Experimental and theoretical study of the displacement process between two electrolyte solutions in a microchannel

Liqing Ren, a Jacob Masliyah, b and Dongqing Li a, *

a Department of Mechanical and Industrial Engineering, University of Toronto, 5 King’s College Road, Toronto, ON, Canada M5S 3G8
b Department of Chemical and Material Engineering, University of Alberta, Edmonton, AB, Canada T6G 2G6

Received 29 May 2002; accepted 17 September 2002

Abstract

Displacement of one electrolyte solution by another in a microchannel is required in many biolab chip devices. The objective of this paper is to develop a better understanding of the displacement process between two electrolyte solutions under an applied electric field in a cylindrical microchannel in terms of the traveling distance of the interface between these two electrolyte solutions. In order to develop a general model to predict the location of the interface, two different situations are considered: one model assumes the presence of a sharp interface between the two solutions and the other model considers a mixing zone between the two solutions. Carefully conducted experiments were carried out to obtain the current–time relationship, which is used in the model to predict the location of the interface. In these experiments, deionized ultrafiltered water (DIUF water), 10 mM KCl, 0.1 mM KCl, and 0.1 mM LaCl₃ solutions were used as the testing liquids. Polyamide-coated silica capillary tubes of internal diameter 100 µm and length 10 cm were employed in this study. The relationship between traveled distance of the interface and time was predicted by a developed model based on the measured current–time relationship for such a displacement process under a constant applied electric field. The characteristics of the nonlinear change of the traveling distance with the time were also discussed in this paper.

© 2003 Elsevier Science (USA). All rights reserved.

Keywords: Displacement; Electroosmotic flow; Microchannel; Electrolyte solution

1. Introduction

Most studies of electroosmotic flow have focused on the flow of uniform solutions [1–8]. However, the operation of some lab-on-a-chip devices such as on-a-chip biosensors involves displacement of one solution by another solution in a microchannel by electroosmotic pumping [9]. In order to develop such a biosensor on a chip, electroosmotic pumping must be used to control the solution displacement process. In such a solution displacement process, if the two solutions are very different in terms of ionic type, valence, and concentration, the zeta potentials of the microchannel wall and the EDL fields will be different in the different sections of the microchannel. The displacement process would bring more complications to electroosmotic flow in microchannels.

A recent study [10] proposed an experimental approach to evaluating the average velocity of electroosmotic flow by finding the slope of the current–time relationship in a process where one solution displaces another similar solution in a microchannel. In this method, a capillary tube is filled with an electrolyte solution and then brought into contact with another solution of the same electrolyte but with a slightly different ionic concentration. Once the two solutions are in contact, an electric field is applied along the capillary in such a way that the second solution is pumped into the capillary and the first solution flows out of the capillary from the other end. As more and more of the second solution is pumped into the capillary and the first solution flows out of the capillary, the overall liquid conductivity in the capillary changes, and hence the electric current through the capillary changes as well. When the second solution completely displaces the first solution, the current reaches a constant value. It has been observed and verified that, despite the nonlinear current–time relationship at the beginning and ending sections, the measured current–time relationship is linear in most part of
the process. This linear relationship between current and
time allowed a method to be developed for determining
the average velocity of the displacement process between
very similar solutions using the slope of the current–time
relationship.

However, the linear current–time relationship is only
valid for a displacement process between similar electrolyte
solutions having a small concentration difference (i.e., 5% difference). When the two solutions are very different in
terms of their ionic type, valence, and concentration, the
electric current will change nonlinearly with time during
the displacement process [11]. In addition, only the average
velocity for the whole displacement process can be predicted
by the slope method, which is close to the electroosmotic
velocity of any of these two similar solutions. More detailed
information of a displacement process, such as the location
of the interface between these two solutions, which is very
important in operating biochips, cannot be provided by this
method.

In order to develop a better understanding of the displace-
ment process where one solution is displaced by another dif-
ferent solution in a cylindrical capillary under an applied
electric field, two models were developed to predict the inter-
face position. As well, careful experiments were conducted
to monitor the current–time relationship to allow the use of
such models.

