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A comprehensive numerical investigation of DC dielectrophoretic particle–particle interactions and assembly

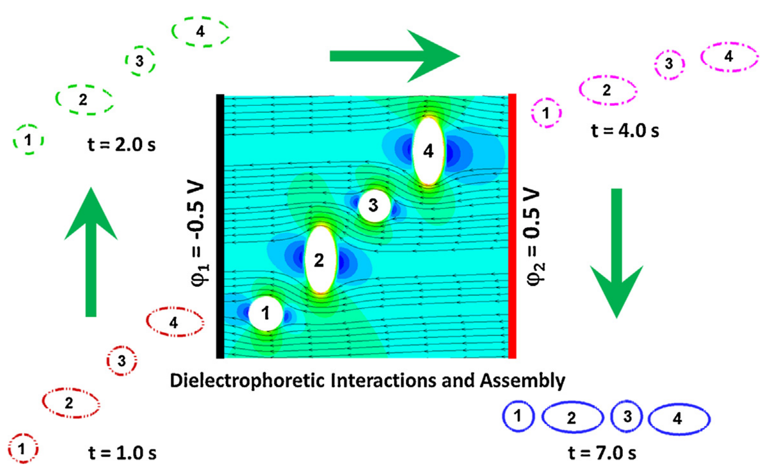
Mohammad R. Hossan[a,b,*], Partha P. Gopmandal[c], Robert Dillon[d], Prashanta Dutta[e]

[a] Department of Engineering and Physics, University of Central Oklahoma, OK 73034, United States
[b] Center for Interdisciplinary Biomedical Education and Research (CIBER), University of Central Oklahoma, OK 73034, United States
[c] Department of Mathematics, National Institute of Technology-Patna, Bihar 800005, India
[d] Department of Mathematics, Washington State University, Pullman, WA 99164-3113,United States
[e] School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920, United States

HIGHLIGHTS

- Impact of size and shape of particles on dielectrophoretic assembly is presented.
- Dielectrophoretic force on elliptical particles depends on the orientations.
- The interaction time span depends on the particles size as well as shape.
- Electrically similar particles form chain along the direction of electric field.
- Electrically dissimilar particles form chain in orthogonal to the electric field.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a comprehensive numerical study of dielectrophoretic (DEP) interactions and assembly of particles with various size, shape and electrical properties. A hybrid immersed boundary-immersed interface method is employed to solve coupled electric field and fluid flow equations. DEP forces are estimated from Maxwell's stress tensor. Results show that the final orientation depends on the electrical properties of the particles and fluid media. Particles that are identical in their electrical conductivities form an assembly parallel to the applied electric field regardless of their sizes, shapes and initial orientations. On the other hand, particles with dissimilar electrical conductivities (i.e. combination of more and less conductivities than the fluid media) form an assembly perpendicular to the electric field regardless of their sizes, shapes and initial positions. However, the interaction time span depends on the particles size and shape. In parallel assembly, particles rotate in a clockwise direction, while in perpendicular assembly particles rotate in counter-clockwise direction to reach to the final orientation.

* Corresponding author at: Department of Engineering and Physics, University of Central Oklahoma, OK 73034, United States.
E-mail addresses: mhossan@uco.edu, robiulme@gmail.com (M.R. Hossan).

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The simulation results qualitatively match with the experimental observation. This study provides critical insight on DEP interactions and assembly for a class of particles.

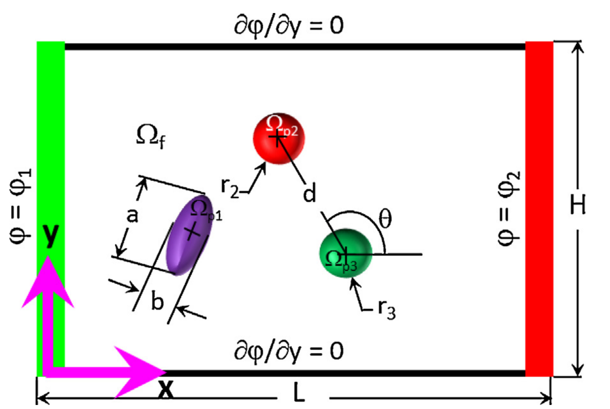

Fig. 1. Schematic representation of a rectangular domain that contains particles (Ω_p) with different sizes and shapes in a fluid medium (Ω_f). The center to center distance, d and initial orientation angle, θ of the particle 2 and particle 3 are shown. The major and minor axis of the elliopsoidal particle are denoted as a and b, respectively. The electric potential is applied on the left (φ_1) and right (φ_2) boundaries while top and bottom boundaries are insulated ($\partial\varphi/\partial y = 0$).

