Electroosmotic flow with Joule heating effects

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Electroosmotic flow with Joule heating effects was examined numerically and experimentally in this work. We used a fluorescence-based thermometry technique to measure the liquid temperature variation caused by Joule heating along a microcapillary. We used a caged-fluorescent dye-based microfluidic visualization technique to measure the electroosmotic velocity profile along the capillary. Sharp temperature drops close to the two ends and a high-temperature plateau in the middle of the capillary were observed. Correspondingly, concave-convex-concave velocity profiles were observed in the inlet-middle-outlet regions of a homogeneous capillary. These velocity perturbations were due to the induced pressure gradients resulting from axial variations of temperature. The measured liquid temperature distribution and the electroosmotic velocity profile along the capillary agree well with the predictions of a theoretical model developed in this paper.

Introduction

Microfluidic and lab-on-a-chip devices have attracted increasing interest over the last decade.1–4 These integrated, miniaturized devices offer many advantages over conventional laboratory bench-top analytical instruments, such as increased efficiency, throughput, portability, and reduced analysis time, reagent consumption, and cost.5–8 Generally, an electric field is often applied to induce electroosmotic flow of liquids and electrophoretic motion of particles in microfluidic devices. In comparison with conventional pressure-driven flow, electroosmotic flow is much simpler (no moving parts) and possesses a plug-like velocity profile (all variations are restricted to the thin electrical double layer region adjacent to the channel wall) resulting in less solute dispersion.7

While electrokinetic means have great advantages in the flow control and species transport in microfluidic devices, there exists inevitable Joule heating in the liquid when an axial electrical field is applied to bring about the electrokinetic flow. This internal heat source can lead to significant increase and non-uniformity in the liquid temperature.8–13 The electrical field and the flow field are therefore strongly affected via temperature dependent electrical conductivity and viscosity of the liquid.14–16 In the absence of Joule heating effects, the electroosmotic velocity profile is plug-like only in a homogeneous microchannel.17–21 In heterogeneous microchannel systems,22–24 however, the non-plug-like electroosmotic flow25–28 or multidirectional flow or recirculating flow appears.29–33 In addition, the applied electrical fields in the intersections of many microchannel networks are not uniform and can result in complicated local electroosmotic flow fields.34–40

The temperature effects due to Joule heating on the reduction in the electrophoretic separation efficiency have been investigated extensively.11–13 The temperature effects on electroosmotic flow, however, was not addressed until recently. Li and his colleagues14–16 argued that Joule heating effects on the electric field, the temperature field and the flow field in the microchannel should be considered simultaneously via temperature dependent electrical conductivity, thermal conductivity and viscosity of the liquid. In the absence of thermal end effects, Xuan and Li16 derived an analytical formula for the electroosmotic flow considering only the radial temperature profile in a capillary. It was demonstrated that the electroosmotic velocity profile remains plug-like except in the thin electrical double layer region, despite that the magnitude of velocity is increased due to the drop of liquid viscosity. Erickson, Sinton and Li15 examined Joule heating and heat transfer in a T-shaped microchannel intersection in poly(dimethylsiloxane) (PDMS) microfluidic systems, and experimentally observed dramatic temperature gradients as predicted by their “whole-chip” simulation. While these authors numerically computed the flow field within the intersection and predicted a significant increase of flow rate due to Joule heating effects, the profile of electroosmotic flow in the whole channel (i.e., from inlet to outlet) is still unknown.

Xuan, Sinton and Li16 conducted a comprehensive numerical simulation of the electroosmotic flow in a complete capillary with the consideration of the Joule heating and thermal end effects. A non-uniform electric field along the capillary was revealed for the first time. These authors predicted a slightly convex cross-stream velocity profile except in the regions near the capillary ends where concave profiles were found. They noted that these velocity gradients were induced by the axial temperature variations via temperature dependent liquid viscosity.

In this work we show that Joule heating effects can also induce perturbations to the electroosmotic velocity profiles in a homogeneous capillary. We applied recently developed fluorescence-based thermometry and velocimetry techniques, which will be explained in the experimental section, to measure the liquid temperature and the electroosmotic velocity, respectively, at several different points along a homogeneous capillary. A theoretical model was also developed to simulate the temperature field, electric field and flow field in the whole capillary system. The comparison between experimental results and numerical predictions are made.

