AC Electrokinetic Stirring and Focusing of Nanoparticles

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12.1. INTRODUCTION

Immunoassay-based sensors rely on specific antigen-antibody binding for identification of proteins. These sensors have applications in both clinical laboratories for medical diagnostics, and in research laboratories for highly-multiplexed testing. In these cases, throughput is a key consideration. One factor limiting test duration is diffusion of analyte to the reporter. An incubation step of minutes to hours is required for diffusion-limited reactions to reach detectable levels. These tests are usually performed at centralized labs where high throughput is achieved through robotics and highly parallel assays. However, if the assay could be moved from a centralized lab to the point of care, the test could be much faster, as well as smaller, while maintaining high sensitivity.

In response to this need, microfluidic assays for diagnostics have developed dramatically in recent years. This facilitates the use of the lab-on-a-chip concepts for point-of-care diagnosis, and high throughput screening for molecular diagnostics. The small length scales associated with microfluidic devices permit small sample sizes and shorter assay incubation times. In addition, on-chip sample preparation reduces fluid handling steps. Though greatly aided by their small length scales, these assays can still be diffusion limited. Ac electrokinetic stirring can potentially reduce incubation times, and can be adaptable to a wide variety of assay configurations.
12.2. AC ELECTROKINETIC PHENOMENA

Ac electrokinetics refers to induced particle or fluid motion resulting from externally applied ac electric fields. Dc electrokinetics has been widely successful for lab-on-a-chip applications such as capillary zone electrophoresis (Aclara and Caliper [1, 5], capillary gel electrophoresis for DNA fractionation [19] and electroosmotic pumping [3, 4]. However, ac electrokinetics has received relatively little attention. Ac electrokinetics have the advantages over its dc counterpart by (1) largely avoiding electrolysis, and (2) operating at relatively lower voltages (1 ~ 20 V). Ac electrokinetics can be classified into three broad areas: dielectrophoresis (DEP), electrothermal flow, and AC electro-osmosis [18].

Dielectrophoresis is a force arising from differences in polarizability between the particle and the fluid medium in the presence of a non-uniform electric field. DEP has been used to separate blood cells and to capture DNA molecules [7, 12, 21, 23, 24], provides an overview). However, since the force scales with the cube of particle radius, it has limited effectiveness for manipulating nanoscale molecules (such as 10 nm-scale antigen).

AC Electroosmosis arises when the tangential component of the electric field interacts with a field-induced double layer along a surface. It becomes less important for sufficiently large electric field frequencies. For example, in an aqueous saline solution with an electrical conductivity of $\sigma = 2 \times 10^{-3} \text{ S/m}$, it is predicted that AC electroosmosis is not important above 100 kHz [17].

Transport enhancement for small proteins may be most successful through electrothermally driven flow (ETF). A non-uniform electric field produces non-uniform Joule heating of the fluid, which gives rise to spatial variations in electrical conductivity and permittivity. These variations create electrical charge density variations, even for electrically neutral fluids. The electrical charge density coupled with the applied electric field gives rise to Coulomb body forces in the fluid. The Coulomb body forces induce local fluid stirring. These characteristic swirling flow patterns can be used to transport suspended molecules towards a heterogeneous binding region, or for non-local focusing of particles away from the electrode surface. This can increase the binding rate of immuno-assays, and therefore can improve the response time and overall sensitivity of microfluidic-based sensors.

12.3. DEP: A SYSTEM THEORY APPROACH

If a dielectric particle is suspended in an ac electric field, acting within a dielectric medium, it will polarize. The magnitude and direction of the induced dipole will depend on the frequency and the magnitude of the applied electric field and the dielectric properties of the particle and the medium. A nonhomogeneous electric field acting on the induced dipole in turn produces a force on the dipole, called the dielectrophoretic (DEP) force. Thus, dielectrophoresis is the force exerted on a particle in the presence of a non-uniform electric field [16] (see Fig. 12.1).

To explain this in more detail we describe a systems theory of dielectrophoresis, as developed in Chang et al. 2003. The induced dipole moment, $m(q, t)$, in a particle due to an external electric field, $E(q, t)$, depends linearly on the electric field [6, 10]. This linear