EFFECTS OF ELECTROTHERMAL FLOW ON PARTICLE DEFLECTION AND TRAPPING IN INSULATING (ELECTRODELESS) DIELECTROPHORESIS DEVICES

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ABSTRACT

We present new results quantifying the effects of electrothermal flow on particle deflection and trapping in insulating dielectrophoresis (iDEP) devices with coupled electrical, fluid, and thermal governing equations. Using a numerical approach, we simulate electrothermally-induced flow in polymeric iDEP systems at finite thermal Péclet (Pe_T) number and calculate particle trajectories that include the effects of electrothermal flow, electroosmosis, electrophoresis, and dielectrophoresis. Our results indicate that electrothermal flows become significant at solution conductivities greater than 1 mS/m and electric fields greater than 300 V/cm.

KEYWORDS: Electrothermal flow, Insulating Dielectrophoresis (iDEP)

INTRODUCTION

Electric field nonuniformities in iDEP devices are generated by insulating constrictions in the electric current path (Figure 1). These electric field nonuniformities cause localized Joule heating, which gives rise to a local electrothermal flow that has the potential to confound or enhance the operation of iDEP devices.

THEORY

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We simulate fluid flow with electroosmotic boundary conditions along the channel walls and zero viscous stress boundary conditions at the inlet and outlet. Within the channel we solve the incompressible Navier-Stokes equations with an electrothermal body force term:

$$\rho_m \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \nabla \cdot (\eta \nabla \mathbf{u}) + \mathbf{f}_{ET}$$

where $\rho_m$ is the mass density, $p$ is the pressure, $\eta$ is the temperature-dependent viscosity, and $\mathbf{f}_{ET}$ is the electrothermal body force. The time-averaged electrothermal body force is given in [1] by:

$$\mathbf{f}_{ET} = \frac{1}{2} \mathbf{R} \left( \frac{\sigma_m \nabla \eta_m - \epsilon_m \nabla \sigma_m}{\sigma_m + i \omega \epsilon_m} \cdot \mathbf{E} \right) \mathbf{E} - \frac{1}{4} \mathbf{R} \left[ \mathbf{E} \cdot \mathbf{E} \right] \nabla \epsilon_m$$

where $\sigma_m$ and $\epsilon_m$ are the temperature-dependent medium conductivity and permittivity, respectively, and $\mathbf{E}$ is the time-averaged electric field magnitude. The electrothermal body force is driven by perturbations in the local electric field due to nonuniform permittivity and conductivity.

The resulting fluid flow convects heat away from the channel constriction, where Joule heating is locally high, skewing the temperature distribution downstream. In addition to heat convection, we model heat conduction through 1mm of Zeonor polymer surrounding the channel, as well as conduction and free convection into the air surrounding the device. These heat transfer mechanisms through the device boundaries are linearized (with less than 2% error in the temperature distribution) using a heat transfer coefficient at the wall:

$$q = \frac{k_T}{l} \xi (T - T_0)$$

where $q$ is the time-average heat transfer through the channel boundary, $k_T$ is the thermal conductivity of Zeonor, $l$ is the thickness of the device, $T_0$ is the room temperature, and $\xi$ is the linearized heat transfer coefficient. Fluid temperature at the channel inlet is assumed to be at $T_0$ and heat is convected via fluid flow at the outlet. The temperature distribution within the channel is the result of Joule heating and heat convection:

$$\rho_m C_p \mathbf{u} \cdot \nabla T = k_m \nabla^2 T + \sigma_m \mathbf{E} \cdot \mathbf{E}$$

where $C_p$ and $k_m$ are the temperature-dependent specific heat and thermal conductivity of the media, respectively.

The electric field drives fluid electroosmosis (u_{wall} = (\epsilon_m \xi_{wall} / \eta)E), particle electrophoresis (u_{EP} = (\epsilon_m \xi_{particle} / \eta)E), and particle dielectrophoresis.

Figure 1: Simulation domain showing channel constriction and mesh. Mesh resolution is highest along channel boundaries and in the constriction region. Total number of mesh elements is >100,000.
The electric field boundary conditions specify a potential between the inlet and outlet and electrical insulation (zero normal current) at the channel walls. Subject to these boundary conditions, Gauss's Law and charge conservation are solved within the channel domain.

These equations are solved using COMSOL multiphysics software to simulate parametric variations in channel geometry, fluid properties, and electric field parameters from a datum state. The simulated channel geometry is characterized by a constriction aspect ratio, \( r \): the ratio of bulk channel depth to constriction channel depth. The applied electric field contains both DC and AC components and is characterized by \( \alpha \), the ratio of the peak AC potential magnitude to the DC potential (constant, 10V). Additional parameters used in the simulations presented here are \( \zeta_{\text{wall}} = -40\text{mV}, \zeta_{\text{particle}} = -60\text{mV} \), and \( a = 0.5\mu\text{m} \). \( \zeta_{p}, k_{m}, \sigma_{m}, \eta, \) and \( \varepsilon_{m} \) are temperature-dependent and specified in [5].