1. Introduction

Recently the study of dielectrophoretic (DEP) particle–particle interactions and assembly has become a subject of growing interest to diverse fields such as colloidal, biological, electronic, photonic, magnetic and biomaterials research [1–3]. In DEP particle manipulation, an electric field either DC, or AC, or a combination of AC and DC is applied. The applied electric field polarizes particles, which causes a net force on the particles due to the effect of the electric field on the polarized electrical charges. The DEP force facilitates particle–particle interaction and assembly formation. DEP force is highly sensitive to the size and shape of particles, electrical properties of particles and fluids, and electric field parameters such as magnitude and frequency [4,5].

DEP interactions and particle assembly have been demonstrated in the development of functional biological structures as well as engineered materials with desired properties [6,7]. For instance, a DEP mechanism was employed to assemble, align and package semiconducting nanotubes, and form electronically functional nanotube arrays for high performance electronic devices [8]. Velev and coworkers reported the formation of electrically functional microwires between planar electrodes [9] and a biocompatible material by patterning live cell and functionalized particles using DEP [10]. Huan et al. [11] used a similar technique to create multilayered cellular structures mimicking bone-like tissue in a 3D scaffold. The creation of an engineered Hematon—a blood producing cellular microenvironment- was also reported in the literature using DEP cell assembly [12].

In support of experimental exploration, an ongoing effort is being made to better understand the underlying mechanism of DEP by developing numerical simulations [13]. In general, numerical simulations involve solution of electric and flow fields with proper estimation of DEP and hydrodynamic forces acting on the constituent particles. Based on the force estimation, there are two approaches for modeling and simulation of DEP [13]. In a simplified approach, effective dipole moment (EDM) and Stokes drag (SD) approximations are used to calculate DEP and hydrodynamic force respectively [13]. Rosenthal and Voldman [14] used this simplified model to simulate and verify experimental observation of DEP cell patterning in a microfluidic trap. A similar approach was used by other researchers as well [15–17]. However, the simplified approach has limited application in microfluidics because these approximations do not hold when particles are close to each other or to boundary walls. Also this type of simplified model is not useful for nonspherical particles or if particle size is comparable with microfluidic dimension [13,18,19].

An interface resolved approach addresses the limitation of the simplified approach [13] by using the Maxwell's stress tensor (MST) and Cauchy stress tensor (CST) to estimate DEP and hydrodynamic forces respectively. Hossan et al. [20–22] developed a hybrid immersed interface-immersed boundary method to study the effect of electrical conductivities and particle size on DEP particle–particle interaction and assembly. Other methods such as arbitrary Lagrangian-Eulerian (ALE) method [23,24], boundary element method (BEM) [25], finite volume based sharp interface method [26] and Lagrange distributed method [27] have also been used to study DEP interaction between spherical shaped particles using stress tensor approach. Recently we extended our hybrid immersed interface-immersed boundary method to study the interactions of elliptical bipolar particles [28]. Note that the aforementioned studies were limited to the investigation of DEP interactions between identical circular or elliptical particles.

Recent experimental studies report that the interactions and assembly of irregularly shaped particles are important for development of smart materials, engineered biological cellular structure and tissue formation [29,30]. The size, shape and electric field parameters has significant impact on DEP interactions and particle assembly [31]. To the best of our knowledge, there have been no comprehensive studies that report the interactions or assembly among particles of different shapes, size and electrical properties. In this paper, we present a systematic comprehensive numerical study of DEP interactions and assembly of both identical and nonidentical particles with respect to their size, shape and electrical properties. The electric field and fluid flow equations are solved using our hybrid immersed interface-immersed boundary method. The results of interaction and assembly of nonidentical particles are compared with the results of corresponding identical particles.

2. Theory

The application of electric field causes accumulation of net electrical charges along the interface between fluid and particles because of polarization. In a spatially nonuniform electric field, particles experience a net force due to the action of the electric field on the accumulated charges. This dielectrophoretic (DEP) force can be used to manipulate particles in fluid media. Both AC and DC electric field can create DEP forces and work equally on charged or neutral particles. In this study, we employ DC electric field to facilitate DEP. However application of DC electric field introduces other electrokinetic effects such as electrophoresis and electroosmosis. Since particles in this study are electrically neutral and of micrometer scale, these effects are ignored. A detailed justification can be found elsewhere [21,23,25].