JOULE HEATING EFFECTS ON INSULATOR-BASED DIELECTROPHORESIS
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ABSTRACT
We present an experimental and numerical study of Joule heating in a polymeric insulator-based dielectrophoresis (iDEP) device. In this study, we used a microscale thermometry technique based upon the temperature-sensitive fluorescence of Rhodamine B dye to monitor the fluid temperature within our iDEP microfluidic devices. We then complemented our experiments with 3D finite element simulations of the fluid flow, electric field and heat transport to analyze the temperature distributions in the fluid and polymer regions. Our investigation reveals that Joule heating has a significant impact on the fluid and particle behavior within iDEP devices.

KEYWORDS: Joule heating, dielectrophoresis, numerical modeling, separation

INTRODUCTION
In insulator-based dielectrophoresis (iDEP), insulated structures are introduced in a microchannel (Figure 1a) to produce non-uniform electric fields which can be used to filter microbes [1]. Selective iDEP-based separation of microbes has been shown previously in glass-based devices [2]; however, polymeric devices are preferred for water analysis and filtration due to their lower cost and disposability [3]. We have observed differences in trapping behavior and particle motion between cyclic olefin copolymer (Zeonor 1060R) and glass devices, especially at high flow-rates (>60µL/min). We note that Joule heating is a likely cause of these discrepancies, since the low thermal conductivities of plastic devices lead to increased channel temperatures.

Figure 1. (a) Schematic of iDEP microfluidic device (iDEP). (b-c) Temperature distribution in the iDEP device for 20 µL/min flow of tap water (σ = 90 µs/cm). (b) before 1500V pulse, (c) after 15s pulse. (Flow is left to right).

EXPERIMENTAL
To monitor the fluid temperature distribution within our iDEP microfluidic devices, we used an optical thermometry technique based upon the temperature-sensitive fluorescence of Rhodamine B dye [4]. First, a calibration curve was generated using a temperature-controlled fluorometer to accurately measure the dependence of Rhodamine B fluorescence on temperature in drinking water. Fluid tempera-
ture profiles were then extracted by converting intensity values to temperature using the calibration curve and image processing (Figure 1b, c). We then performed a parametric study to investigate the influence of voltage (over the range 500 to 1500V), flow-rate (10 to 60 µL/min), and conductivity (60-150µs/cm). Figure 2 shows select results from this study. These experiments reveal that higher flow-rates reduce the amount of Joule heating in the polymeric iDEP devices (Figure 2c). The increase in current (Figure 2b) is due to the increase in electrical conductivity of water which has a significant dependence on temperature primarily through viscosity (which decreases approximately changes 2% per degree) [6].

**Figure 2.** (a) Down-stream temperature distribution (b) temporal current in the iDEP device as a function of flow rate for ultra-filtrated (UF) water (σ = 105 µs/cm) where 1250V pulse was applied for the period of t=5s till t=20s.

**THEORY**

The dielectrophoretic induced particle velocity [5] is given by the product of the gradient of the electric field squared, \( \nabla (E \cdot E) \), with the dielectrophoretic mobility (\( \nu_{DEP} \)):

\[
\nu_{DEP} = (\varepsilon_m r^2 / 3\mu)(\varepsilon_p - \varepsilon_m / \varepsilon_p + 2\varepsilon_m)
\]

Since conductivity and viscosity change with temperature, both the electric field and dielectrophoretic mobility must change when voltage is applied. We used 3D finite element simulations of the fluid flow and heat transport to describe the temperature distributions within the fluid and plastic regions (Figure 3a). It is observed that heat is generated primarily at the post array and simultaneously conducted through the plastic and convected down-stream (Figure 3b).

**Figure 3.** Three-dimensional simulation of joule heating in the iDEP zeonor chip. Temperature distribution and streamlines are shown (b) Temperature distribution for upstream and down-stream for 10 µL/min flow of UF water (σ = 105 µs/cm) for 1500V pulse.
RESULTS AND DISCUSSION

As noted in the Theory section, Joule heating has a significant effect on the electric field and dielectrophoretic force on particles, and thus on microbe trapping in iDEP devices. Experiments run at high conductivity and electric fields produced non-regular motion and failed to trap. We attribute the irregular motion to Joule heating causing a reduction of the trapping force and introducing complex 3D electric fields (Figure 4). These results reveal that there is a tradeoff between the efficiency of iDEP filtration and its throughput; operating at higher flowrate makes it harder for the iDEP force to overcome the fluid drag.

CONCLUSIONS

In summary, Joule heating effects in iDEP polymeric devices is characterized using thermometry experiments and numerical modeling. We show good agreement between experiments and simulations, which represents a first step towards a validated simulation that will be a useful design tool for optimizing iDEP devices. We also observe that Joule heating creates an asymmetric temperature distribution that disturbs the distribution of electric field and electrokinetic forces. Our future work will include a theoretical analysis and detailed numerical study of electrokinetic forces in presence of Joule heating.

ACKNOWLEDGEMENT

This work was performed by Sandia National Laboratories for the US Dept. of Energy, contract DE-AC04-94AL85000.

REFERENCES