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Dielectrophoretic motions of a pair of particles in the vicinity of a planar wall under a direct-current electric field

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ABSTRACT

This paper presents direct simulations on the two-dimensional dielectrophoretic (DEP) motion of a pair of particles in a viscous fluid, interacting with a nearby planar wall, to further understand the DEP interaction among multiple particles and a wall. Results show that, under an external direct-current electric field parallel to the wall-fluid interface, the nearby wall has significant effects on the DEP motion of both particles including their revolution, alignment and aligned movement. Regardless of their particle conductivity, the wall being less (more) conductive than the fluid pushes (draws) both particles to move away from (toward) it.

1. Introduction

In this paper, we have performed a direct numerical simulation based study on the dielectrophoretic (DEP) motion of a pair of particles suspended freely in a viscous fluid, interacting with a nearby planar solid wall, under an external direct-current (DC) electric field to further understand the DEP interaction among multiple particles and a wall. Here, the direct numerical simulation refers to a numerical approach where one solves the Maxwell's equation or its variation for the electric potential (or the electric field) and then integrates the Maxwell stress tensor over the surface to compute the DEP force acting on each particle, while one solves the continuity and momentum equations for the flow field and the force-balance based kinetic equation for the particle motion. Since the approach does not involve any approximation, it may be very accurate compared with other existing semi-analytical approaches [1–9]. Note that two types of interactions are compositively involved in the DEP motion considered in the present study: one is the particle-particle DEP interaction and the other is the particle-wall DEP interaction. In literature, up to now, even more attention has been paid to the former than the latter out of the two types of interactions.

With the purpose of understanding the pure particle-particle DEP interaction, quite a few studies based on the direct numerical simulation have been performed so far on the DEP motion of multiple particles suspended freely in an unbounded viscous fluid without a nearby wall under an external uniform DC electric field. First of all, Ai and Qian [1] performed direct numerical simulations on two-dimensional DEP motions of a pair of perfectly non-conducting (or insulating) particles, where the flow field, electric field and particle motion are simultaneously solved using an arbitrary Lagrangian-Eulerian method. Subsequently, Kang and Maniyeri [2] extended the same work to the DEP motion of two to five particles by applying a smoothed profile method to the solutions of the electric potential and flow field. Both early studies mentioned above drew a common conclusion that, in most cases where a uniform DC electric field is externally applied, all the particles revolve and finally get aligned in a line with the electric field. Despite such a remarkable conclusion, they assumed that all the particles involved should be non-conducting, that is they should have zero electric conductivity ($\sigma_p = \sigma_p^*/\sigma_f^* = 0$). It implies that the normal component of the electric current density or electric displacement field at each particle-fluid interface should vanish, which can be easily accessible to numerical simulations. In real applications, however, such an assumption is not general, but very exceptional. That is, each particle may usually have its own non-zero finite value of the conductivity.

Some follow-up studies, therefore, for tackling such a general problem involving non-zero values of the electric conductivity have also been performed since then. Hossan et al. [3] performed direct numerical simulations on two-dimensional DEP motions of two

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and three identical particles with either of two values of the electric conductivity, $\sigma_p = 10$ and $1/1000$, under an external uniform DC electric field. For the simulations, they applied an immersed interface method to the solution of the electric potential and a feedback-forcing based immersed-boundary method to that of the flow field. Subsequently, Kang [7] extended the similar work to two-dimensional DEP motions of a pair of particles with more diverse sets of the conductivity, $\sigma_p = 1/100$, $1/2$, 2 and 100, by employing a sharp interface method and a direct-forcing based immersed-boundary method to the solutions of the electric potential and flow field, respectively. Recently, Xie et al. [9] also performed similar direct numerical simulations on two-dimensional DEP motions of two and three particles using an arbitrary Lagrangian-Eulerian method.

The results from the above follow-up studies indicated that the DEP motion of both particles depends significantly on the combination of their electric conductivity signs. Here, the conductivity of a particle or a wall that is smaller and larger than that of the fluid is defined to be negative- and positive-signed, respectively. When both particles have the same sign of the conductivity (negative or positive), they revolve in a variety of fashions depending on their initial configuration and finally get aligned in a line with the external electric field. Note that more multiple particles with the same sign should also lead to their final alignment in a line with the electric field. With different signs, on the other hand, they revolve in the opposite direction and finally get aligned in a line perpendicular to the electric field. As reviewed above, lots of numerical studies have been performed so far on the pure particle-particle DEP interaction.

