PARTICLE MANIPULATION IN MICROFLUIDICS: THE ROLE OF DIELECTROPHORESIS, ELECTROHYDRODYNAMICS AND AC ELECTROKINETICS

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INTRODUCTION

The application of a.c. electric fields to control and manipulate isolated particles in suspension using microelectrode structures is a well-established technique. In particular, the dielectrophoretic manipulation of sub-micron bioparticles such as viruses, cells and DNA is now possible. As the size of the particle is reduced, so the effects of Brownian motion become greater. Therefore, to enable the dielectrophoretic manipulation of sub-micron particles using realistic voltages, the characteristic dimensions of the system must be reduced, to increase the electric field. However, a high strength electric field also produces a force on the suspending electrolyte, setting it into motion. Indeed, this motion may be a far greater limiting factor than Brownian motion.

Owing to the intensity of the electric fields required to move sub-micrometre particles, Joule heating can be a problem, often giving rise to electrical forces induced by the variation in the conductivity and permittivity of the suspending medium (electrothermal forces) [1]–[3]. In certain circumstances Joule heating may be great enough to cause buoyancy forces. In addition to Joule heating, the geometry of the electrodes used to generate dielectrophoretic forces produces a non-zero tangential electric field at the electrode-electrolyte double layer. This induces steady motion of the liquid, a flow termed ac electroosmosis, because of its similarity to electroosmosis in a dc field [5]-[7]. It should be emphasised that the ac electroosmotic flow observed over microelectrodes differs from ac electroosmosis observed in capillaries. In the later case the electric field is time-varying, but the diffuse double layer charge is fixed and the fluid motion is oscillatory, whereas in the former case both the electric field and double layer charge are time-varying and give rise to a steady fluid motion.

Based on these mechanisms, the magnitude and direction of the surface and volume forces acting on the liquid can be predicted analytically, or alternatively using numerical simulations. This means that it should be possible to design and develop microelectrode structures that can translate experimental and theoretical understanding into a given specification. However, the precise design of a complicated microelectrode structure would require extensive numerical calculations. This requires to develop a general framework which outlines the basic constraints of a system, thus reducing the need for intensive computation. A first step in this process is prior knowledge of how the forces on the particle scale with the size of the system, the shape of the electrodes, the particle diameter, the magnitude and frequency of the applied ac electric field, and the conductivity of the suspending solution [8].

The aim of this presentation is to highlight these scaling laws for the control of particles. First, we present an analysis of the motion of particles caused by gravity, dielectrophoresis (DEP) and Brownian motion only. Second, the mechanical, electrical and thermal equations that govern liquid motion in these microelectrodes structures are formulated. Thirdly, the volume and surface forces acting on the system are given, emphasizing how these forces scale with system parameters. Finally, the relative importance of the drag force, (which comes from electrohydrodynamic flow) is discussed and compared with Brownian motion, DEP and gravitational forces.

RESULTS

The measurement and analysis of flow has been performed using a simple electrode design consisting of two coplanar rectangular electrodes fabricated on a glass substrate. The electrodes are 2mm long and 500 μm wide, with parallel edges separated by a 25 μm gap. Because the gap is small compared to the length and width of the electrodes the system can be considered to be two-dimensional so that the analysis is restricted to the 2D cross-section.

For the following results we use typical physical quantities for aqueous saline solutions at ambient laboratory temperature (25 K). For particles we use sizes ranging from 0.1 μm up to 10 μm. Typical examples are viruses (0.01-0.1 μm), bacteria (0.5-5 μm), or cells (5-15 μm). These bioparticles are usually suspended in an aqueous saline solution with a conductivity that ranges between 10^{-4} and 1 S/m. Typical system lengths of the microelectrodes (interelectrode gaps) used in the dielectrophoretic manipulation of bioparticles vary from 1 to 500 μm. The signals applied to these electrodes can be up to 20 Volts giving rise to electric fields that can be as high as 2×10^7 V/m. The applied signals have frequencies in the range 10^2 to 10^9 Hz.

