ENERGY CONVERSION EFFICIENCY ENHANCEMENT FOR ELECTROKINETIC MICROCHANNEL BATTERY

Chen-Kuang Lien¹, Yu-Feng Chen², Chueh Yang¹, Fan-Gang Tseng¹,³, Ching-Chang Chieng¹, Chien-Pin Chen⁴ and Chi-Chuan Wang⁵

¹Department of Engineering and System Science, National Tsing Hua University, Taiwan
²Industrial Technology Research Institute, Energy and Environment Research laboratories, Taiwan
³Division of Mechanics, Research Center for Applied Science, Academia Sinica, Taiwan
⁴Department of Chemical and Materials Engineering, University of Alabama, USA.

Abstract: This study demonstrates that the energy conversion efficiency from hydrostatic energy to electrical power can be enhanced by decreasing channel depth and the stack microchannel design inside the planar channel for electrokinetic microchannel battery.

Key Words: Electrokinetic, Debye Length, microchannel stack

1. INTRODUCTION

Electrokinetic microchannel battery is developed based on a streaming current due to the electrical double layer (EDL) between the electrolyte solution and channel wall for pressure-driven flow inside a fine channel. Very low energy transfer efficiency, less than 1% [1-4] by theories and far less than 1% [1, 2] by experiments, has been achieved by means of electrokinetic phenomena in previous studies. Recently, Van der Heyden et al. [5] suggested the tremendous increase of efficiency up to 12% by the decrease of ion mobility due to ionic conductance leading to power dissipation, but no experiment has been conducted to support the theory. To optimize the performance of the electrokinetic microchannel battery, the KCl electrolyte concentration and the channel depth are the parameters of interest in the present study. Furthermore, the conversion efficiency is significantly improved by the stack microchannel design inside the planar channel.

2. THEORY

For a solid surface in an electrolyte solution, the charged surface will induce counter ions to accumulate near the surface, whereas co-ions will be repelled by electrostatic force. This region is known as the electrical double layer and the characteristic thickness is the Debye length \( \lambda_D \). In the present study, a rectangular microchannel is considered as parallel plates for the channels with width to depth ratio larger than 10. According to the Debye-Hückel approximation, \( \lambda_D \) is equal to \( 1/\kappa \) and \( \kappa \) is the Debye-Hückel parameter defined as

\[
\frac{1}{\kappa} = \frac{\varepsilon_0 k_b T}{2 n_\infty e^2 z_0^2}
\]

where \( \varepsilon \) is the permittivity of the dielectric, \( \varepsilon_0 \) is the permittivity of free space, \( k_b T \) is the thermal energy, \( n_\infty \) is the ionic concentration in the neutral electrolyte, \( e \) is the elementary charge, and \( z_0 \) is the valence of ion.

For a one-dimensional pressure-driven electrokinetic flow in a parallel plate, the non-dimensional volume flow rate (\( \bar{Q} \)), streaming current (\( \bar{I}_s \)) and streaming potential (\( \bar{E}_s \)) for steady condition are related by [6]

\[
\bar{Q} = \frac{2G_1}{3} - \frac{4G_1 E_s}{K^2} \left[ 1 - \frac{1 - \cosh(K)}{K \sinh(K)} \right]
\]

\[
\bar{I}_s = -\frac{2G_1 \zeta \beta_1}{K^2} + 4G_1 E_s \beta_2 \left( \frac{\zeta}{K \sinh(K)} \right)^2
\]

\[
\bar{E}_s = \frac{2G_1 G_3 \zeta \beta_1}{K^2 + 4 \beta_2 G_2 G_3 (\zeta \sinh(K))^2}
\]

where \( K = d/2\lambda_D \) is a dimensionless parameter comparing the channel’s depth \( d \) and Debye length \( \lambda_D \). \( G_1, G_2, G_3, \beta_1, \) and \( \beta_2 \) are dimensionless terms as \( G_1 = \frac{d^2 P}{4 \mu V_0}, G_2 = \frac{n_\infty e^2 z_0^2}{4 \mu V_0 L} \), and \( \beta_1 = \frac{e^2 z_0}{2 \mu V_0}, \beta_2 = \frac{e^2 z_0}{2 \mu V_0 L} \).
\[ G_i = \frac{V_i n z e L}{\zeta \lambda_d}, \quad \beta_i = 1 - \frac{\cosh(K) - 1}{K \sinh(K)}, \]

and \[ \beta = \frac{\sin(K) \cosh(K) - 1}{2K} + \frac{1}{2}, \]

