Simultaneous mixing and pumping using asymmetric microelectrodes

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This study proposes ideas for simultaneous mixing and pumping using asymmetric microelectrode arrays. The driving force of the mixing and pumping was based on electroosmotic flows induced by alternating current (ac) electric fields on asymmetric microelectrodes. The key idea was to bend/incline the microelectrodes like diagonal/herringbone shapes. Four patterns of the asymmetric electrode arrays were considered depending on the shape of electrode arrays. For the diagonal shape, repeated and staggered patterns of the electrode arrays were studied. For the herringbone shape, diverging and converging patterns were examined. These microelectrode patterns forced fluid flows in the lateral direction leading to mixing and in the channel direction leading to pumping. Three-dimensional numerical simulations were carried out using the linear theories of ac electro-osmosis. The performances of the mixing and pumping were assessed in terms of the mixing efficiency and the pumping flow rate. The results indicated that the helical flow motions induced by the electrode arrays play a significant role in the mixing enhancement. The pumping performance was influenced by the slip velocity at the center region of the channel compared to that near the side walls. © 2007 American Institute of Physics. [DOI: 10.1063/1.2794375]

I. INTRODUCTION

Alternating current (ac) electro-osmosis has recently received great attention due to its remarkably low working voltages for moving liquid in a microchannel. While direct current (dc) electro-osmosis, a traditional method, mostly needs several kilovolts at electrodes, ac electro-osmosis requires generally very low voltage, less than about 5 V.1–8,10,11

The operation under such low voltage has many important advantages: (a) reducing the electrode degradation caused by Faradaic reactions, which lengthens the life span of a microfluidic device; (b) preventing air bubble generation; and (c) not changing significantly the properties of working fluid. Ac electro-osmotic flow was explored by Green’s group and their earlier studies were focused on the symmetric electrodes.1–4 Adjari5 predicted a net flow by introducing asymmetric arrays of electrodes. Thereafter, ac electro-osmosis was developed into a microfluidic pump. Brown et al.,6 verified the net flow experimentally. Ramos et al.,7 conducted numerical simulations using the analytical theory established by González et al.,3 and searched for the optimal geometry of electrodes for maximal pumping. Moreover, Olesen et al.8 found the global optimum condition for maximal pumping and investigated the effects of the channel height, the Faradaic reaction in the vicinity of electrodes, and nonlinear surface capacitance of the Debye layer. Most previous studies have been for pumping based only on a two-dimensional model.1–8

Most of the previous microfluidic pumps using ac electro-osmosis have generally straight electrodes perpendicular to the channel direction. Each electrode pair consists of a narrow electrode and a wide electrode, and the pairs are periodically displaced on the bottom wall. When an ac voltage is applied to each electrode pair, a slip velocity occurs at the electrode surface. The direction of the resulting net flow is toward the wide electrode. In the meantime, the work by Stroock et al.9 has been recognized as a breakthrough in the field of micromixers, thanks to its good mixing performance. The fluids inside the channel globally rotate along the channel wall while going downstream, by the help of grooves with diagonal/herringbone shapes on the bottom wall. However, there is a limitation as a passive mixer, i.e., it requires an additional pump to work. In fact, micropumps and micromixers have been independently developed and their performances are considered to be sufficient.

The purpose of this study is to realize a microfluidic device for simultaneous mixing and pumping, making use of the principles of the ac electro-osmosis pump and the staggered herringbone mixer. The key idea is to bend/incline the microelectrode strips like diagonal/herringbone shapes. Consequently, such an arrangement of electrodes produces a slip velocity with the lateral direction for mixing and with the channel direction for pumping. This kind of multifunctional device (simultaneous mixing and pumping) is expected to be useful in microfluidic systems such as lab-on-a-chip. Most importantly, the number of small devices on a microfluidic system can be reduced. This means that the microfluidic system can be miniaturized further or can work with more functionality by adding other devices. In addition, the possibility of malfunction of the system can be reduced because of the smaller number of parts on the microfluidic system.
Numerical simulations were performed to test the effects of the proposed ideas. In contrast to the previous studies, the present study employed three-dimensional simulations. The electrode geometries were the same as those adopted by Brown et al., and the optimal frequency for the maximal pumping corresponding to the dimensions followed Olesen et al. The channel height was determined such that a large recirculating flow can be generated above the leading edges of the wide electrodes. The slip velocity for fluid flow was obtained by solving the Laplace equation, the flow motion was simulated by using the Stokes equation, and then the concentration distribution was obtained through the convection-diffusion equation. Four patterns of the asymmetric electrode arrays were chosen depending on the shape of electrode arrays. Concerning the diagonal shape, repeated and staggered patterns of the electrode arrays were studied. For the herringbone shape, diverging and converging patterns were examined. The pumping ability was assessed by the flow rate and the mixing degree was quantified by the mixing efficiency.