We quantify the effects of electrothermal flow by conducting parametric simulations over device geometry via the constriction ratio, \( r \), and the AC-to-DC ratio, \( \alpha \), and calculating particle trajectories. Deflection, \( d \), and trapping are the two most common modes of operation for iDEP devices, where particles are deflected transverse to fluid streamlines by DEP forces near a constriction [2] or trapped between fluid drag and negative DEP forces [3,4], respectively. Particle trajectories were calculated using fluid drag (from electroosmotic and electrothermal flows), particle electrophoresis, and particle dielectrophoresis forces.

**RESULTS AND DISCUSSION**

The results of our simulations show that electrothermal effects are significant at lower aspect ratios and higher solution conductivities. The results of our simulations show that particle deflection is enhanced by electrothermal flow when the device aspect ratio is below 6.7 and \( \alpha \) is greater than 25 (Figure 2). At low aspect ratios and high values of \( \alpha \), electrothermal body forces dominate electroosmotic fluid flow. As the device aspect ratio increases, the electric field within the constriction region increases. The local electric field determines the magnitude of both Joule heating and the electroosmotic boundary condition. For device aspect ratios above 10 (with \( \sigma_{m} = 1\text{mS/m} \) and \( \alpha = 40 \)), shear within the constriction region dominates the increases in local temperature gradients and prevents electrothermal recirculation (Figure 3). The percent difference in particle deflection due to electrothermal body forces therefore decreases as the constriction ratio increases (Figure 2, center).

Increasing solution conductivity increases Joule heating within the channel according to equation (4). However, this increase does not result in significant changes to particle deflection (Figure 4, left) until electrothermal forces begin to...

**Figure 2:** (left) Particle deflection, \( d \), due to nDEP and electrothermal flow as a function of constriction ratio. Both \( \alpha \) and \( r \) influence particle deflection. (center) The percent difference between particle deflection with and without the electrothermal body force term. Electrothermal effects are mostly independent of constriction ratio, but increase with increasing \( \alpha \). (right) The AC-to-DC ratio at trapping is a strong function of constriction ratio. The upper (blue) line neglects electrothermal body forces while the lower (red) line includes them. Electrothermal flow is significant at lower constriction ratios where high values of \( \alpha \) are required to trap particles.

**Figure 3:** The competing effects of electrothermal flow and electroosmosis give rise to decreasing electrothermal effects as the constriction ratio increases. At low constriction ratio, electrothermal forces give rise to regions of recirculation near the constriction corners and displaced, counter-rotating recirculation further from the constriction. At higher constriction ratios, the local electric field is higher, leading to a dominant electroosmotic boundary condition which obscures the increase in electrothermal flow due to Joule heating induced temperature gradients. With the exception of constriction ratio, simulation parameters are identical: \( \sigma_{m} = 1\text{mS/m} \) and \( \alpha = 40 \). Background color table is logarithmic and denotes temperature gradients. Maximum values (3.2e4K/m, top; 4.6e4K/m, bottom) are grouped with the highest contour for clarity.
Electrothermal effects increase with increasing conductivity (Figure 4, center) and become significant for solution conductivities below 1 mS/m for the conditions simulated here. Particle trapping results (Figure 4, right) are consistent with these results. The value of \( \alpha \) at trapping is identical for simulations with and without the electrothermal body force, diverging only as \( \sigma_m \) exceeds 1 mS/m and \( \alpha > 20 \). At this point electrothermal effects become significant and serve to decrease the trapping value of \( \alpha \), thereby enhancing nDEP effects. The upper (blue) line neglects electrothermal body forces while the lower (red) line includes them.

CONCLUDING REMARKS

This work has numerically investigated the effects of electrothermal flow on particle trajectories in a polymeric iDEP device at finite thermal Péclet number as a function of channel geometry \( (r) \), electric field parameters \( (\alpha) \), and solution conductivity \( (\sigma_m) \). The results show that heat convection contributes to the temperature distribution and temperature gradients responsible for electrothermal flows. We found that particle deflection and trapping are strong functions of the device aspect ratio, \( r \), and independent of solution conductivity below a threshold value of \( \sigma_m \), above which, the electrothermal body force significantly perturbs the flow. The electrothermal body force becomes significant as \( \sigma_m \) exceeds 1 mS/m and \( \alpha > 20 \), but can be attenuated at higher constriction ratios due to the increasing electroosmotic boundary conditions and local shear within the constriction region.

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REFERENCES


