FIELD-INDUCED DIELECTROPHORESIS AND PHASE SEPARATION IN SUSPENSIONS

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Summary We report observations of a new electric field- and shear-induced many-body phenomenon in the behavior of suspensions whose origin is dielectrophoresis accompanied by the field-induced phase separation. As a result, a suspension undergoes a field-driven phase separation leading to the formation of a distinct boundary between regions enriched with and depleted of particles. The theoretical predictions are consistent with experimental data even though the model contains no fitting parameters. It is demonstrated that the field-induced dielectrophoresis accompanied by the phase separation provides a new method for concentrating particles in focused regions and for separating biological and non-biological materials, a critical step in the development of miniaturizing biological assays.

Compared to other available methods, ac dielectrophoresis is particularly well-suited for the manipulation of minute particles in microfluidics [1]. The concepts currently favored for the design and operation of dielectrophoretic micro-devices consider the trend of the field-induced particle motions by computing the spatial distribution of the field strength over a channel as if it were filled only with a liquid and then evaluating the direction of the dielectrophoretic force, exerted on a single particle placed in the liquid. However, the exposure of suspended particles to a field generates not only the dielectrophoretic force acting on each of these particles, but also the dipolar interactions of the particles due to their polarization. Furthermore, the field-driven motion of the particles is accompanied by their hydrodynamic interactions. These long-range electrical and hydrodynamic interparticle interactions are entirely neglected in analyzing the performance of currently used micro-fluidic devices. In [2-4], we demonstrated that a single-particle model which only takes into account the dielectrophoretic force, the Stokes drag force, and the gravity force acting on a particle predicts fairly well the rate of the field-driven particle redistribution for dilute suspensions containing ~ 0.1% (v/v) but does not predict the aggregation pattern formed by these particles. Furthermore, the presence of the interparticle dipole-dipole interactions was found to imposes a lower bound on the scale of microelectrode arrays for the precise positioning of positively polarized particles in selected locations of a dielectrophoretic micro-channel even for ~0.1% (v/v) suspensions [4]. Now we report observations of ac dielectrophoresis accompanied by a field-induced phase separation whose origin is the interparticle electric interactions.

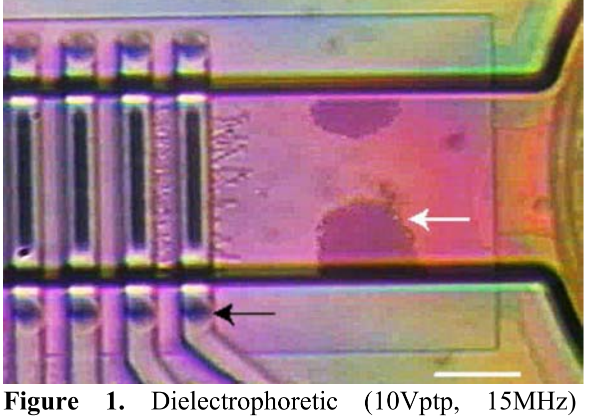

Figure 1. Dielectrophoretic (10Vptp, 15MHz) separation of bacterial cells and beads. The cells adhere to the energized electrode (black arrow) while the beads experience negative dielectrophoresis accompanied by a phase separation (white arrow). The flow is from right to left. Scale bar = 20 μm [6].

Microfluidic devices for experiments were fabricated in Sandia National Laboratories Microelectronics Development LAB using Sandia's SwIFTTM (Surface micromachining with Integrated microFluidics Technology) process [5] for producing highly-integrated monolithic multilayer structures. The fluidic channels [6], fabricated using single 6 inch Si wafers, are 40 μm wide, 6 μm high, and 570μm long and contain 6 μm wide p-doped polysilicon traces, with each trace being split into two electrically-connected electrodes located on the ceiling and the floor of the fluidic channel and arranged perpendicular to the flow (Fig. 1). The suspension was delivered into the channel at a flow rate ranging from 0.24 pL/s to 9.6 pL/s. The electrodes were energized with a sinusoidal wave, 10 V peak-to-peak (ptp) and 15-30 MHz while the silicon substrate was grounded. These electrodes act like "dielectrophoretic gates," that control the motion of polarized particles flowing through the channel. The photo presented in Fig. 1 illustrates the ac dielectrophoretic separation of a heterogeneous mixture of negatively polarized 1μm polystyrene spherical beads (1.05 g/cm3, Duke Scientific Co.) and positively polarized heat-killed bacterial cells (Staphylococcus aureus; Molecular Probes) dispersed in DI water. The beads, experiencing negative dielectrophoresis, are repelled from the dielectrophoretic gate and accumulate in a region near the electrodes (Fig. 1). On account of compressive electric and shear stresses, the layer of these beads forms two boluses with a distinct front between the regions enriched with and depleted of particles. The average particle concentration in the boluses was estimated to run as high as 40-50% (v/v).