II. NUMERICAL METHODS

A. Theory of ac electro-osmosis

The present study uses the linear theory established by González et al. (2000), which has been a basis of the works of Ramos et al. (2003), Olesen et al. (2006), and Urbanski et al. (2007). The previous studies were made using the following assumptions for symmetric electrolyte: (a) the electrical double layer in the vicinity of electrodes can be approximated as a simple capacitor showing linear behavior. This assumption is theoretically valid for low voltages applied to the electrodes; (b) the electrosynthesis of electrolyte does not occur; (c) the electrolyte is ideally polarizable. In other words, the free charge flow between electrolyte and electrodes is negligible; (d) the applied frequency is even lower than the charge relaxation frequency of electrolyte during whose period the electrical double layer forms (\( \omega = 2 \pi f < \alpha / \sigma e \)), where \( \sigma \) and \( e \) are the electrical conductivity and the permittivity of electrolyte, respectively. Under this condition, the double layer can be assumed to be in quasi-equilibrium; (e) the ions within the double layer are transported mainly by the electrical field rather than fluid flow. This assumption enables us to solve the fluid velocity independently of the electrical potential problem.

A schematic diagram of the geometrical layout of the channel used in the present work is given in Fig. 1. The electrolyte motion is governed by the Stoke equation,

\[
0 = - \nabla p + \mu \nabla^2 U, \tag{1}
\]

where \( p \), \( \mu \), and \( U \) are the static pressure, the absolute viscosity, and the velocity vector of fluid, respectively. This equation is appropriate for microfluidics where the inertial term is negligible compared with the viscous term. No-slip velocity is imposed on the insulating walls, whereas time-averaged slip velocity is set on the electrode surface.\(^{17}\)

\[
\langle U_{\text{slip}} \rangle = - \frac{e}{4 \mu (1 + \delta)} \nabla |V_{\text{ext}} - \phi|^2, \tag{2}
\]

where \( \nabla \) stands for a gradient along the electrode surface and \( \delta \) is the capacitance ratio of the diffuse layer to the Stern layer when the layers are modeled as capacitances, \( V_{\text{ext}} \) the external voltage applied to electrodes, \( \phi \) the electrical potential of electrolyte. Since \( |V_{\text{ext}} - \phi| \) is the potential drop across the double layer, we have to know the potential distribution inside the electrolyte, specifically at the boundaries where the diffuse layer ends. The electrical potential associated with \( |V_{\text{ext}} - \phi| \) shows a harmonic motion synchronized with ac. It is therefore convenient to deal with Eq. (2) in a phase mode, so that \( V_{\text{ext}} \) and \( \phi \) are complex variables circulating with identical frequency in the phase domain. The electrolyte outside the double layer is assumed to be electrically neutral.

Accordingly, the potential of the electrolyte is governed by the Laplace equation,

\[
\nabla^2 \phi = 0. \tag{3}
\]

The boundary conditions at the insulating walls and the electrodes are given as follows, respectively:

\[
\mathbf{n} \cdot \nabla \phi = 0, \tag{4}
\]

\[
\mathbf{n} \cdot \nabla \phi - \frac{e \omega}{\sigma \lambda_D (1 + \delta)} \mathbf{i} \phi = - \frac{e \omega}{\sigma \lambda_D (1 + \delta)} V_{\text{ext}}, \tag{5}
\]

