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Dielectrophoretic motions of multiple particles under an alternating-current electric field

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ABSTRACT

In this paper, we have performed direct numerical simulations on two-dimensional dielectrophoretic (DEP) motions of two or three identical particles in close proximity suspended freely in a viscous fluid under an externally applied alternating-current (AC) electric field with the purpose of further understanding AC DEP particle–particle interactions among multiple particles. For the simulations, we solve the Maxwell's equation with a large sharp jump in the complex electric permittivity across the particle–fluid interface for the complex electric potential and then integrate the Maxwell stress tensor to compute the time-averaged DEP force acting on each particle, while we solve the continuity and Stokes equations for the flow field. To solve the relevant governing equations, we employ a finite-volume based numerical approach, where a sharp interface method is adopted for the solution of the complex electric potential and a direct-forcing based immersed-boundary method is for that of the flow field. Results show that the AC DEP motion of two particles depends significantly on their signs of the real part of the Clausius–Mossotti (CM) factor. When both particles have the same sign (positive or negative), they revolve and finally get aligned 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. In addition, three particles with the same sign finally get aligned in a line with the electric field like the case of two particles. With mixed signs, however, they eventually exhibit one of the certain regular arrangements depending on their initial configuration and sign combination.

1. Introduction

When subjected to a locally 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. In general, the DEP motion can be generated either by using direct-current (DC) or alternating-current (AC) electric field. Since the DEP forces depend strongly on the electrical properties of the fluid and particles, the shape and size of the particles, and the frequency of the electric field (in case of AC), the particles can be easily manipulated and separated by utilizing DEP. In recent years, accordingly, 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]. Due to its great importance, therefore, a large number of analytical or numerical studies have been conducted, together with experimental studies, on the DEP motion.

In general, an analytical or numerical study on the DEP motion of multiple particles requires obtaining the DEP and hydrodynamic forces acting on each of the constituent particles and then applying them to each motion equation to trace the particle behavior. Thus, accurate prediction of such forces is an essential factor for a successful study on the DEP motion. Early-stage studies showed that the DEP force was usually obtained by employing the point dipole (PD) model [5–7], while the hydrodynamic force was obtained by utilizing the Stokes drag (SD) model [8,9]. Here, the PD model was developed under an assumption that a particle should be negligibly small compared with other length scales and enough far away from another particle or a wall, while the SD model was derived under an assumption of trivially low Reynolds number. Since they involve approximations and thus exhibit low accuracy, the models have very limited applications in many practical circumstances where such assumptions may not be valid.

To avoid such limitations inherent in the early-stage models, the so-called direct numerical simulation approach for strictly

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Table 1
Numerical methods and physical models used in previous studies to compute the DEP and hydrodynamic forces. PD = point dipole model; MST = Maxwell stress tensor model. SD = Stokes drag formulation; NS = Navier–Stokes (or Stokes) model. ALE = arbitrary Lagrangian–Eulerian method; AMR = adaptive mesh refinement method; BEM = boundary element method; DF/FD = direct-forcing/fictitious-domain method; DLM = distributed Lagrange multiplier method; FDM/FEM/FVM = finite difference/element/volume method; d-IBM/f-IBM = direct-forcing/feedback-forcing immersed boundary method; IIM = immersed interface method; SIM = sharp interface method; SPM = smoothed profile method.

Researchers	Currents	DEP force	Hydrodynamic force
Kadaksham et al. [5]	DC	PD	NS (DLM–FEM)
Aubry and Singh [6]	DC	MST (body-fitted FEM)	–
Kang and Li [8]	DC	MST (semi-analytical)	SD
Al-Jarro et al. [9]	AC	MST (simple FDM)	SD
Le et al. [15]	AC	MST (BEM)	NS (IIM/FDM)
Ai and Qian [10]	DC	MST (ALE/FEM)	NS (ALE/FEM)
Loucaides et al. [7]	DC	PD	NS (body-fitted FEM)
Shi et al. [11,12]	DC	MST (SIM/FDM)	NS (DF/FD/FDM)
Kang and Maniyeri [13]	DC	MST (SPM/FVM)	NS (SPM/FVM)
Hossan et al. [2]	DC	MST (IIM/FDM)	NS (f-IBM/FDM)
Ai et al. [4]	AC	MST (ALE/FEM)	NS (ALE/FEM)
Bhalla et al. [16]	AC	MST (AMR/FDM)	NS (DLM/FDM)
Hossan et al. [3]	AC	MST (IIM/FDM)	NS (f-IBM/FDM)
Kang [14]	DC	MST (SIM/FVM)	NS (d-IBM/FVM)