Theory

Consider the electroosmotic flow in a glass capillary that is suspended in the air and supported at the two ends by two liquid reservoirs. The set of equations governing the temperature, electric potential and flow fields with the consideration of the Joule heating effects are summarized below in this section.

Temperature field

As an axial electrical field is applied to induce the electroosmotic flow in a capillary, the electric current passing through the buffer solution results in Joule heat. This Joule heat is then con-
of the capillary were the edges of the liquid domain. The potentials at the inlet and the outlet are dependent liquid viscosity. The net charge density where \( \sigma(T) \) and the solution of the electrical double layer potential field vanish in the solid domain because there is neither liquid flow nor electric current in the capillary wall. The whole capillary system is initially at equilibrium with the ambient temperature \( T_0 \). We imposed isothermal conditions at both ends of the capillary, a symmetric condition with respect to the axis, and a convective boundary condition surrounding the capillary with a heat transfer coefficient \( h \). Although both reservoirs, particularly the downstream reservoir, receive heat from the liquid flowing in the capillary, this heat contribution is negligible as the reservoir volumes are of the order of microlitres.

**Electric field**

Due to the temperature dependence of liquid conductivity \( \sigma(T) \), the electric field \( \mathbf{E} = -\nabla \phi \) becomes non-uniform along the capillary, where the externally applied electric potential \( \phi \) is determined by

\[
\nabla \cdot [\sigma(T) \nabla \phi] = 0
\]

In solving for \( \phi \), insulation conditions were imposed along the edges of the liquid domain. The potentials at the inlet and the outlet of the capillary were \( E_D \), and 0, respectively, where \( E_D \) represents the externally applied electric field and \( L \) is the length of the capillary.

**Flow field**

Since electroosmotic flows are generally restricted to the range of small Reynolds numbers, the inertia terms in the Navier–Stokes equations can be ignored and thus the liquid motion is governed by the Stokes and the continuity equations,

\[
0 = -\nabla p + \nabla \cdot \mu(T) \nabla \mathbf{u} + \mathbf{p} \cdot \mathbf{E} \quad \nabla \cdot \mathbf{u} = 0
\]

where \( p \) is the hydrodynamic pressure, \( \mu(T) \) the temperature dependent liquid viscosity. The net charge density \( \rho \), formed by the electrical double layer is zero except in the thin electrical double layer region adjacent to the capillary wall (the characteristic thickness is on the order of nanometers). Therefore, we applied a slip boundary condition \( U_{wall} = -\varepsilon(T) \varepsilon_0 E_z/\mu(T) \) at the capillary wall, dropped the electrical force term (the last term on the RHS) in eqn. (3) and the solution of the electrical double layer potential field was thus avoided.\(^{32,41} \) In the definition of \( U_{wall} \), \( \varepsilon(T) \) denotes the temperature dependent dielectric constant of the liquid, \( \varepsilon_0 \) the permittivity of the vacuum, \( \varepsilon \) the zeta potential of the capillary wall, and \( E_z \) the axial component of the local electrical field \( \mathbf{E} \). Other boundary conditions for the flow field include fully developed velocity profiles at the ends of the capillary and a symmetric condition with respect to the axis.

\( \dagger \) In practice, the Joule heat generated inside the liquid is transferred to the surroundings through both convection and radiation if the main body of the capillary is kept out of contact with the supporting stage. However, the radiation counts only a small part of the total heat dissipation. Therefore, we neglected the heat radiation and simply assumed a free-air convection around the capillary in this paper.

\( \ddagger \) Reynolds number in a cylindrical tube is defined as \( Re = \rho UR/\mu \) where \( \mu \) is the dynamic viscosity, \( U \) the characteristic liquid velocity and \( R \) the internal radius of the tube. In typical electroosmotic flows \( Re \ll 1 \).

**Numerical method**

The above coupled field equations were solved through the finite element method using an in-house written code. We employed 6-noded quadratic triangle elements for the electric potential, velocity and temperature, and 3-noded linear triangle elements for the pressure. A non-uniform grid along the axial direction was generated with grid refinement in the regions near the capillary inlet and outlet. At each time step (step size is 0.5 s), we used properties evaluated with the last temperature field (initially at room temperature) to determine in turn the potential field, wall slip velocity and flow field. Then, known values of potential and velocity fields were used to solve for the new temperature field at the current time step. These steps were repeated until the time designated by the user.