where \( \mathbf{n} \) denotes the normal vector to the surface, \( \lambda_D \) the Debye length of the diffuse layer, and \( \mathbf{i} \) the unit imaginary value.\(^{17}\) Equations (1)–(5) can be rewritten with the dimensionless parameters listed in Table I. The characteristic parameters with the superscript "\( \ast \)" are dimensionless.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{ext}} )</td>
<td>( V_{\text{ext}} / V_0 ) Electrical potential applied to electrodes</td>
</tr>
<tr>
<td>( \phi )</td>
<td>( \phi / V_0 ) Electrical potential of electrolyte</td>
</tr>
<tr>
<td>( W_1 )</td>
<td>( W_1 / G_1 ) Width of the narrow electrode</td>
</tr>
<tr>
<td>( W_2 )</td>
<td>( W_2 / G_1 ) Width of the wide electrode</td>
</tr>
<tr>
<td>( G_2 )</td>
<td>( G_2 / G_1 ) Distance between electrode pairs</td>
</tr>
<tr>
<td>( H_2 )</td>
<td>( h / G_1 ) Channel height</td>
</tr>
<tr>
<td>( \omega )</td>
<td>( G_1 \epsilon \omega_0 / \sigma \lambda_D (1 + \delta) ) ac frequency</td>
</tr>
<tr>
<td>( U_0 )</td>
<td>( \omega_0 \mu G_1 (1 + \delta) ) Characteristic velocity [m/s]</td>
</tr>
</tbody>
</table>
The potential applied to the electrodes is $V_0$ and the characteristic voltage ($V_0$) is the peak-to-peak voltage applied to the electrodes. Equations (2) and (5) are converted into a simple dimensionless form as follows:

$$\nu^* = - \frac{1}{4} \nabla^2 V^* - \frac{\omega^*}{\lambda} \nabla V^*.$$

In order to validate the numerical scheme developed, we compared it with the previous studies.\(^7\,^8\) The dimensions of the geometry are $W_1 = 1$, $W_2 = G_1 = 10/3$, and the frequency is $\omega^* = 1.24$. The channel width (lateral length) is much longer than the channel height. In addition, the channel height is sufficiently high such that the top wall does not affect the flow structure anymore. The simulation domain included one pair having narrow and wide electrodes. Periodic boundary conditions were imposed on the inlet and outlet of the domain. Figure 2 shows the slip velocity profile along the electrode surface. The narrow electrode is located from $x^* = 0$ to 1. Only one reference is plotted in Fig. 2, since the results for other two references are the same. Our data are in excellent agreement with those of Olesen et al.,\(^5\) which verify the accuracy of our simulations.

### B. Simulations

In this study, the simulations are extended into three-dimensional geometries, because the electrodes are inclined against the channel direction. The widths of electrodes and their gaps are the same as those of Brown et al.\(^5\) The detailed simulation conditions are given in Table II. The applied frequency ($\omega^* = 1.12$) is optimal for maximal pumping in two-dimensional simulations with the present geometrical dimensions.\(^5\) The potential applied to the electrodes is $V_0 = 3$ V, which is free of bubble generation at the present electrode gap ($5 \mu$m).\(^11\) The working fluid is potassium chloride solution with $10^{-3}$ M, whose properties are almost the same as those of water, except for the electrical conductivity. The temperature is $25^\circ$C. The capacitance ratio $\delta = 4$ is taken from the previous studies.\(^2\,^10\)

The slip velocity is simply proportional to the square of the applied voltage, according to the linear theory of the electrical double layer. In addition, the flow structure is not affected by the applied voltage provided that the frequency remains unchanged from the linearity of the Stokes equation. Thus, if the flow rate is obtained for one applied voltage ($V_0 = 3$ V), the flow rates can be readily calculated for other applied external voltages. The mixing performance is evaluated by observing how the concentration distribution of a chemical reagent changes along the downstream direction. The concentration distribution is obtained by the convection-diffusion equation,

$$\frac{U^*}{\text{Pe}} \nabla^2 c^* = \frac{1}{\text{Pe}} \nabla c^*,$$

where the Peclet number is $\text{Pe} = U_0 G_1 / D = 5610$. The corresponding diffusion coefficient is $D = 2.5 \times 10^{-10}$ m²/s, which is a general value for commonly used chemical reagents.

Figures 3 and 4 depict a variety of electrode patterns on the bottom wall for simultaneous mixing and pumping. Hereafter, the dimensionless parameters will be expressed without the superscript "*." Figure 3 shows two different patterns of electrode pairs having diagonal shapes: a repeated pattern [Fig. 3(a) — type A] and a staggered pattern [Fig. 3(b) — type B]. The lengths of two patterns are $L = 39.04$ and 51.04, respectively, and the widths are the same as $l = 12$. Each pattern is repeated with a period of $L$ on the bottom wall. The first electrode pair for each type starts from the point (1,0). The arrows indicate the overall direction of fluid flow, predicted by the fact that the net flow is from the narrow electrode to the wide electrode in the case of two-dimensional flow. Accordingly, simultaneous mixing and pumping can be

