QUANTITATIVE DESIGN AND ANALYSIS OF SINGLE-PARTICLE DIELECTROPHORETIC TRAPS

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Abstract

We present modeling and experiments demonstrating quantitative single-particle trapping using dielectrophoresis-based (DEP-based) particle traps. Using microfabricated thin-film gold quadropole-electrode structures, we have measured the minimum fluid flow needed to dislodge captured polystyrene beads under a given set of conditions. This flow has been compared to predictions made using models we have developed, and found to be in excellent agreement with experimental measurements *with no fitted parameters*. In addition, we have shown the utility of these modeling tools for analyzing arbitrary DEP-based traps. The model can now be used to design general DEP-based traps for microscale analysis systems.

Keywords: dielectrophoresis, single-particle analysis, force measurement

1. Introduction

Dielectrophoresis (DEP) refers to the interaction of non-uniform electric fields with the polarization charge they induce in objects [1,2]. Using a suitable arrangement of generating electrodes, DEP forces can create electromechanical potential energy wells that can trap many types of bioparticles at either electrode edges (positive DEP) or electric-field intensity minima (negative DEP). These traps are an important tool for microscale cell analysis, having been extensively used for cell separations [3,4], trapping/manipulation of micron/submicron particles [5-7], field-flow fractionation [8], and even trapping of single particles [7] and cells [6].

We are interested in applications using large arrays of DEP-based particle traps for the capture and analysis of many individual particles. In these applications it is likely that fluid will be used to deliver and remove particles (perhaps selectively) from the traps. Ultimately, reaching this potential will require a large array of DEP-based single-particle traps, and thus the need for *systematic quantitative analysis* of their efficacy, which we define as their ability to hold a cell against fluid flow.

To this end we have developed a modeling environment that can predict the efficacy of DEP-based single-particle traps using almost arbitrary trap geometries, flow conditions, and experimental conditions. With this tool, we can quantitatively design the traps necessary for our application. In this report we use this modeling environment to predict the holding of plastic beads in planar quadropole electrode structures as verification of the model and show its extensibility by modeling extruded quadropole traps similar to ones recently presented [7].

2. Modeling Environment

A detailed description of the modeling environment is presented elsewhere [9]. In brief, the modeling environment takes as inputs electric field data and experimental parameters and outputs predictions of the strength of the trap, as shown in Figure 1.

The electric field data used as input can be obtained from any field solver, giving good generalizability. This data is used with parameters such as solution conductivity, applied frequency, etc., to initialize the system. The modeling environment then computes forces on
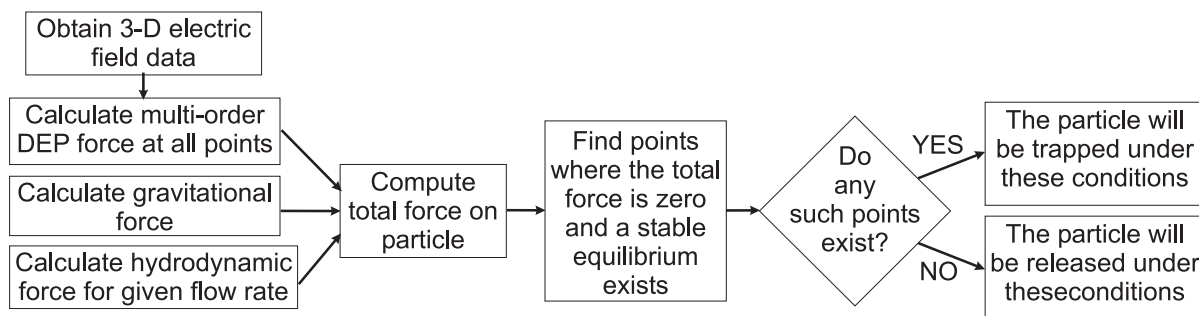
Figure 1: Overview of modeling environment.

the particle in the system in all space, including multipolar DEP forces, hydrodynamic (HD) drag forces, gravitational forces, and rigid substrate bottom boundaries. The multipolar DEP forces are computed using an iterative algorithm that trivializes the ability to calculate arbitrary multipoles, giving us the ability to model complicated non-analytical geometries.

The forces in space are summed to determine where the total forces on the object are zero. Points where these occur that are stable are force minima and represent holding points – where the particle may be found at steady state. The modeling environment varies experimental parameters such as the flowrate to find the threshold flow at which these points cease to exist, which is defined as the release flowrate and can be experimentally measured. These calculations are then repeated as voltage, frequency, or other parameters are varied, giving quantitative predictions of the design space of single-particle traps.

3. Experimental methods

Planar quadropole electrode traps (Figure 2*A*) were microfabricated on standard glass slides using photolithography and lift-off. The electrodes – with 4-μm radii and electrode separations of 32 μm – consisted of 1 μm of gold on top of 200 Å of chrome.