**Experimental**

A variety of experimental techniques have been developed to measure the liquid temperature inside microfluidic systems, such as backscatter interferometry,\(^{42} \) nuclear magnetic resonance (NMR),\(^{39} \) Raman spectroscopy,\(^{44} \) and temperature sensitive probes (e.g., thermochromic liquid crystal,\(^{45} \) fluorescent dye\(^{46} \) etc.). Temperature sensitive rhodamine B dye was used in our temperature experiment. In this microscale thermometry technique, rhodamine B’s fluorescence intensity is measured and its relative variation is then converted into the liquid temperature using the calibrated intensity vs. temperature relationship.\(^{15,46} \) As for the measurement of electroosmotic velocity in microchannels, micrometer-resolution particle image velocimetry,\(^{47,48} \) particle tracking velocimetry,\(^{49} \) and caged-fluorescence flow visualization\(^{50-52} \) have been recently proposed. We employed caged fluorescein dyes to realize the flow visualization in a capillary. In this microfluidic velocimetry technique, the transport of a sheet of fluorescein dyes photo-injected by a pulse of ultraviolet light is imaged onto a CCD camera. Then, the liquid velocity profile is calculated from the positions of the maximum concentration of the dyes as a function of time.\(^{33,54} \)

**Chemicals and materials**

Sage grade rhodamine B dye (Acros Organics, Pittsburgh, PA) was initially dissolved in pure water (Fisher Scientific Canada, Ottawa, ON) at a concentration of 1 mM and stored at –30 °C. Prior to the temperature measurements, the dye was further diluted to 50 μM in 25 mM sodium carbonate buffer solution at pH 8.5. For the velocity measurements, fluorescein bis-(5-carboxymethoxy 2-nitrobenzyl) ether dipotassium salt (CMNB-caged fluorescein) was used as supplied by Molecular Probes (Eugene, OR). Stock solutions of caged dye (3 mM in pure water stored at –30 °C) were diluted to 1.5 mM in 25 mM carbonate buffer before the experiment. All solutions were filtered before use with 0.2 μm syringe filters (Whatman, Fisher Scientific Canada, Ottawa, ON).

**Capillary flow system**

The external polyimide coating of a 10 cm long fused-silica capillary (Polyimicro Technologies Inc., Phoenix, AZ) was oxidized and totally removed to make it transparent to both ultraviolet and visible lights. The inner and outer diameters of the bare capillary are 200 μm and 320 μm, respectively. In order to make the heat transfer conditions uniform around the whole capillary, an assembly of poly(dimethylsiloxane) (PDMS)–glass reservoirs was custom designed, in which the capillary was suspended only at the two ends by the reservoirs such that the condition of free air convection was realized. Prior to experiments, the capillary was rinsed with pure water, base (1 M NaOH) and pure water in order, followed by filtered buffer. For the velocity measurements, the capillary and the upstream reservoir were filled with the solution of caged fluorescein dye, and the downstream reservoir contained only pure buffer. For the temperature measurements, however, both...
the capillary and the two reservoirs were filled with the solution of rhodamine B dye. Two platinum electrodes were placed in the solution in each of the reservoirs, and connected to a high-voltage DC power source (CZE1000R, Spellman, Hauppauge, NY). At each end there was around 5 mm long capillary in contact with the solution. Hence, the effective length of the capillary surrounded by air is 9 cm. The whole capillary flow system was mounted on a three-axis translation stage, so that the thermal and fluidic behaviors at several different points along the capillary could be investigated through adjusting the stage.

Imaging acquisition

The details of the experimental setup have been described elsewhere. Uncaging of the caged fluorescein dye was performed with a pulse of ultraviolet light (provided by a pulsed nitrogen laser, 337 nm, pulse energy 300 µJ, pulse width < 4 ns, Laser Science Inc., Franklin, MA) focused into a sheet perpendicularly to the flow direction. A four-channel delay generator (Stanford Research Systems, Sunnyvale, CA) controlled the firing of the nitrogen laser. A single-line argon laser (488 nm, 200 mW, American Laser Corp., Salt Lake City, UT) continuously excited the uncaged fluorescein dye or the rhodamine B dye. The resulting fluorescence emission was transmitted first through an epi-fluorescent microscope head (Leica Microsystems (Canada), Richmond Hill, ON) equipped with a 32 × NA (Numerical Aperture) = 0.6 air objective, and then through a 0.63 × C mount into a progressive CCD camera (Pulnix America Inc., Sunnyvale, CA). The camera was run at 15 Hz with individual exposure times of 1/60 s. The acquired images had a resolution of 640 × 484 pixels corresponding to 350 µm visible length of capillary. While the mismatch of refractive indices of the capillary wall (fused silica, n ≈ 1.46) and the air (n = 1) causes image distortions in the radial direction, the extraction of axial velocity data remains intact due to the zero curvature along the flow direction. Since the internal diameter of the performed capillary is known, we can determine the radial position of dyes and thus the radial velocity profile.