An electro-hydrodynamic model [6] proposed for simulating the bolus formation generalizes a thermodynamic theory [7] for a suspension subject to a spatially non-uniform ac field. This model encompasses the quasi-steady electrodynamic equations together with the momentum and continuity balance equations of the "mixture" model for a suspension, which are averaged over the field oscillations. The suspension is viewed as an effective Newtonian fluid the viscosity which varies with the particle concentration according to the Leighton-Acrivos expression. The bulk electric force exerted on a suspension, and the particle velocity relative to the suspending fluid are expressed in terms of the chemical potential of the particles [7]. The theoretical predictions for the bolus growth, for the particle concentration in the bolus, and the fact that particles travel around the circumference of the bolus and are then drawn into the bolus side closest to the electrode, are consistent with the observations.

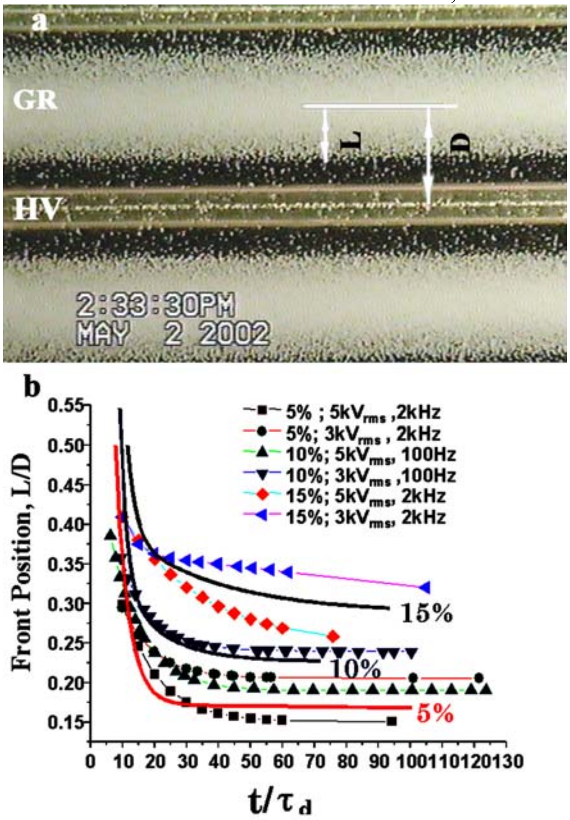

Figure 2. (a) The photo illustrates how the front location was measured; HV and GR refer to the high-voltage and grounded electrode respectively. (b) The experimental data (symbols) and computational results (solid lines) for the front propagation in 5, 10, and 15% (v/v) suspensions [8].

To test theoretical predictions quantitatively, experiments were conducted [8] on 5%–15 %(v/v) suspensions of neutrally buoyant spherical (average diameter of 87 μm) polyalphaolefin particles (AVEKA, Woodbury, MN) suspended in corn oil ($0.92 g/cm^3$, 59.7 cp at 23^0C) which exhibit negative dielectrophoresis [8]. The experiments were performed in a horizontal parallel-plate chamber (6 cm wide, 12 cm long, and 3 mm high). The bottom of the chamber was equipped with electrodes (1.6 mm wide) which were embedded into groves at 2 mm intervals and were alternately connected to the high voltage and to the ground (Fig. 2a). The top of the chamber, consisting of a transparent glass coated with a conducting layer of indium tin oxide, was grounded. Under these conditions, the field configuration consists of two high-strength regions near the electrode edges and a wide low-strength region above the center of the grounded electrode near the channel midplane [8]. We found that, due to interparticle electrical interactions, such suspensions undergo a phase separation when subjected to a high-gradient ac field (~ kV/mm), and form a propagating distinct front between the regions enriched with and depleted of particles (seen as white spots in Fig. 2a). As time progressed, the front slowly moved away from the high field regions and the particles became progressively confined to a thin column above the grounded electrode. Note that the same configuration of an electric field does not lead to the front formation in dilute suspensions, ~0.01%-0.2% (v/v) [2]. The theory predicts that the use of the characteristic time for dielectrophoresis, τ_d [2, 3], makes it possible to combine the data on the time dependence of the front position for different voltages and frequencies (Fig. 2b) into one band. As can be seen from Fig. 2b, the simulation results are in a reasonable agreement with the experimental data for $t/\tau_d \le 20$ even though the model contains no fitting parameters.

In conclusion, we demonstrated that ac dielectrophoresis accompanied by a field-induced phase transition provides a powerful method for strongly concentrating particles and for separating biological and non-biological particles. In particular, the use of dielectrophoretic gates enables one to remove any substance less polarizable than water (nearly all inorganic materials) from aqueous solutions.

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