2. Mathematical model

The local electric current vector in a microchannel is
given by [12]

$$\vec{i} = e\vec{u} - e\sum_j z_j D_j n_j \frac{\partial n_j}{\partial x} - \frac{e^2 \psi}{kT} \sum_j z_j^2 D_j n_j,$$

where $\vec{i}$ and $\vec{u}$ are local electric current density vector and
local velocity vector, respectively. $\psi$ is the local electrical
potential. The $j$th ionic species has a valence of $z_j$, a dif-
fusion coefficient of $D_j$, and an ionic number concentration
of $n_j$. Here, $e$, $k$, and $T$ represent the fundamental elemen-
tary charge, the Boltzmann constant, and the system absolute
temperature, respectively. When an electric field is applied
across the capillary, in the absence of end effects, the current
is along the axial direction. The total current is given by

$$I = e\int_A \sum_j z_j n_j dA - e\int_A \sum_j D_j z_j \frac{\partial n_j}{\partial x} dA - \frac{e^2 \psi}{kT} \int_A \sum_j z_j^2 D_j n_j \frac{\partial \psi}{\partial x} dA,$$

where $A$ is the cross-sectional area of the capillary. For fully
developed flow, one can neglect the second term of Eq. (2)
deleting the current flow due to diffusion. For large $\kappa a$
capillary, where the electric double layer is very thin,
electroneutrality is assumed to dominate in the channel and
the first term of Eq. (2) defining the current transport due
to convection can be neglected. Here $a$ is the capillary radius
(i.e., 100 µm) and $\kappa^{-1}$ is the Debye double layer thickness
(i.e., less than 30 nm). Consequently, for large $\kappa a$ flows, one
can write for the electric current

$$I = \frac{Ae}{kT} \sum_j z_j^2 D_j n_j \infty E,$$

where $E$ is the electric field strength in the $x$-direction and
$n_j \infty$ is the ionic number concentration for an electrolyte
solution. For a given electrolyte solution, Eq. (3) can be
written as

$$I = A \lambda E,$$

where $\lambda$ is the electric conductivity of the electrolyte
solution. Equation (4) is an expression of Ohm’s law for
electrically neutral dilute solutions or solutions in capillary
having large values of $\kappa a$ with negligible axial concentration
gradients [13].

We will make use of Eq. (4) to derive two models to
evaluate the interface position in the microchannel with time.

2.1. Model I

In this model, we assume that there is a sharp interface
between the two solutions during the displacement process.
The schematic diagram of the solution displacement process
is shown in Fig. 1a. The total length of the capillary is $L$
and the traveling distance of the liquid–liquid interface at

![Fig. 1. Schematic diagram of one solution displacing another solution in a
capillary (a) where a sharp interface between the two solutions is assumed
and (b) where a mixing zone between the two solutions is assumed.](image-url)
a given time is \( x \). In the present configuration, the Debye electrical double layer thickness is very small for the system under consideration. As well, the aspect ratio of the capillary length to the diameter is very large. Consequently, once can safely assume the applicability of Eq. (4) to our system. The total resistance of this capillary is assumed to be made up of two resistances, \( R_1 \) and \( R_2 \), corresponding to the two solutions. That is,

\[
R_{\text{total}} = R_1 + R_2. 
\]

According to Ohm’s law, the electric resistances are given by

\[
R_1 = \frac{L}{A_{\lambda b_1}}, \quad \text{and} \quad R_2 = \frac{x}{A_{\lambda b_2}},
\]

where \( \lambda_{bi} \) is the electric conductivity of the \( i \)th electrolyte solution. The current, in turn, can be determined by

\[
I = \frac{E \cdot L}{R_{\text{total}}} = \frac{E \cdot L}{\frac{x}{A_{\lambda b_1}} + \frac{L}{A_{\lambda b_2}}}. 
\]

From Eq. (7), the traveling distance of the interface can be obtained as

\[
x = \frac{E \cdot L \cdot A \cdot \lambda_{b2} \lambda_{b1}}{I \cdot (\lambda_{b1} - \lambda_{b2})} - \frac{L \cdot \lambda_{b2}}{(\lambda_{b1} - \lambda_{b2})}. 
\]

Equation (8) shows that once the current is known, the traveling distance, \( x \), can be determined since the total applied voltage, the conductivities of the individual solutions and the total length of the capillary are constant through the displacement process.

However, a detailed analysis [11] shows that there exists a mixing zone between the two solutions, instead of the sharp liquid–liquid interface assumed in Model I. In the mixing zone, the ionic concentration and the electric conductivity vary between the bulk solutions. The size of the mixing zone depends on the diffusion coefficients of the electrolytes in the two solutions, the concentration difference, the speed of the flow, and the time. Therefore, in order to make the analysis of the displacement process closer to the real system, the displacement processes, with a consideration to the mixing zone, are studied.