Measurements of temperature and EO flow

In both temperature and flow field measurements, several points close to the two ends and in the middle region of the capillary were investigated. At each point, three different electric fields (5, 10 and 15 kV m⁻¹) were applied, between which approximately 2 min were allowed to let the whole capillary system cool to room temperature. For the temperature measurements, the direction of the electric field was switched once at each point. Hence, the same point in focus could be close to the inlet or the outlet of the capillary depending on the direction of the applied electric field. The electric field and the CCD camera were turned on simultaneously. When the liquid flow was visualized, however, the electric field was always run in one direction to ensure that the uncaged dye went into the waste reservoir (initially filled with pure buffer). Furthermore, before and after the velocity measurement at each applied electric field, the flow measurements under zero applied voltage were conducted to verify that the magnitude of the mean velocity resulting from a hydrostatic pressure gradient (due to the leveling of the capillary) along the length direction was minimum (i.e., less than 10 µm s⁻¹). In the flow measurements, the uncaging pulse of ultraviolet light was triggered by a TTL signal every 5 s to ensure that the uncaged dyes from the last uncaging event could go sufficiently far away from the field of view. The electric field was applied immediately after the dye was uncaged. For both temperature and velocity measurements, the electric field was left on for about 20 s. These two experiments were conducted twice at different days to verify their repeatability.

Image processing

To extract the temperature data from the captured fluorescent images of rhodamine B dyes, the average intensity of a square of 20 × 20 pixels in the middle of each image was calculated (the background intensity was subtracted) and then normalized by the one read from the first image at the same electric field (i.e., the very first image immediately after the electric field and the camera were simultaneously turned on, whose intensity corresponds to the room temperature and may be called the reference intensity). In other words, we did not use constant reference intensity for all runs. This treatment is necessary for different points under observation. The calibration curve (a third-order polynomial fit) provided in Ross et al.⁴⁶ was employed to convert the above obtained intensity values to temperature. Erickson et al.⁴³ have verified the applicability of this treatment to the buffer and dye concentrations used in this work. To determine the electroosmotic velocity profile from the images of uncaged fluorescein dyes, a zero gradient marker point was located along each axial line of pixels, using a weighted average of the highest concentration (reflected by the pixel intensity) values on that line. The resulting profiles of the highest concentration markers in a series of images could then provide the velocity profile by dividing the distance between the profiles by the corresponding time-step.⁵³ This velocity, however, is not the true electroosmotic velocity but the vector addition of liquid electroosmotic velocity and the dye electrophoretic velocity. In order to correctly extract the electroosmotic velocity profile in the presence of Joule heating effects, Sinton and Li⁴⁴ proposed a scalar image velocimetry to compensate for the temperature dependence of the electrophoretic mobility of dyes without explicit knowledge of the liquid temperature. This velocimetry method was applied in this work, where the dye mobility was taken as −3.3 × 10⁻⁴ m²V⁻¹s⁻¹ at room temperature.⁴⁸⁴⁹

Results and discussion

Joule heating effects cause both temperature rises and temperature gradients inside the whole capillary. The axial temperature gradients will make the electric field and the flow field non-uniform along the length direction via temperature dependent electrical conductivity and viscosity, and hence induce axial pressure gradients in the liquid in order for the continuity equation to be fulfilled. Consequently, the electroosmotic velocity profile is differently curved in different regions of the capillary. Here we examine the temperature and flow fields using independent experimental and numerical approaches, as described in the previous sections. Table 1 gives the physico-chemical properties of the buffer solution (assumed to be identical with pure water except for the electrical conductivity at room temperature which was measured at a low electric field before experiments) and the capillary wall (fused silica). The heat transfer coefficient for the free-air convection around the capillary is estimated⁵³ as h = 55 W m⁻² K⁻¹.