Fluidic inlet and outlet holes were drilled in the slide using a diamond drill (C.R. Laurence, Los Angeles, CA). The slides were packaged by inserting them into a parallel-plate flow chamber where the top surface was a plain glass slide and poly(dimethylsiloxane) was used as the spacer material (7 mm x 730 μm), clamped together by an aluminum bracket (Figure 4*B*). Flow was initiated by a syringe pump (KD-101, KD Scientific, Boston, MA).

Polystyrene beads of 10.00-μm diameter (0.09-μm std. dev.) were purchased from Bangs Laboratories (Fishers, IN). They were washed and re-suspended in stock solutions consisting of Hank's Balanced Salt Solution (GibcoBRL, Grand Island, NY) with DI water and 0.05% Triton X-100 (Sigma, St. Louis, MO) at a conductivity of 0.01 S/m.

Sine-wave electrical excitation (1 MHz for these experiments) was provided by an HP 3314A signal generator (Hewlett-Packard, Palo Alto, CA). The signals were split and inverted by 4 high-speed buffers (LM7171, Analog Devices, Norwood, MA), sent and contacted to the slide via coaxial spring-contact probes (Interconnect Devices, Inc., Kansas City, KS) to the contact pads at the edge of the glass slide.
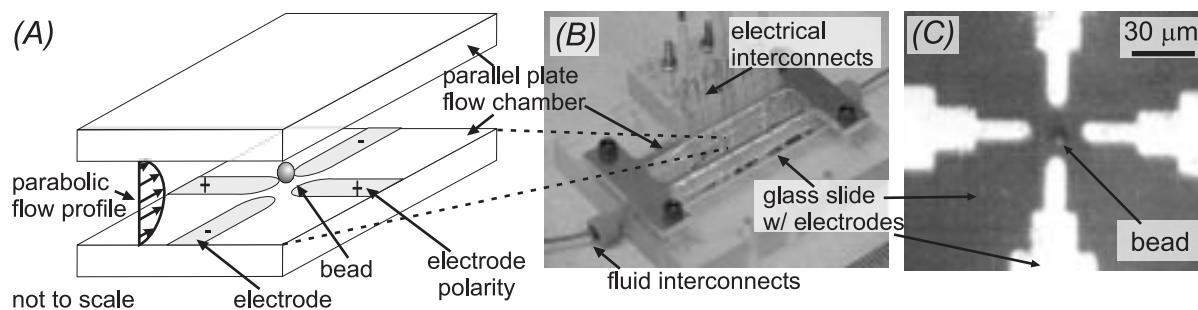
Figure 2: Overview of single-bead experiments. (*A*) Schematic of planar quadropole electrode trap with a particle held in the potential energy minimum at the trap center. (*B*) Close-up of package with flow chamber and glass slide with planar quadropole electrode trap. (*C*) Micrograph of bead trapped in quadropole trap.

4. Results and discussion

Figure 2*C* shows a single 10.00-μm bead held in a DEP trap. As can be seen, we have demonstrated single-particle capture even with these un-optimized traps. When two beads are captured in a trap, the second bead will be held with much less force than the first. We can thus apply a flowrate that will selectively remove the second bead while still holding the first. Further optimization will yield even more precise discrimination.

To evaluate the model, we have predicted how the release flowrate will vary with applied voltage – the holding characteristic. More extensive verifications of the model are provided elsewhere [10]. The results, shown in Figure 3, demonstrate that the model accurately predicts the shape and values of the holding characteristic, even in the absence of fitting parameters.

The behavior of the release flowrate with applied voltage is initially non-intuitive, but becomes apparent when one realizes that the DEP force affects the particle levitation height. Examining Figure 3, three distinct regions can be observed. At low voltages, the upward-directed DEP forces cannot levitate the particle, and thus as the voltage is increased the containment force increases (Figure 3a). At a certain voltage, the upward-directed DEP lift force will exactly counteract the gravitational force and the particle will be levitated. The rapid initial ascent of the particle with voltage (---) causes the drag forces to increase more quickly than the confining forces, and thus the release flowrate decreases (Figure 3b). At higher voltages, the particle height (and thus the drag force for a given flowrate) becomes linear with voltage (Figure 3c, ---). At this point, the contribution to the drag force from particle height increases exactly compensates the increasing DEP confining forces, and the release flowrate levels out and saturates.

There are several implications of these results for such future trap design. First, larger voltages are not necessarily better; optimal holding occurs in our structures at ~0.3V. The best trapping occurs when particles are "deep" in a potential energy well. For these planar quadropole traps, this occurs when the particles are on the substrate or just barely levitated. Second, the particle escape path for these structures is up and over the potential energy well, so preventing this escape path would greatly increase the holding forces.