2.2. Model II

In this model, we consider a situation where one solution displaces another solution and there exists a mixing zone between the two solutions during the displacement process. The two solutions contain the same electrolyte or different electrolytes, and have different concentrations, \( C_1 \) and \( C_2 \). The electrophoretic flow is from left to right as shown in Fig. 1b. The mixing zone, with a length of \( L_{\text{mix}} \), is defined as a region where the left boundary of the mixing zone has a concentration of \( C_2 + 0.01\% (C_1 - C_2) \) and the right boundary of the mixing zone has a concentration of \( C_2 + 99.99\% (C_1 - C_2) \). Assuming that \( x \) is the position of the left boundary of the mixing zone at a given time, the length of the channel filled with the electrolyte solution 1 is \( L - x - L_{\text{mix}} \).

In this model, it is assumed that the total resistance is made up of three components corresponding to the three regions and it takes the form

\[
R_{\text{total}} = R_1 + R_{\text{mix}} + R_2, 
\]

where \( R_{\text{mix}} \) is the resistance of the mixing zone. Now assume that the mixing zone is divided into \( N \) small sections and the length of each section, \( L_{\text{mix}} \), is so small that the conductivity of the liquid, \( \lambda_{\text{mix}} \), in this section can be considered as a constant. Therefore, the total resistance of the mixing zone is a summation of the resistance of each section, \( R_{\text{mix}} = \sum R_{\text{mix}}(i) \), where \( R_{\text{mix}}(i) \) is the resistance of the \( i \)th section of the mixing zone. According to Ohm’s law, the resistances can be written as

\[
R_1 = \frac{L - x - \sum L_{\text{mix}}(i)}{A_{\lambda b_1}}, \quad R_2 = \frac{x}{A_{\lambda b_2}}, \quad R_{\text{mix}} = \sum R_{\text{mix}}(i) = \sum \frac{L_{\text{mix}}(i)}{A_{\lambda_{\text{mix}}(i)}}. 
\]

The current, in turn, can be given by

\[
I = \frac{E \cdot L}{R_1 + R_{\text{mix}} + R_2} 
\]

\[(10a)\]

\[
= \frac{E \cdot L}{\frac{L - x - \sum L_{\text{mix}}(i)}{A_{\lambda b_1}} + \sum \frac{L_{\text{mix}}(i)}{A_{\lambda_{\text{mix}}(i)}} + \frac{x}{A_{\lambda b_2}}}. 
\]

(11)

Taking the derivative of current with respect to time, we obtain

\[
\frac{dI}{dt} = -\left[ \left( \frac{1}{\lambda_{b2}} - \frac{1}{\lambda_{b1}} \right) \bar{u}_x + \sum \left( \frac{1}{\lambda_{\text{mix}}(i)} - \frac{1}{\lambda_{b1}} \right) \frac{dL_{\text{mix}}(i)}{dt} \right] \frac{I^2}{E \cdot L \cdot A}. 
\]

(12)

where \( \bar{u}_x \) is the cross-sectional average velocity, given by \( \bar{u}_x = dx/dt \). As explained earlier, \( L_{\text{mix}}(i) \) is dependent on the concentration distribution in the capillary. The concentration distribution during the displacement process is governed by

\[
\frac{\partial C}{\partial t} + u_x \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial x^2}. 
\]

(13)

From the order of magnitude analysis of the convection and diffusion terms in Eq. (13), \([u_x] \frac{[C]}{[x]} \) and \([D] \frac{[C]}{[x]} \), we found that the order of magnitude of the convection term is approximately \( 10^{-2} \text{ mol} / (\text{m}^3 \text{ s}) \), and that of the diffusion term is approximately \( 10^{-7} \text{ mol} / (\text{m}^3 \text{ s}) \) (\( C \sim 1 \text{ mol} / \text{m}^3, u \sim 10^{-3} \text{ m/s}, x \sim 10^{-1} \text{ m}, D \sim 10^{-9} \text{ m}^2/\text{s} \)). Therefore, the contribution of the diffusion to the concentration distribution can be neglected. Consequently, the length of the \( i \)th section of the mixing zone, \( L_{\text{mix}}(i) \), is determined by the initial
condition and the convection term. The $i$th section of the mixing zone has two boundaries, $x(i)$ and $x(i+1)$; the length of the $i$th section can be calculated by $L_{mix}(i) = x(i+1) - x(i)$. Taking the derivative of $L_{mix}(i)$ with respect to time, we obtain

$$\frac{dL_{mix}(i)}{dt} = \frac{d[x(i+1) - x(i)]}{dt} = \bar{u}_x(i+1) - \bar{u}_x(i). \quad (14)$$