### Table II. Detailed conditions for three-dimensional simulations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$</td>
<td>3 V</td>
<td>$U_0$</td>
<td>2.805 m/s</td>
</tr>
<tr>
<td>$G_1$</td>
<td>5 $\mu$m</td>
<td>$\nu$</td>
<td>$6.943 \times 10^{-10}$ C²/N m²</td>
</tr>
<tr>
<td>$W_1$</td>
<td>1</td>
<td>$\mu$</td>
<td>0.000891 Pa s</td>
</tr>
<tr>
<td>$W_2$</td>
<td>5</td>
<td>$\sigma$</td>
<td>0.01468 S/m</td>
</tr>
<tr>
<td>$G_2$</td>
<td>3</td>
<td>$\lambda_0$</td>
<td>10 nm</td>
</tr>
<tr>
<td>$H^*$</td>
<td>5</td>
<td>$\delta$</td>
<td>4</td>
</tr>
<tr>
<td>$\omega^*$</td>
<td>1.12</td>
<td>Pe</td>
<td>5160</td>
</tr>
</tbody>
</table>

FIG. 3. Two patterns of the electrode pairs with a diagonal shape (top view). Each pattern is repeated with period of $L$ on the bottom wall. (a) Repeated shape (type A); (b) staggered shape (type B).
achieved through the diagonal flows. Because the driving force caused by the slip velocity is divided into the channel and lateral directions, the pumping performance is then expected to be reduced to some extent, compared with the general pump having electrode lines perpendicular to the channel direction. The pumping may be useful for short channels, but not for long ones, because the latter may need a high pressure gradient to propel liquid. Figure 4 shows two staggered herringbone patterns: a diverging case of fluid flow [Fig. 4(a)—type C] and a converging case of fluid flow [Fig. 4(b)—type D]. The starting point of the first electrode is (1,0). As shown, the difference between types C and D is whether the diagonal flows converge to the center region or diverge to the side walls. The staggered patterns facilitate the mixing enhancement further. The patterns in Figs. 3 and 4 are periodically positioned on the bottom wall.

In order to determine the channel height for the above four types, we conducted preliminary two-dimensional simulations. Two different flow structures are illustrated in Fig. 5. The main difference is whether a recirculating flow is made in the region at a distance vertically from the leading edge of the wide electrode. The channel height \( H = 5 \) was selected for the present three-dimensional simulations because of the relatively complicated flows for mixing.

### III. RESULTS AND DISCUSSION

The numerical results are analyzed in terms of the flow streamlines, slip velocity, and concentration distribution in the center. Figure 6 displays the representative flow streamlines and the slip velocity on the electrode for type A, the repeated pattern of electrode pairs with a diagonal shape. The streamlines can be divided into two kinds. One is that the fluid in the vicinity of the starting point of each electrode pair flows along the leading edge of the wide electrode, showing helical motions. This unexpected flow may be attributed to the height effect explained in Fig. 5(a) and the fluid flow diagonally approaches the side wall. There are course helical fluid motions along the narrow electrodes. However, their sizes are so small, compared to the helical motions relating to the wide electrodes, that they are not drawn in Fig. 6(a). The main spiral motions in Fig. 6 are initiated mostly from the left and lower region of the first wide electrode \( (x = 3, \ y = 0) \) and terminated at the right and upper region \( (x = 15, \ y = 12) \). The other is that the fluid being at a distance from the starting point of each electrode pair tends to gather in the middle region of the electrodes and pass through the electrodes. This flow is similar to the expected flow in Fig. 3(a). The flow direction is just perpendicular to the electrode lines, having the cross-sectional flow structure shown in Fig. 5(a). These two representative flow patterns appear again in the region of the second electrode pair. In this manner, the upper and lower fluids in Fig. 6 exchange places on going downstream. In the meantime, the slip velocity is almost symmetric throughout the narrow electrodes, but it is asymmetric throughout the wide electrodes. Such an asymmetrical slip velocity distribution plays a primary role in inducing a net flow, which is consistent with previous studies. As for the wide electrodes, the slip velocity in the \( x \) direction \( (u_{\text{slip}}) \) is strong at the points where the leading edges contact with the side walls [some nearby points are marked with the symbol + in Fig. 6(b)], while the slip velocity in the \( y \) direction \( (v_{\text{slip}}) \) is dominant in the middle region.