Temperature field

As can be seen in Fig. 1, the numerically and experimentally predicted temperature distributions (15 s after electric fields were applied) agree well along the whole capillary. Each experimental temperature data point is the average value of 15 images. As numerically predicted, sharp temperature drops close to the two ends and a high-temperature plateau in the main body of the capillary were observed. However, the numerical simulation tends to slightly overestimate the flow effect in the downstream region. In the presence of electroosmotic flow, the axial temperature profile of the liquid is inclined to the downstream. The higher the liquid flow is, the more significant the inclination becomes. The experimental results indicated very small radial temperature difference in the capillary. This can also be seen from the model predicted temperature contour (see Fig. 2).

The comparison between numerical and experimental predictions of temperature transients at two different points of the capillary is displayed in Fig. 3. Each experimental temperature data point is an average value obtained from 6 images. This treatment
could smooth the inevitable temperature fluctuations during the measurements. Overall, the numerical simulation predicted the trend of temperature development. However, it seems that the total heat capacity of the capillary system was overestimated in the simulation. As a result, the experimentally obtained liquid temperatures rose more quickly in the first several seconds (about 5 s in Fig. 3) and then slowly approached to their final steady values.

**Flow field**

The electrical conductivity of the liquid is linearly increased with the rise of temperature (see Table 1), resulting in locally higher electric fields in the inlet and outlet regions of the capillary. Fig. 4 illustrates the profiles of axial electric field strength scaled by their nominal values. As expected, the scaled electric field strength in the main body of the channel is lower than unity. While both the dielectric constant and viscosity are inversely proportional to the temperature, the electroosmotic slip velocity at the wall \( U_{\text{slip}} = -\varepsilon(T)\varepsilon_0 E_z/\mu(T) \) is increased at lower temperatures near the two ends of the capillary. As a result, positive pressure gradients, as shown in Fig. 4, have to be induced near the capillary ends to reduce the liquid velocity in the center of channel cross-section. Correspondingly, a negative pressure gradient is generated in the middle part of the channel to balance the positive pressure gradients at the ends. The resulting electroosmotic velocity profile is thus convex in the main body of the capillary while becoming concave in its inlet and outlet regions.

A series of images of electroosmotic flow (revealed by the motion of uncaged fluorescein dyes) at a point close to the inlet, a point in the middle section and a point close to the exit of the capillary is shown in Fig. 5 (15 s after applying an electric field of 15 kV m\(^{-1}\)). The moving, curving and dispersing of the dye bands are clearly seen despite that an air objective was used in the flow visualization without any refractive indices matching. As theoretically anticipated, the dye bands (the net migration velocity of dyes is the vector addition of the liquid electroosmotic velocity and the dye electrophoretic velocity) became concave near the capillary ends while convex in the middle region. As seen in Fig. 5, the uncaging pulse of ultraviolet laser (see the first image at each column) was not perfectly adjusted to be perpendicular to the flow direction. However, the slightly inclined dye bands do not affect the velocity profile to be extracted because it is the relative distances between profiles of the highest concentration markers that determine the final velocity profile.

Fig. 6 compares the profiles of electroosmotic velocity obtained from the numerical simulations and measurements, respectively. The numerical and experimental predictions of velocity profiles are in reasonably good agreement in both the inlet and the outlet regions of the capillary (see the top left and top right plots in Fig. 6). The concave curvature, however, is underestimated by the simulations in Fig. 6, particularly at high electric fields (15 kV m\(^{-1}\)). One cause for this discrepancy is an increase in conductivity of the solution (found to be approximately 10%) over the duration of the velocity experiments. The conductivity increased during the measurements for two reasons. Firstly, evaporation of water at the free surfaces in the fluid reservoirs concentrated the solution over time. Secondly, the progressive uncaging release of fluorescent dye increased the ionic concentration of the solution. Although experiments were conducted in a timely manner, these two effects are believed to have contributed to the discrepancy between experimental results and numerical results (which did not include these effects). Another potential source of error in the numerical simulations lies in the assumption that the physical buffer properties are identical to those of pure water. Since these properties are temperature dependent (see Table 1), they all affect the curvature of velocity profiles. A considerably curved profile of electroosmotic velocity was observed in the middle region of the capillary (see the top middle plot in Fig. 6). Even at a low electric field (e.g., 5 kV m\(^{-1}\)) the convex profile is noticeable. According to the numerical simulation, however, the velocity profile is only slightly convex in this region (see the plot of velocity vector at the bottom of Fig. 6, not in scale). Johnson et al.\(^{24}\) saw a slightly convex velocity profile in a straight microchannel. They argued that this slight curvature was due to a non-uniform density of surface charges and a non-uniform radial temperature profile. Indeed, the latter could make the electroosmotic velocity parabolic-like. However, the electroosmotic flow profile remains plug-like if we account for only the radial temperature gradient. Hence, the resulting net migration velocity should be concave because the uncaged dyes carry negative charges opposite to those of the capillary wall.\(^{1,31–34}\)

