Micropumping of biofluids by alternating current electrothermal effects

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Electrokinetics is a preferred technique for microfluidic systems, but it is typically applied on fluids that are not too conductive (lower than 0.02 S/m), which excludes most biological applications. To solve this problem, this letter investigates microfluidic actuation by ac electrothermal (ACET) effect that was largely overlooked by the community. ACET originates from temperature gradients in the fluids, and it becomes more pronounced in more conductive fluids. This letter discusses two ACET pump designs, and pumping was demonstrated with biobuffers (e.g., lysogeny broth at 0.754 S/m). © 2007 American Institute of Physics [DOI: 10.1063/1.2746413]

Recent years have witnessed many advances in microfluidics and micrototal analysis systems, however, effective micropumping and mixing still remain a challenge. Due to high surface/volume ratio at microscale, conventional pressure-driven flow becomes inefficient. Additionally, micromechanical pumps are difficult to fabricate and almost unusable if the fluid contains particles. As an alternative, electrokinetics has attracted much interest for microfluidic actuation. Electrokinetics involves no moving part, so it is easy to fabricate, unsusceptible to particulate contamination and compatible with microsystem integration.

Traditional electrokinetic pumps apply high dc voltage across the microchannel, with side effects of bubble generation and pH gradients from electrochemical reactions. To minimize these adverse effects, low voltage pumping by ac electro-osmosis (EO) has been studied in recent years. Ac EO induces mobile charges at the interfaces of fluid/electrode, and the charges move along the electrical fields tangential to the electrodes to produce microflows. Since the induced charges and the electric field switch polarities simultaneously, the flow directions are sustained over the voltage cycles.

However, electro-osmotic pumping is not effective at high fluid conductivity. The layer of induced mobile charges becomes greatly compressed at high conductivity and loses its drag on fluid. The highest fluid conductivity to sustain EO flow was reported as 84 mS/m. Unfortunately, biochemical analysis frequently involves samples with conductivities higher than that. So it is highly desirable to develop an electrokinetic technique suitable for conductive fluids. Here we report a type of micropumps by ac electrothermal (ACET) effect. Pumping was demonstrated at low voltages (<15 Vrms) for fluid conductivity of 0.02–1 S/m with fluid velocity of 100–1000 µm/s.

When an electric field $E_{rms}$ is applied over a fluid body, energy is dissipated within by $\langle P \rangle = \alpha E_{rms}^2$ ($\alpha$: electrolyte conductivity). Nonuniform electric field will lead to nonuniform temperature rise, i.e., temperature gradient $\nabla T$, which will produce gradients in conductivity and permittivity as $\nabla \varepsilon = (\partial \varepsilon / \partial T) \nabla T$, $\nabla \sigma = (\partial \sigma / \partial T) \nabla T$. In turn, $\nabla \sigma$ and $\nabla \varepsilon$ generate mobile space charge $\rho$ in the fluid bulk, by $\partial \rho / \partial t + \nabla \cdot (\sigma \varepsilon \nabla) = 0$ and $\rho = \nabla \cdot (\sigma \varepsilon) = \nabla \varepsilon \cdot E + \varepsilon \nabla \cdot E$. The induced space charge can be expressed as $\rho = (\sigma / \partial t) \nabla \cdot (\sigma / \partial T)/(\sigma + i \omega \varepsilon) \cdot E$ by invoking $\partial / \partial t = i \omega$ in ac fields. It can be deduced that the induced charges will change their polarities with electric field $E$.

As a result of fluid nonuniformity, electric fields can exert body force $f_E$ on fluids as $f_E = \rho E - \frac{1}{2} \varepsilon E^2 \nabla \varepsilon$, i.e., $f_E = (\sigma / \partial t - \sigma \nabla \cdot (\sigma / \partial T))/(\sigma + i \omega \varepsilon) \cdot E - \frac{1}{2} \varepsilon E^2 \nabla \varepsilon$.

For aqueous solutions, $f_E = (0.009 - 0.002 \cdot E^2) \nabla T$ with $f_E = -0.022 \cdot E^2 \nabla T$ for $\omega \ll \sigma / \varepsilon$ and $f_E = 0.002 \cdot E^2 \nabla T$ for $\omega \gg \sigma / \varepsilon$. Representative values of water are $\sigma = 20$ mS/m and $\varepsilon = 80$, $\sigma / \varepsilon \approx 28$ MHz. So for a typical electrokinetic device, low frequency approximation should be used, and the fluid force arises predominately from the interactions of induced space charges and electric fields, i.e., $f_E = \rho E$. Fluid force $f_E$ gives rise to fluid motion as $\rho \mathbf{u} / dt = -\nabla p + \eta \nabla^2 \mathbf{u} + f_E$ ($\rho_m$: mass density; $\eta$: fluid viscosity; $\mathbf{u}$: fluid velocity), and order-of-magnitude estimation finds fluid velocity $\mathbf{u} = (f_E l / \eta)^{1/2}$, where $l$ is the characteristic length of the device, typically on the order of electrode spacing. Therefore, flows are induced through nonuniform Joule heating, i.e., electrothermal effect. With ac signals, electric fields and the induced charges change polarity simultaneously so that flow directions can be sustained.

The earliest electrothermal micropumps were reported in 1990s by Fuhr et al. at low fluid conductivity (~0.009 S/m), while biochemical analysis routinely encounters fluid conductivity >0.1 S/m. Recently, ACET effect was used to induce vortices within a pressure-driven flow-through system (<0.6 S/m), improving binding rate of antigen antibody. Pumping of conductive fluids by ACET effect alone is yet to be developed.