The flow streamlines for the staggered pattern of electrode pairs with diagonal shapes (type B) are displayed in Fig. 7(a). Similar streamlines are observed on the electrodes, due to the same diagonal shape as type A. As mentioned...
earlier, the fluid near the starting point of each electrode pair flows along the leading edge of the wide electrodes, showing spiral motions. A difference from type A is that there is a larger space between the two electrode pairs, where the fluid flows without any disturbances. Such a large space would make the mixing performance of type B inferior to that of type A. In this study, the outlet condition is specified by

\[ c(x) = 1 - \frac{\int_A |c - c_\infty| dA}{\int_A |c_0 - c_\infty| dA}, \quad (9) \]

where \( c = c(y, z) \) is the cross-sectional concentration profile at a distance \( x \) downstream, and \( c_0 \) and \( c_\infty \) are the concentration profile and the concentration associated with an initial state and a completely mixed state, respectively. To assess the mixing degree quantitatively, we introduced a mixing efficiency, defined by

\[ e(x) = 1 - \frac{\int_A |c - c_\infty| dA}{\int_A |c_0 - c_\infty| dA}. \]

This means that the dominant mass transfer is made by fluid convection. Types A and B show good mixing; however, type A is better than type B. The reason is, as mentioned above, that type B has a larger space between two electrode pairs so that the fluid flows without any disturbance in the space, as ascertained in Fig. 8(b).

Analysis is extended to see the relation between the mixing enhancement and the helical motions observed. Toward this end, the fluid velocity field and the concentration distribution are put in the same figure. Figure 9 is a series of cross-sectional views of the velocity field \((v, w)\) and the concentration distribution, going downstream for type A. A small vortical structure appears first near the narrow electrode [Figs. 9(a) and 9(b)], and then a large vortical structure occurs by the presence of the wide electrode [Figs. 9(c) and 9(d)].

The outlet condition is

\[ n \cdot \nabla c = 0. \]

This means that the dominant mass transfer is made by fluid convection. The mixing efficiency \( e(x) \) was calculated at the outlet \( (x=L) \). The concentration distributions \((z=2.5)\) for types A and B are shown in Fig. 8. One interesting point here is that the concentration distribution shows a cross pattern in the region above the wide electrode. More precisely, the concentration \((6 \leq y \leq 12)\) is going down and up again after the region above the wide electrode, and the concentration \((0 \leq y \leq 6)\) is moving toward the direction parallel to the wide electrode. These behaviors can be easily imagined according to the flow streamlines in Figs. 5(a), 6(a), and 7(a), and by the fact that the concentration distribution is closely related with fluid convection.
is high at the points where the leading edge of the electrodes contacts with the side walls, while it is high at the bending points of the leading edges of the electrodes for type D. Consequently, the helical motions for type D are initiated from the middle region of the channel (the bending points of the electrodes), differently from the other three cases. In the meantime, the helical motions are induced from the fluid flow diagonally approaching the side wall. Therefore, type D has few opportunities to activate the spiral motions because the direction of diagonal flows is toward the center of the channel, instead of the fixed side walls. Such a weak spiral fluid motion affects the mixing performance. Figure 12 verifies that the mixing performance of type D is inferior to that of type C.

For a direct comparison among the four types, the flow rate and mixing efficiency are calculated and summarized in Table III. The flow rate \( Q = \int f(u dy dz) \) was calculated at the outlet \( x = L \). A reference is shown for comparison, which is the typical pump case whose electrode lines are straight and perpendicular to the channel direction. The dimensions of the electrodes are \( W_1 = 1 \), \( G_1 = 1 \), \( W_2 = 5 \), and \( G_2 = 3 \). The total channel length is \( L = 40 \) and the channel width is \( l = 12 \). First, the mixing efficiencies \( \epsilon \) are greatly enhanced by the present four types, compared with the reference in which mixing is made only by diffusion. As mentioned above in qualitative terms, the mixing efficiencies of types A and C are higher than those of types B and D, respectively. Closer inspection of the data in Table III indicates that the mixing efficiency is increased at a cost of the flow rate. The flow rates of types A, B, and C are reduced to the extent of