Fig. 7 compares numerically calculated average velocities with those obtained from different measuring points. The electroosmotic velocities in the absence of Joule heating effects are also shown in Fig. 7. Note that the average velocity equals the volume flow rate divided by the cross-sectional area of the capillary. One can see that Joule heating effects significantly increase the average velocity (i.e., the flow rate) at high electric fields (for example, more than 50% increase at 15 kV m\(^{-1}\) as demonstrated in Fig. 7). The close agreement of average velocities measured from three different

| Table 1 Physico-chemical properties of materials used in the numerical simulation. \( T_0 = 298 \) K denotes room temperature in the table |

<table>
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<tr>
<th></th>
<th>Liquid</th>
<th>Capillary wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho ) (10^3 ) kg m(^{-3})</td>
<td>1.00(^*)</td>
<td>2.15(^*)</td>
</tr>
<tr>
<td>Heat capacity ( C_p ) J kg(^{-1}) K(^{-1})</td>
<td>4.18(^*)</td>
<td>1.00(^*)</td>
</tr>
<tr>
<td>Thermal conductivity ( k ) W m(^{-1}) K(^{-1})</td>
<td>0.61 + 0.001(T - ( T_0 )) (^*)</td>
<td>1.38 + 0.001(T - ( T_0 )) (^*)</td>
</tr>
<tr>
<td>Electric conductivity ( \sigma ) S m(^{-1})</td>
<td>0.2[1 + 0.002(T - ( T_0 ))]</td>
<td></td>
</tr>
<tr>
<td>Dynamic viscosity ( \mu ) kg m(^{-1}) s(^{-1})</td>
<td>2.76E13(1713/( T_0 )) \times 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Dielectric constant ( \varepsilon )</td>
<td>305.7exp(-7)/219</td>
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The electric conductivity at \( T = T_0 \) was measured at a low electric field (1 kV m\(^{-1}\)). The Zeta potential \( \zeta \) of the capillary wall was taken as \(-80 mV\).\(^{53,54}\) The properties with the superscript \(^*\) are obtained from ref. 55, and those without are from refs. 11 and 12.
points (i.e., inlet, outlet and middle points) verifies that our velocimetry method with temperature compensation works well.

It has been shown in Fig. 3 that the liquid temperature quickly rises in the first several seconds immediately after the electric field is applied. Then, we can similarly predict a quick rise in the flow rate. The comparison of computed and measured average electro-osmotic velocities is presented in Fig. 8. In accordance with the temperature transients, the numerical simulation overestimates the transient time required for the flow rate to be stable. One can also see that the measured average velocities at time zero are a little higher than those computed values. This difference is attributed to the finite time delay on measuring the velocity at time zero, during which the Joule heating has taken effect. It should be noted that the electroosmotic flow velocity with no Joule heating effect should be a horizontal line, i.e., independent of time. For graphic clarity, these horizontal lines were not plotted in Fig. 8.

Conclusions
This paper has presented a combined experimental and numerical study of electroosmotic capillary flow where the Joule heating has a significant effect. We show that Joule heating effects can also induce perturbations to the electroosmotic velocity profiles in a homogeneous capillary. Both the liquid temperature and electro-osmotic velocity were measured at different points along a homogeneous capillary. It has been shown that the liquid temperature and volume flow rate could be significantly increased due to Joule heating effects. Sharp temperature drops were observed close to the two ends of the capillary, and the concave-convex-concave velocity profiles from the inlet to the outlet of the capillary were also observed. These phenomena are due to the Joule heating effects via the temperature dependence of electrical conductivity and viscosity of the liquid. With these measurements, we have also examined the temperature and flow rate transients. Overall, the experimentally obtained temperature and velocity results were in good agreement with the predictions of a theoretical model developed in this paper.

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