Because of the continuity condition, at a given time, the cross-sectional average velocity is constant through the whole capillary; i.e., $\bar{u}_x(i) = \bar{u}_x(i+1)$. Consequently, Eq. (14) becomes

$$dL_{mix}(i)/dt = 0. \quad (15)$$

Substituting Eq. (15) into Eq. (12), we obtain

$$\frac{dI}{dt} = \frac{(\lambda b_1 - \lambda b_2)}{\lambda b_1 \lambda b_2} \cdot \frac{I^2}{E \cdot L \cdot A} \cdot \bar{u}_x \quad (16a)$$

or

$$\bar{u}_x = \frac{dI}{dt} \cdot \frac{E \cdot L \cdot A}{I^2} \cdot \frac{\lambda b_1 \lambda b_2}{(\lambda b_1 - \lambda b_2)}. \quad (16b)$$

The traveling distance, $x$, can be calculated by

$$x = \int \bar{u}_x \, dt = \frac{E \cdot L \cdot A \cdot \lambda b_1 \lambda b_2}{(\lambda b_1 - \lambda b_2)} \left(1 - \frac{1}{I_{initial}} \right), \quad (17)$$

where $I_{initial}$ is the electric current generated at the start of the displacement process when the capillary is filled with the electrolyte solution 1. Hence the initial current can be evaluated by

$$I_{initial} = E \cdot L \cdot A \cdot \lambda b_1. \quad (18)$$

Substituting Eq. (18) for the initial current into Eq. (17), the traveling distance of the left boundary of the mixing zone is given as

$$x = \frac{E \cdot L \cdot A \cdot \lambda b_2 \lambda b_1}{T \cdot (\lambda b_1 - \lambda b_2)} - \frac{L \cdot \lambda b_2}{(\lambda b_1 - \lambda b_2)}. \quad (19)$$

Equation (8) and Eq. (19) are identical. It should be pointed out here that the traveling distance of the interface, Eq. (8), derived in Model I, and the traveling distance of the left boundary of the mixing zone, Eq. (19), derived in Model II are the length of the channel filled with the electrolyte solution 2. Therefore, in terms of predicting the length of the channel filled with the electrolyte solution 2, Model I and Model II are equivalent. This implies that Model I, which approximates the mixing zone as a sharp interface, is sufficient to predict the length of the channel filled with an electrolyte solution 2 during the displacement process. For consistency, the length of the channel filled with the electrolyte solution 2 is referred to as the traveling distance of the interface in the following sections and it is determined by Eq. (8).

It should be noted that Eq. (16b) provides a method to determine the cross-sectional average velocity during the displacement process. However, it has been found that the cross-sectional average velocity is highly dependent on the local slope of the current–time relationship during the displacement process. In turn, it strongly depends on the curve fitting to the experimental data of the current–time relationship. A small fluctuation in the experimental data causes a large change in the local slope as determined by the curve-fitting technique. Consequently, such a local fluctuation causes a significant error in the predicted cross-sectional average velocity. Therefore, for accuracy, this work focuses on the investigation of the traveling distance of the interface, except for the special case of displacement between nearly similar solutions.

### 3. Experimental

Polyamide-coated silica capillary tubes of internal diameter 100 µm (Polyamide Technologies Inc., Phoenix, AZ) were cut to length 10 cm and used to connect the electrolyte solutions in reservoir 1 and reservoir 2. In the experiment, reservoir 2 was filled with solution 2. The capillary tube and reservoir 1 were filled with solution 1 at the same level as reservoir 2, as shown in Fig. 2. All the solutions were prepared by using deionized ultrafiltered water (Fisher Scientific, Ontario), KCl (Anachemia Science, Quebec), and LaCl₃ (Fisher Scientific Company, New Jersey). Immediately after the two reservoirs were connected by the capillary tube, a voltage difference was applied between the two reservoirs by setting reservoir 1 at ground potential and reservoir 2 to a higher voltage (HV power source: CZE 1000 R, Spellman, NY) via platinum electrodes.