<table>
<thead>
<tr>
<th>Type</th>
<th>( Q )</th>
<th>( \epsilon )</th>
<th>( c_w )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>0.708</td>
<td>0.127</td>
<td>0.501</td>
</tr>
<tr>
<td>A</td>
<td>0.461</td>
<td>0.948</td>
<td>0.411</td>
</tr>
<tr>
<td>B</td>
<td>0.422</td>
<td>0.863</td>
<td>0.447</td>
</tr>
<tr>
<td>C</td>
<td>0.274</td>
<td>0.949</td>
<td>0.412</td>
</tr>
<tr>
<td>D</td>
<td>0.733</td>
<td>0.769</td>
<td>0.594</td>
</tr>
</tbody>
</table>

**TABLE III.** Pumping performance \( (Q: \text{flow rate}) \) and mixing efficiency \( (\epsilon) \). \( c_w \) is the concentration when completely mixed.
TABLE IV. \( \int u_{\text{slip}} \, dA \) is the integration value of the x-direction slip velocity.

<table>
<thead>
<tr>
<th>Type</th>
<th>( \int u_{\text{slip}} , dA )</th>
<th>( u_{\text{slip,max}} )</th>
<th>( u_{\text{slip,min}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9.174</td>
<td>1.81</td>
<td>-2.60</td>
</tr>
<tr>
<td>B</td>
<td>10.93</td>
<td>1.85</td>
<td>-2.66</td>
</tr>
<tr>
<td>C</td>
<td>10.07</td>
<td>1.87</td>
<td>-2.64</td>
</tr>
<tr>
<td>D</td>
<td>9.978</td>
<td>1.76</td>
<td>-2.63</td>
</tr>
</tbody>
</table>

40–65% of the reference. One point that should be noted here for type D is that, even though the mixing degree is comparatively reduced to those of the other three cases, the pumping and mixing are increased at the same time to the reference value. Such a desirable behavior may be explained by the slip velocity distribution. Recall that the electrodes of type D are arranged to lead to the higher slip velocity \( u_{\text{slip}} \) at the center region of the channel and the slower slip velocity at the electrode edges near the side walls. The energy going into fluid flow from the electrodes is not directed to the side walls where the viscous damping slows the fluid down. On the other hand, the slip velocities in the other three types are higher at the edges close to the side walls.

In order to validate the above analysis, we integrated the slip velocity \( u_{\text{slip}} \) throughout the electrodes, which is associated with the pumping ability. In Table IV, \( \int u_{\text{slip}} \, dA \) is the integration of the x-direction slip velocity over two electrode pairs. As shown, the values of \( \int u_{\text{slip}} \, dA \) are almost the same. This suggests that different flow rates in Table III are caused by different slip velocity distributions. The distributions of slip velocity for the reference and type D are shown in Fig. 13. The reference profile corresponds to the slip velocity profile shown in Fig. 5(a). The slip velocity of the reference does not vary in the y direction. However, the slip velocity for type D is mostly positive in the center region of the channel. Moreover, its magnitude is higher than the reference. This supports that the higher pumping is induced by the contribution of higher slip velocity in the center region of the channel.

IV. CONCLUSIONS

A detailed numerical analysis has been performed to elucidate the simultaneous pumping and mixing in a microchannel using asymmetric electrode arrays. The asymmetric electrode arrays were arranged to enforce fluid flows to the lateral direction for mixing and to the channel direction for pumping. Four patterns of the electrode pairs were chosen with diagonal/herringbone shapes. Concerning the diagonal shape, repeated and staggered patterns of the electrode arrays were studied. For the herringbone shape, diverging and converging patterns were examined. The pumping ability was assessed using the flow rate, and the mixing degree was quantified by a mixing efficiency. As a result, the spiral motion of flow along the leading edges of the wide electrodes played a major role in the mixing enhancement. The mixing performance was greatly increased for all four cases, compared with the reference case in which mixing occurs only by diffusion. The mixing efficiencies for types A, B, and C were increased at a cost of the pumping performances. Their pumping flow rates were reduced to the extent of 40–65% of the reference one. However, for type D, even though the mixing degree was comparatively inferior to those of the other three cases, the pumping and mixing were increased at the same time compared with the reference. Such a desirable behavior was attributed to the slip velocity distribution. The slip velocity is higher at the center region of the channel and slower at the region near the side walls, so that the energy going into fluid flow from the electrodes is not directed to the side walls where the viscous damping slows the fluid down. On the other hand, the slip velocity for types A, B, and C is low in the middle region of the channel and high near the side walls, so that the slip velocity does not make significant contributions to the pumping because of the viscous damping effect of the side walls.

ACKNOWLEDGMENT

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FIG. 13. Comparison of the slip velocity.