Figures 1 and 2 show the different domains of influence of the flows for the case of a particle of radius $a = 0.25\mu$m

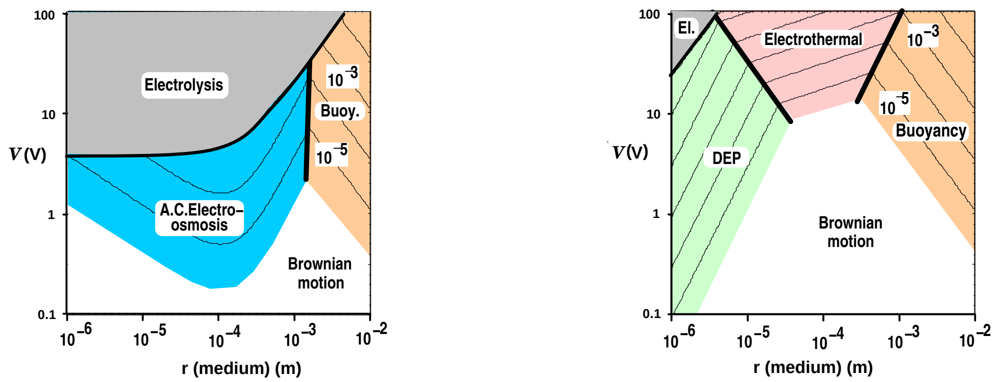

Figure 1. Particle velocity maps in the plane V versus r for a particle with radius $a = 0.25\mu$m in medium with $\sigma = 10^{-3}$S/m: (left) $f = 10^2$ Hz; (right) $f = 10^5$ Hz.

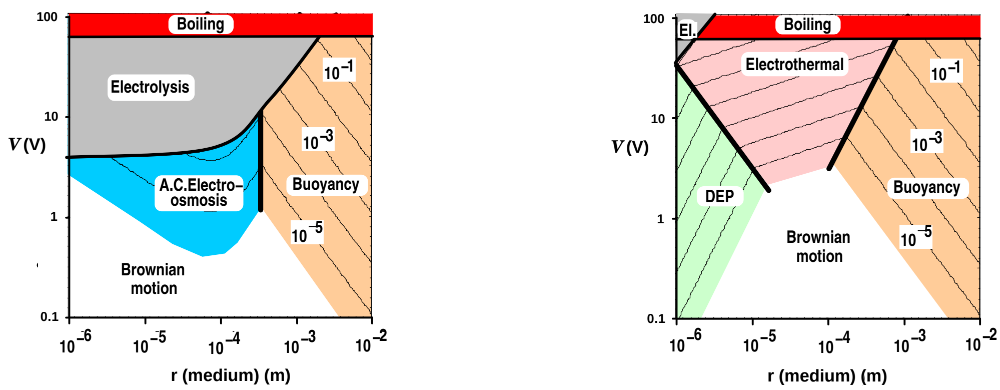

Figure 2. Particle velocity maps in the plane V versus r for a particle with radius $a = 0.25\mu$m in medium with $\sigma = 10^{-1}$S/m: (left) $f = 10^4$ Hz; (right) $f = 10^7$ Hz.

and density $\rho_p = 2 \times 10^3$ Kg/m^3. We assume that 2 volts drop across the double layer is enough to produce electrolysis. Another limit on permissible voltages is given by boiling. The level curves represent the magnitude of the particle velocity (velocities below 0.01 μm/s are considered as dominated by Brownian motion and are represented by a white region in the diagrams). The results indicate that ac electroosmosis dominates fluid motion at low frequencies and small system sizes, electrothermal flow dominates at high frequencies and voltages, and buoyancy at typical system sizes of the order or greater than 1 mm. DEP governs the motion of sub-micrometre particles for small systems and at high frequencies, otherwise, the particle motion is due to fluid drag.

Extending the general results obtained for the 2-D planar electrode to other geometries must be done with care, since in general several different length scales act at the same time. This extension will be illustrated for two cases of practical importance: the hyperbolic polynomial electrode and the castellated electrode.

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