One way to eliminate this escape path is to use 3D extruded electrode structures, which would give equal holding forces irrespective of levitation height. Such a design, consisting of an extruded quadropole structure, was recently presented in [7]. Using the modeling environment we have the ability to determine whether this design would give better holding than a planar quadropole trap, as expected. We have performed these simulations, and the
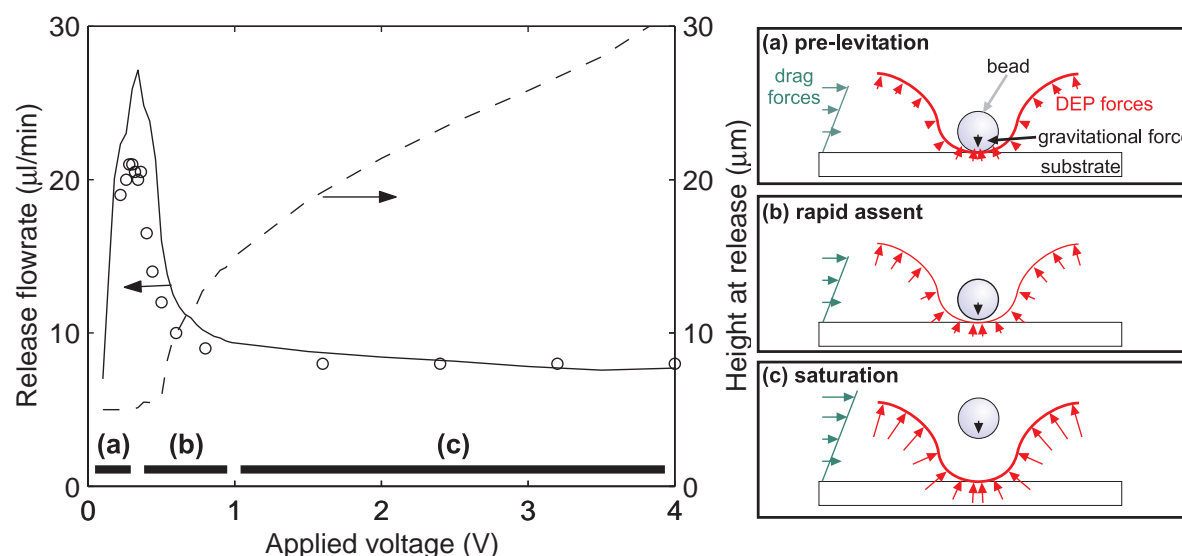
Figure 3: Comparison of experimental (o) and simulated results (—) for a particular electrode geometry. Shown is the release flowrate (—, o) for the planar quadropole trap in Figure 1 as the applied voltage is changed, along with the simulated height (---) of the particle. Three distinct regions can be observed: (a) pre-levitation, (b) rapid assent, and (c) saturation.

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results are shown in Figure 4. As can be seen, the extruded trap can give >100x better holding.

These results demonstrate the usefulness of our approach to designing DEP-based traps. First, we see that the modeling environment is a good predictor of trap efficacy, as evidenced by our remarkable agreement as the voltage is varied (Figure 3). Second, we see that we have the ability to quickly examine other trap geometries and perform comparative analyses. The use of release flowrate as our output variable for both simulations and measurements is advantageous because is many microsystems that *will* be the measure of trap efficacy.
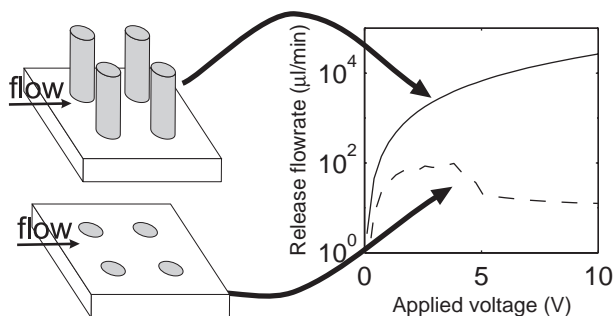
Figure 4: Simulated comparison between planar (---) and extruded (—) quadropole electrode structures. Shown is the release flowrate versus voltage for 10-μm beads in quadropole electrodes with 28 μm center-center separation and 5 μm electrode diameter. The extruded structure is 25 μm high.

5. Conclusions

We have succeeded in making measurements of holding forces on DEP particle traps that are accurately predicted by a model. The results show that for a planar quadropole geometry, traps are most effective at small voltages, and that increasing the voltage past a certain point does not enhance trap strength. The modeling environment used presents an enabling technology for DEP microdevice design and also general microscale cell manipulation systems, as it allows *a priori* design of single-particle traps.

Acknowledgements

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