SEPARATION OF BIOPARTICULATE MATTER USING TRAVELING WAVE DIELECTROPHORESIS

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Abstract
Current biodetection technologies rely upon concentration of airborne bioagents in small volumes of liquid and subsequent detection analysis. The performance of biodetection systems can be significantly improved via sample preconcentration, thereby reducing the demands placed on the detector. Dielectrophoresis-based technologies offer the promise of intelligent particle separation with direct applicability in biodefense. In this paper, we report on design of a traveling wave dielectrophoretic microdevice for bioparticulate separation. The device was conceived and verified using high-fidelity simulational and theoretical analyses. The influence of key parameters such as buffer/particle properties and electrode/channel geometry on device performance was evaluated using multiphysics simulations.

Keywords: Bioparticulates, separation, simulational design, traveling wave dielectrophoresis

1. Introduction
Existing integrated biodetection platforms rely upon sampling and concentration of airborne bioparticulate matter in a small volume of liquid buffer, followed by detection analysis. The overall performance of biodetection systems can be improved significantly via intelligent discrimination of the agent particulates of interest amidst atmospheric clutter. Dielectrophoresis (DEP) is a promising development in bioparticle separations that can be harnessed to achieve particle sorting based on size and/or electrical properties \[1,2\]. DEP has been successfully demonstrated for a variety of biological applications including cell sorting and manipulation \[3\] as well as viral/nanoparticle separations \[4\]. DEP-based devices offer several key benefits over traditional (inertial) methodologies, which render DEP particularly attractive for bioagent separation, including: (1) low power consumption, (2) high viability, high efficiency, high resolution separations, (3) high degree of adaptability for varying threats, and (4) applicability to viruses and toxins. However, large-scale deployment of DEP-based separation technologies to address emergent threat scenarios is hampered by expensive trial and error design development process. Simulation-based analysis coupled with experiments represents a shifting paradigm and provides for a time and cost effective alternative to traditional technology development process. In the present research, we have successfully employed hierarchical design analyses to develop a novel traveling wave dielectrophoretic separator for bioparticulates.
2. Theory

The twDEP separator consists of multiple inlets and outlets to facilitate simultaneous separation of multiple agents while maximizing device adaptability. A series of running electrodes (electrodes laid parallel to flow direction) are present in the first half of the separation chamber as shown in Figure 1. These electrodes may be energized using a direct (DC) or alternating (AC) electric field. The sample from the concentrator/collector is injected through one of the inlets while buffer solution is pumped through the other inlets. The width of the injection port is designed to enable focused delivery of the particulate sample near the microelectrodes. The injection port is maintained at a higher elevation to minimize particle trapping in any convective eddies formed near the electrodes due to electrothermal effects. A traveling wave DEP force is generated in the spanwise direction, which induces differential migration velocities in the particles in the direction of phasor and causes separation.

![Figure 1. Schematic diagram of twDEP separator](image)

First, a theoretical analysis was carried out to establish the feasibility of present twDEP separator design for size-based separation of bioparticles. Scaling arguments suggest that if the electrode spacing is identical to electrode width, the separation time varies as

\[ t \propto \frac{d^4}{d_p^2 V_0^2} \]  

(1)

where \( d \) is electrode width, \( d_p \) is particle size, and \( V_0 \) is the applied (peak-to-peak) voltage. Note that particle migration velocity exhibits a quadratic dependence on particle size. Based on this analysis, a scale down of 10 would result in 10 times faster separation provided that sample throughput and applied voltage are adjusted to maintain residence time and electric field strength.

3. Results and discussion

As a second step in the design development process, physics-guided simulations with variations in system parameters (buffer/particle electrical properties, electrode width/spacing, chamber geometry, etc.) were performed to develop design guidelines for the device. Sample results demonstrating the influence of device scaling on
separation times are shown in Figures 2 and 3. As time progresses, the particles move toward the left due to traveling wave forces. Differential migration velocities result in separation of the particle sample. Note that the time needed for particle separation reduces by a factor of approximately 10 in the miniaturized (10 μm electrode width) configuration. This is in agreement with Eq (1).

Based on design rules developed in the present research, an optimal twDEP separator design was obtained. The final design based on actual device dimensions was verified via high-fidelity simulations using CFD-ACE+ [5]. A fully coupled set of equations for the electric field, fluid flow and particle dynamics were solved. Particle sample (comprising of four sizes; 2, 4, 6, 8 micron) was released into the twDEP separator and particles were tracked subject to fluidic drag, gravity and DEP forces. Particle and buffer properties were taken to be typical of biological matter and deionized water respectively. Simulations were carried out to demonstrate separation in both continuous and batch modes of operation using the current design. Sample simulation snapshots at different time frames are presented in Figure 4. Note that the particles get separated due to twDEP force in the spanwise direction. The velocity field is also observed to be uniform to a large extent, with the influence of the sidewalls confined to small regions. This implies that the design has successfully marginalized non-idealities due to transverse variations, which may influence separation adversely.
4. Conclusions

We have successfully developed and demonstrated a microfabricated, traveling wave dielectrophoresis particle separator for biodetection. A novel virtual prototyping approach was employed for design development in this effort. Approximate design rules were established using theoretical analysis based scaling arguments as well as multiphysics parametric simulations. Optimal design of twDEP separator was verified and demonstrated via high-fidelity simulational analysis. The twDEP separator was demonstrated to achieve particle separation in both batch and continuous modes of operation. Physical prototyping of the optimal design is currently being pursued using state-of-the-art microfabrication techniques and results from experimental testing of the device will be reported in a future communication.

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References