The applied electric field results in an electroosmotic flow in the capillary tube. The electrolyte solution from reservoir 2 gradually displaces the electrolyte solution in the capillary tube. As a result, the overall electric resistance of the liquid in the capillary tube changes. A PGA-DAS 08 data acquisition chip (OMEGA Engineering, Quebec) was used to record the voltage (kV) and current (µA) as a function of time. Once the solution in the capillary tube is completely displaced by the solution in the reservoir 2, the current reaches a constant value. Once the current–time relationship is obtained, the front interface of solution 2 can be determined using Eq. (8) as derived in Model I.
the experimental study, each test was repeated at least five times for a given set of conditions. All experiments were conducted at 25 °C.

4. Results and discussions

In the following analysis, Eq. (8) is used to predict the position of the interface, \( x \), with time, \( t \), while solution 2 displaces solution 1 from left to right. A careful analysis of Eq. (7) would reveal that the electric current is not dependent on the direction of displacement. In other words, when an interface is located at \( x \), the current is the same whether the interface location has been achieved through solution 2 displacing solution 1 (left to right) or solution 1 displacing solution 2 (right to left). Conversely, by conducting one experiment with solution 2 displacing solution 1 (left to right) and a second experiment with solution 1 displacing solution 2 (again left to right), the current is the same when the interface is at \( x \) for the first experiment and at \( L - x \) for the second experiment.

Figure 3 shows the interface location, \( x \), for a 10 mM KCl solution displacing a 0.1 mM KCl solution and the interface location in terms of \( L - x \) for a 0.1 mM KCl solution displacing a 10 mM KCl solution. The interface location in Figs. 3a and 3b is for electric field strengths of 35 and 70 kV/m, respectively. As would be expected, the data for each set of experiments coincided with each other. The near perfect data agreement would suggest that the current is the same for an interface location, \( x \), for the first displacement experiment and \( L - x \) for the second displacement experiment. This would indicate that the mixing zone is not significant. This needs to be true as, except for the midpoint, the traveling distance in the two sets of experiments is not equal and the mixing length is a function of the traveled distance.

Figure 4a shows the current–time relationship during the displacement process of a 10 mM KCl solution displacing a 0.1 mM KCl solution under electric fields of 35 and 70 kV/m, respectively. Figure 4b shows the change of the traveling distance of the interface with time and Fig. 4c shows the variation of the current with the traveling distance of the interface, separately. As shown in Fig. 4b, the traveling distance increases until it reaches a constant value when the second solution completely displaces the first solution. The variation of the traveling distance with time shows very different behavior from that of the current. When the traveling distance reaches 90% of the total length of the capillary (i.e., \( x = 0.9L \)), the corresponding current is still very low (i.e., around 3.8 µA) as compared with the current when the traveling distance reaches 100% of the total length of the capillary (i.e., around 37.8 µA). This is because the conductivity of the 10 mM KCl solution is approximately 100 times higher than that of a 0.1 mM KCl solution (see Table 1). Even when the traveling distance is approximately 90% of the total length of the capillary (i.e., only 10% of the total capillary length is filled with the 0.1 mM KCl solution), the total resistance, given by \( R_{\text{total}} = x/(\lambda_{10 \text{mM KCl}} \cdot A) + (L - x)/(\lambda_{0.1 \text{mM KCl}} \cdot A) \), is still dominated by the low conductivity of the 0.1 mM KCl solution. Consequently, the total resistance is very high and the corresponding current is very low. In addition, Figs. 4a and 4b show that when the electric field strength is increased, the time required for a 10 mM KCl to displace a 0.1 mM KCl solution decreases. This is because when the electric field strength is increased, the electroosmotic velocity of the electrolyte solution increases. As a result, the time required for the displacement process decreases. From Fig. 4c, we can see that when the electric field strength is increased, the electric current increases. This is because the electric resistance, which is independent of the applied electric field strength, is the same as long as the interface travels the same distance during the two replacing processes. Consequently, the current, given by \( I = (E \cdot L)/R_{\text{total}} \), increases with the applied electric field strength at the same traveling distance.

Figure 5a shows the current–time relationship in the process of a 0.1 mM KCl solution displacing a 10 mM KCl solution under electric fields of 35 and 70 kV/m, respectively. Figure 5b shows the relationship between the traveling distance of the interface and time. As shown in Fig. 5, when the interface travels a very short distance, the current drops significantly to a very low value. This
Fig. 4. (a) Current–time relationship in the process of 10 mM KCl displacing 0.1 mM KCl solution under electric fields of 35 and 70 kV/m, respectively, (b) relationship between traveling distance and time in the same displacement process, and (c) relationship between current and traveling distance in the same displacement process.