ACET as a fluid body force subjects to non-slip boundary condition. Too small a hydraulic diameter will inhibit ACET flows, which might have hindered the development of miniaturized ACET devices. Fluid conductivity is another consideration. Heat generation may not be sufficient at low conductivity, so external source is needed. However, at high conductivity, excessive temperature rise tends to happen and buoyancy force will dominate over ACET effect. With the buoyancy force as $f_B = g \Delta \rho g \partial (\partial \rho / \partial T) \Delta T$, the ratio of ACET to buoyancy force can be approximately given as $f_E / f_B = 7.95 \times 10^{-12} (\nabla T / \Delta T) E_{rms}^2$ for aqueous solutions. So high $\nabla T / \Delta T$ is critical to induce ACET effect. This letter...
presents two designs of ACET micropumps that require only electricity to operate. Electrodes with good thermal conductivity ensure high \( \nabla T/\Delta T \). Pumping was demonstrated with biobuffers such as lysogeny broth medium at 0.754 S/m, and minimal salts medium (MSM) at 0.145 S/m.

ACET pumping can be produced using a pair of electrodes of unequal width. The side view of such an electrode pair is shown in Fig. 1, along with FEMLAB® simulation results. The electrodes on the channel bottom function as a source of heat and electric fields. Because electric fields are stronger around the electrodes than in the bulk, more heat is generated there. With the electrodes acting as heat sinks (fixed at room temperature), maximal thermal gradient \( \nabla T \) occurs close to the electrodes. Hence, the induced charge density is the highest close to the electrodes, where \( E \) is also the highest. Consequently, ACET force near the electrodes defines the flow field. For the asymmetric electrodes in Fig. 1, the fluid above the both electrodes experiences similar \( \nabla T \) (hence similar \( \rho \)), and the flow spends more time over the wider electrode, so a net flow is generated and its direction is determined by that over the wider electrode.

For experiments, Au/Ti (100/5 nm) electrode arrays were evaporated on silicon substrate, patterned by lift-off into 100/180 \( \mu \)m width with 20 \( \mu \)m gap at 400 \( \mu \)m pitch. Polymer microchannel of 0.5 mm \((H)\times3 \) mm \((W)\) was sealed over the electrodes. Fluids of 0.02–0.78 S/m were used and were seeded with 500 nm fluorescent particles to trace microflows. Pumping was observed when applying 4.2–8.2 V\( \text{rms} \) at 200 kHz. The volume flow rate for \( \sigma = 0.224 \) S/m is \( \sim 150 \) nL/s at 7 V\( \text{rms} \) for our channel cross section. The flow rate can be easily scaled up with wider channels.

ACET velocity is proportional to \( E^2 \nabla T \). \n\n\( \nabla T \) can be induced externally or by electric conduction in fluid. If electric field alone is used to generate \( \nabla T \) and \( \nabla T \approx E^2 \), then \( u \approx E^3 \). Figure 2 gives the dependence of fluid velocity on \( E \) extracted by both experiment and simulation for fluid \( \sigma = 0.224 \) S/m, which fits well with \( u \approx E^3 \). Fluid velocity was observed to increase with the conductivity, which is expected as energy dissipation \( (P) = \sigma E^2 \text{rms} \).

Forces other than ACET can affect the velocity of tracer particles. Of particular concern is dielectrophoresis (DEP). Order of magnitude estimation shows that 500 nm particles will exhibit 0.11 \( \mu \)m/s DEP velocity when they are 10 \( \mu \)m from the electrode edge at 5 V\( \text{rms} \). Since ACET velocity often exceeds 100 \( \mu \)m/s, DEP velocity can be neglected in the analysis. Asymmetric electrode arrays were previously reported for micropumping, but the mechanism was ac electro-osmosis with the fluid conductivity limited to below 90 mS/m. Our ACET experiments used conductive fluids up to 0.75 S/m and operated at high frequency (>100 kHz) to avoid electrolysis that is prone to happen at such high conductivity.

Capitalizing on the nonuniformity in electric and thermal fields, another electrode design with a higher degree of asymmetry was studied, i.e., pin-line “T” configuration, as shown in Fig. 3. The fluid moved from the back of the pin toward its tip and over the transversal electrode, forming longitudinal flows. At the pin tip, the flow rates exceeded 1 mm/s at 14 V\( \text{rms} \), \((E = 2.8 \times 10^4 \text{ V}\text{rms}/\text{m})\) for \( \sigma = 0.21 \) S/m, about ten times higher than the first design. Numerical simulation (Fig. 4) further corroborates ACET as the pumping mechanism. Here the electrodes assume thermal
continuity except at the sides where room temperature is applied. The highest $\nabla T$ and $\rho$ occur between the transverse electrode and the tip, while other area around the pin has the highest $\Delta T$ but not $\nabla T$. Consequently, the fluid field was dominated by the flows going over the transversal electrode. This design achieves unidirectional flow solely through geometric asymmetry, and the coupling between adjacent electrode pairs still produces flows in the same direction. High efficiency pumping is expected for T array and is currently under development.

In summary, this letter presents a micropumping mechanism by ACET. Two pump designs were discussed and demonstrated. ACET expands the capability of electrokinetics to conductive fluids, and further exploitation is expected to generate a variety of techniques for effective manipulation of biofluids.

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