On the particle-wall interaction, only a few direct numerical simulation based studies can be found in literature. Since most of the real applications involve micro-fluidic devices or channels bounded by solid walls, rigorous understanding of the wall-induced DEP motion or the particle-wall interaction is very crucial. Very recently, Kang [10] studied two-dimensional DEP motions of a single particle suspended freely in an unbounded viscous fluid, interacting with a nearby planar wall, by performing direct numerical simulations. The results indicated that, under an external electric field parallel to the wall-fluid interface, one particle moves only in a direction normal to the interface due to the DEP force induced by the presence of a nearby wall and the motion depends strongly on the combination of the electric conductivity of the particle and wall and the separation gap between them. It was found that the direction of particle motion is determined only by the wall conductivity, irrespective of the particle conductivity: the particle is repelled to move farther away from the wall with a negative sign of the conductivity and attracted to migrate closer toward the wall with a positive sign. The intensity of particle motion is significantly influenced by the combination of their conductivity as well as the separation gap. Although obtained just from one single particle, the above results obviously imply that the wall can also play an important role even in inducing or modifying the DEP motion of multiple particles. It strongly motivates the present study.

In the present study, we have numerically examined two-dimensional DEP motions of a pair of particles suspended freely in an unbounded viscous fluid in contact with a planar solid wall under a uniform DC electric field applied externally in parallel with the wall-fluid interface. In addition, we also assume that any other electrokinetic effect except the DEP effect should not be involved at all. Particularly, the electrophoretic effect that may commonly occur in micro- and nano-fluidic 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. 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. In general, the external electric field is not always parallel to the wall-fluid interface in real applications, that is they may have a non-zero included angle between them for various purposes [11,12]. As a first attempt, nevertheless, we assume in this study that the external electric field should be parallel to the interface. For the simulations, we have extended the same numerical method developed and then validated by Kang [7,10] to the present study. In other words, we employ a finite-volume based numerical approach, where a sharp interface method is adopted for the solution of the electric potential and a direct-forcing based immersed-boundary method is for that of the flow field. Then, we have also carried out parameter studies by systematically varying the combination of the electric conductivity signs of the two particles and one wall and the initial particle configuration including a separation gap between the particles and wall.

2. Numerical methods

2.1. Mathematical modeling

Consider the DEP motion taken by a pair of particles ('p') suspended freely in an unbounded viscous fluid ('f') in contact with a stationary planar solid wall ('w') on the bottom side. Here, the particles have an equal radius, a_p^*, and are assumed non-Brownian and neutrally buoyant, while the fluid has mass 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 (toward the positive x-direction) parallel to the wall-fluid interface. All the variables ('$*$' dropped) introduced in this manuscript are normalized by the above mentioned dimensional parameters ('$*$' attached), a_p^*, ρ_f^*, μ_f^*, σ_f^*, ε_f^*, and E_0^*.

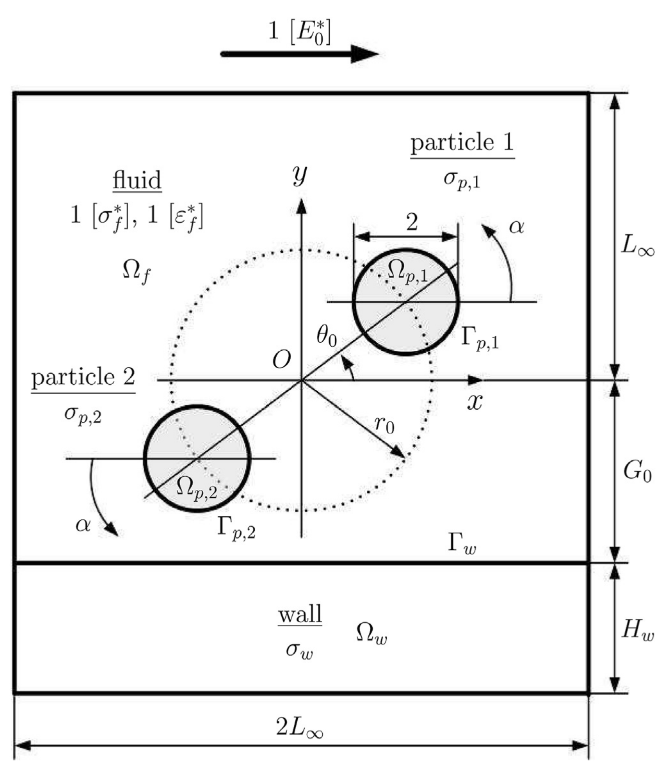

Fig. 1. Non-dimensional schematic diagram of the flow geometry and computational domain.