Table 1
The measured bulk conductivity of the electrolyte solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mM KCl</td>
<td>0.1412</td>
</tr>
<tr>
<td>0.1 mM KCl</td>
<td>$0.1514 \times 10^{-2}$</td>
</tr>
<tr>
<td>0.1 mM LaCl$_3$</td>
<td>$0.4020 \times 10^{-2}$</td>
</tr>
<tr>
<td>DIUF water</td>
<td>$0.1476 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

is because the 0.1 mM KCl solution has a conductivity much lower than that of the 10 mM KCl solution (see Table 1). Once a small amount of the low-conductivity 0.1 mM KCl solution is pumped into the capillary, the total resistance is dominated by the resistance in this section of the capillary and it increases significantly with the traveling time. Consequently, the current drops sharply. Figure 5b shows that the interface moves faster under an electric field of 70 kV/m than under an electric field of 35 kV/m. This is because as the electric field strength is increased, the electroosmotic velocity of the liquid increases. Although the relationship between current and time shows similar behavior for the two electric field strengths, the slope of the relationship between the traveling distance and time are markedly different for the two electric field strengths.
Fig. 5. (a) Current–time relationship in the process of 0.1 mM KCl displacing 10 mM KCl solution under electric fields of 35 and 70 kV/m, respectively and (b) relationship between traveling distance and time in the same displacement process.

Figure 5 shows the current–time relationship during the process of a 10 mM KCl solution displacing DIUF water under an electric field strength of 35 kV/m. Figure 6b shows the variation of the traveling distance of the interface with time. As shown in Fig. 6b, the traveling distance increases very quickly at the beginning of the displacement process and then slows down until the interface reaches the end of the capillary. This is because the channel wall in DIUF water has a much higher zeta potential (i.e., around 240 mV) than that in the 10 mM KCl solution (i.e., around 65 mV). Consequently, the electroosmotic velocity of DIUF water in the capillary is higher than that of 10 mM KCl solution. At the beginning of the displacement process, most of the capillary is filled with DIUF water and hence the average velocity of the liquid in the capillary is higher. However, when the interface moves toward the end of the capillary, more and more of the 10 mM KCl solution is pumped into the capillary to displace DIUF water. As a result, the section length of the capillary with a lower zeta potential becomes longer, and the average zeta potential of the capillary decreases. Consequently, the average electroosmotic velocity decreases. This causes the interface to move slower than that at the beginning of the displacement process.

Figure 6a shows the current–time relationship in the process of 10 mM KCl displacing DIUF water under an electric field of 35 kV/m and (b) relationship between traveling distance and time in the same displacement process.

Fig. 6. (a) Current–time relationship in the process of 10 mM KCl displacing DIUF water under an electric field of 35 kV/m and (b) relationship between traveling distance and time in the same displacement process.

Figure 7a shows the current–time relationship in the process of a 0.1 mM KCl solution displacing a 0.1 mM LaCl₃ solution under an electric field of 35 kV/m and Fig. 7b shows the change of the traveling distance of the interface with time. As observed in Fig. 7a, the current decreases fairly linearly during the displacement process. This is because the difference of the conductivity between these two solutions is small (see Table 1); as a result, no significant changes occur in the total resistance and the total current during the displacement process. In addition, the traveling distance almost increases fairly linearly when the second solution gradually displaces the first solution. This is because there is a small difference in the electroosmotic velocity of the two solutions when the two solutions have the same ionic concentration [10], allowing the interface to move at a relatively constant velocity.

Figure 8a shows the current–time relationship in the process of a 0.1 mM LaCl₃ solution displacing a 0.1 mM KCl solution under an electric field of 35 kV/m and Fig. 8b shows the variation of the traveling distance of the interface with time. The traveling distance continuously increases
until it reaches a constant value when the first solution is completely displaced by the second solution. The fairly linear change of the traveling distance and the current during the displacement process, as shown in Fig. 8, can be understood by recognizing that the electric conductivities of the two solutions are nearly the same, as shown in Table 1.

No attempt was made to present the interface velocity from the slope of the relationship between the traveling distance and time. This was because we found that the slope evaluation was prone to large errors.

5. Summary

In this paper, two situations were considered to develop the models to predict the location of the interface between two solutions in the process where one electrolyte solution displaces another electrolyte solution in a cylindrical capillary under an applied electric field. It is found that an assumption of the existence of a sharp interface between two electrolyte solutions in the displacement process is sufficient in terms of predicting the length of the channel filled with electrolyte solution 2.