tackling more complex problems existing in practical circumstances has been applied to a variety of DEP motions. In the new approach, one solves the Maxwell's equation (Gauss's law) for the (real or complex) electric potential and then integrates the Maxwell stress tensor to compute the DEP force acting on each particle, while one solves the continuity and Navier–Stokes or Stokes equations for the flow field and then computes the hydrodynamic force on each particle by integrating the Cauchy stress tensor. Since the approach does not include any approximation, it may be very accurate. Therefore, it has enabled one to understand DEP particle–particle interactions among multiple particles and to trace accurate long trajectories which are little accessible by the early-stage models. Table 1 shows a list of numerical methods and physical models used in previous studies to compute the DEP and hydrodynamic forces either under an external DC or AC electric field. According to the table, quite a few direct numerical simulations have been conducted on the DC DEP motion so far [2,10–14].

In recent years, the AC DEP motion has been drawing increasingly more attentions than the DC counterpart in practical applications because of some preferable advantages [1,4,17]. First of all, the DC DEP requires high electric voltage to generate sufficient DEP force, which may lead to a serious Joule heating effect inside the micro device. The AC DEP, on the other hand, needs low voltage that prevents Joule heating and moreover simplifies the equipment for generating the electric field. In addition, the AC DEP can not only prevent the electrophoresis effect of inherently charged particles, but also the water electrolysis that cannot be avoided by the DC DEP. The DEP motion can also be readily switched between negative and positive DEPs by tuning the frequency of AC electric field (see the definitions of the negative and positive DEPs in Section 2.2 in advance). Such advantages of the AC DEP strongly motivate the present study. In this study, therefore, we want to investigate a variety of DEP particle–particle interactions that may exist among multiple particles in close proximity suspended freely in a viscous fluid under an external AC electric field.

Up to date, some direct numerical simulations have also been performed on the AC DEP motion [3,4,15,16]: see Table 1 for more details. Le et al. [15] designed a hybrid electrical–mechanical trap based on the AC DEP for single-cell trapping by performing direct numerical simulations and then reported on the effect of different combinations of electrode positions and mechanical properties of the trap on the maximum loading and unloading. Subsequently, Ai et al. [4] performed direct simulations on two-dimensional DEP motions of two particles under an external AC field to reveal the mechanism of an AC DEP based particle assembly technique. Results showed that a mutual DEP interaction between two particles in negative DEP always tends to attract particles and form a chain parallel to the applied electric field. Bhalla et al. [16] developed a new numerical approach (combined adaptive mesh refinement and distributed Lagrange multiplier methods) and then addressed a broad range of problems, including the DEP motion of particles in microfluidic channels, three-dimensional nanowire assembly, and the effects of rotating electric fields to orient particles and to separate cells using their DEP properties in a lab-on-a-chip device. Hossan et al. [3] proposed a new numerical approach for solving the complex-valued Maxwell's equation for the complex electric potential by converting it into two real-valued Maxwell's equations under an assumption that the complex electric permittivity is piecewise constant. Numerical results showed that, in the case of negative DEP, particles form a chain parallel to the applied electric field irrespective of their initial orientation when an AC electric field is externally applied.

Despite many achievements, however, an intensive systematic numerical study has little been conducted on the AC DEP particle–particle interactions among multiple particles (or cells) in the literature so far. For instances, Le et al. [15] briefly reported on the effect of a second cell moving downstream on a first cell already trapped in a cavity. Ai et al. [4] examined two-dimensional AC DEP motions of two particles, but their study was confined only to the negative DEP particle–particle interaction. Bhalla et al. [16] and Hossan et al. [3], on the other hand, mainly focused on the development of new numerical approaches for simulating on the AC DEP motion. That is, the particle–particle interaction issue was briefly considered only as an example for the purpose of validating their developed approaches in their studies: a set of three cells (two disk-shaped cells in negative and positive DEPs and one rod-shaped cell in negative DEP) by Bhalla et al. [16] and a set of four particles in negative DEP by Hossan et al. [3].

In this paper, we have numerically scrutinized two-dimensional DEP motions of two or three identical particles suspended freely in a viscous fluid under an externally applied AC electric field to further understand the AC DEP motion of multiple particles. Here, the particles should be in close proximity enough to make vigorous interactions with one another. Note that multiple particles in positive DEP as well as in negative DEP are considered in the present study. For the simulations, we have extended the same numerical method used in Kang [14] for direct simulations on the DC DEP motion to the AC DEP motion considered in the present study.