for calculating its electrophoretic mobility. They claimed that the DEP force plays an important role in the force balance on the particle by showing that previous omission of the DEP force led to underestimated separation gaps. In addition, the force is always repulsive in nature and monotonically increases with decreasing particle-wall separation gap.

Next, Kang et al. [9] proposed a method of controlling a (nonconducting) spherical particle trajectory in a microchannel by utilizing the DEP force induced by nonuniform electric field formed

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around a (nonconducting) hurdle and then experimentally and numerically demonstrated it. They also observed that the particle near the wall experiences repulsive DEP force and its trajectory can be significantly affected by the force. Lo and Lei [10] analytically derived quasistatic force and torque acting on a (nonconducting or conducting) spherical particle in generalized dielectrophoresis in the vicinity of a (nonconducting) wall and found that the wall effect is minor for electrorotation and traveling wave DEP, but significant for conventional DEP. Subsequently, such a theory of the wall effect on DEP was experimentally validated by the same group [11].

Liang et al. [12,13] experimentally demonstrated lateral migrations or DEP motions of a (nonconducting) spherical particle in electrophoresis through a (nonconducting) rectangular microchannel, resulting from the DEP force induced by nonuniform electric field around the particle. They predicted that the wall-induced DEP motion decays rapidly when the particle is away from the channel wall, and vanishes in the center of the channel. Liang et al. [14] performed an experimental study for quantitative validation of the enhancement of particle electrophoretic mobility near a (nonconducting) solid channel wall by simultaneously determining the electrophoretic mobility and particle-wall separation gap. They demonstrated that the enhancement of electrophoretic mobility can be tunable by electrically controlling particle-wall separations via balancing the wall-induced DEP force and electroosmosis-induced lift force against the gravitational force.

It is well known that the wall-induced DEP motions should depend strongly on the separation gap between the particle and wall and their combination of electric properties such as conductivity and permittivity. As reviewed previously, quite a few studies have been successfully performed on the wall-induced DEP motions. Despite such significant achievements, however, understanding of the DEP motions is still far from perfect. For example, there have been some studies on the effects of the particle-wall separation gap on the DEP motions in literature. Methodical investigation, to the contrary, on the effects of the electric properties of the particle and wall has little been conducted. To the best of the author knowledge, there is no previous study to systematically scrutinize the effect of the electric–property combination of the particle and wall on the wall-induced DEP motions. This provides the present study with strong motivation.

In this paper, we have numerically examined two-dimensional DEP motions of a single particle suspended freely in an unbound viscous fluid in contact with a planar solid wall on one side under an externally applied uniform direct-current (DC) electric field to further understand DEP particle-wall interactions. For the simulations, we have extended the same numerical method developed and then validated in Kang [15] for direct simulations on the DEP particle–particle interactions to the wall-induced DEP motions considered in the present study. Then, we have also carried out parameter studies by systematically varying the particle-wall separation gap and the electric–conductivity combination of the particle and wall.

2. Numerical methods

2.1. Mathematical modeling

Consider DEP motions taken by one particle (‘*p*’) suspended freely in a semi-infinite viscous fluid (‘*f*’) in contact with a stationary planar solid wall (‘*w*’) on the bottom side under an externally applied uniform DC electric field. Here, the particle has a radius, a_p^*, and is assumed non-Brownian and neutrally buoyant, while the fluid has density, ρ_f^*, viscosity, μ_f^*, and electric conductivity and permittivity, σ_f^* and ε_f^*. A uniform electric field, E_0^*, is externally applied in the horizontal, from left to right, direction (positive *x*-direction). All the variables (‘*’ dropped) to be introduced in this manuscript from now on are normalized by the above mentioned dimensional parameters (‘*’ attached), a_p^*, ρ_f^*, μ_f^*, σ_f^*, ε_f^*, and E_0^*.

To focus only on the pure DEP particle-wall interaction, we assume that any other electrokinetic effect except the DEP effect is not involved at all. Particularly, the electrophoresis effect that may commonly occur in micro- and nanofluidic applications is neglected under an assumption that the electric double layer (EDL) thickness should be much smaller than the particle size and the particle-wall separation gap. That is, the ion transport phenomenon in the fluid (electrolyte) is not considered. Since the EDL thickness is generally on the order of nanometers, therefore, the particle radius and the separation gap should be at least on the order of micrometers in the present study.

Fig. 1 shows the corresponding nondimensional schematic diagram of the flow geometry and computational domain, which is composed of a fluid subdomain with a size of $L_x \times L_y \times L_z$ and a wall subdomain with a thickness of H (all the length scales are normalized by the particle radius, a_p^*). Here, the origin is situated at the center of the wall–fluid interface. The fluid subdomain is assumed enough large compared with the particle size to mimic the semi-infinite extent of the fluid ($L_i \gg 1$, where $i = x,y,z$), while the wall subdomain is determined enough thick to have little size effect on the electric field. The particle has density, ρ_p [$\rho_p = \rho_p^*/\rho_f^*$], and electric conductivity, σ_p [$\sigma_p = \sigma_p^*/\sigma_f^*$], and is located with a center at $\mathbf{X}_p$=(0,1 + g,0), where g is the particle-wall separation gap. The wall, on the other hand, has electric conductivity, σ_w, and is attached at the bottom of the fluid subdomain, following the study of Zhao and Bau [16] that examined the effects of the wall permittivity on the forces acting on a particle in induced-charge electroosmosis next to a solid wall. In the present study,

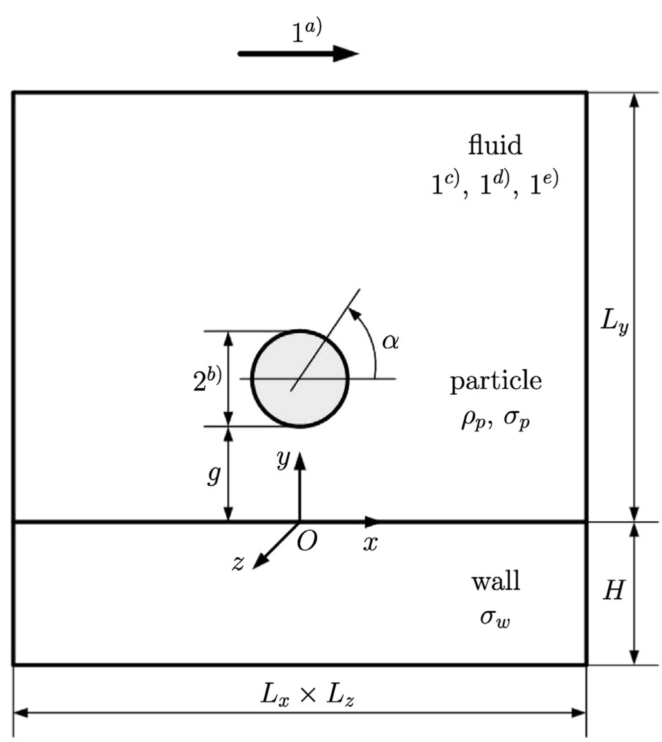

Fig. 1. Nondimensional schematic diagram of one particle suspended freely in a viscous fluid, interacting with a nearby planar solid wall at the bottom, under an external uniform electric field. Here, the numbers with superscripts, a), b), c), d), and e), denote external electric field, diameter of particle, and density, electric conductivity and permittivity of fluid, respectively.