\( \zeta \) is the zeta potential, \( P_z \) is the pressure gradient. \( G_i \) represents the contribution of the applied pressure gradient. From Eq. (4), the magnitude of pressure gradient (\( G_i \)) is the essential to hold high streaming potential. For the battery, the energy conversion efficiency is the ratio of output power to the input energy [4],

\[ E_{\text{eff}} = \frac{1}{2} E_z I_z \frac{1}{P_z Q} \]  \hspace{1cm} (5)

3. EXPERIMENTAL

3.1 Experimental Setup

The schematic of experimental setup is illustrated in Fig. 1. The working fluid (0.01 mM or 0.001 mM KCl electrolyte) was driven by a syringe pump (MASTERFLEX), the resultant streaming current and voltage were measured by a multi-meter (KEITHLEY), and the pressure drop across the channel was recorded by a pressure sensor and transmitter (YOGOGAWA). The DAQ driver (NI, DAQPAd-6015) was connected to record the signal (LabView). The microfluidic chip of a single channel (Fig 2a) or of a planar channel with a stack of microchannels (Fig.2b) was implemented to the test section as shown in Fig.1. Ag-AgCl electrodes were connected to the electrical circuit.

3.2 Microfluidic chip fabrications

The first microfluidic chip was composed of a single channel and reservoirs as shown in the top figure of Fig.2a. The single channel was constructed with a converging inlet and a diverging outlet (Fig. 2a). The single channel was replaced by a planar channel for the second microfluidic chip (Fig.2b) and a stack of multiple microchannels is positioned at the throat of the planar channel (Fig. 2b). The chips were patterned on a glass wafer by lithography process and the wafer was etched by BOE. The width and length of the single channel were 40µm and 200µm but the depths were 2, 4, or 6µm. The depth, width and length of the planar channel were 4µm, 1.6mm and 5mm. 20 parallel microchannels of the same size as the one for the single channel on the first chip were patterned for the stack microchannels on the second chip, i.e. the width and length were 40µm and 200µm).

The glass chip was bonded with PDMS plate on top to form a closed channel. Successful bonding was achieved by the ultraviolet exposure of wavelength of 172nm under intensity of 4mW/cm² for 400sec.

Fig. 1: Schematic diagram of experimental setup.

(a) Reservoir  Reservoir

(b) 40µm

Stack of Parallel Microchannels

Fig. 2 Schematic diagrams of (a) the single channel chip, (b) the planar channel chip with twenty parallel microchannels.
3. RESULTS

3.1 The Control of Channel Wall Condition

After the ultraviolet exposure, the channel wall was functionalized with hydroxyl (OH) groups with varied hydrophilic degree and the history of contact angle was plotted in Fig. 3. The surface hydrophilic degree reached stable condition after 15 hours. The wall surface was varied from very hydrophilic to much less hydrophilic in 15 hours, i.e. the contact angles of glass and PDMS were $\sim 60^0$ and $\sim 40^0$. The energy conversion experiments were conducted after the wall surface conditions of microchannels were stabilized.

![Fig. 3: Contact angle histories on glass and PDMS surfaces](image)

3.2 The Effect of Channel Height and Electrolyte Concentration for a Single Channel Battery

Present study compares the energy conversion efficiency for electrokINETic microchannel batteries using microchannels with channel depth from 2 to 6 $\mu$m for KCl electrolyte concentration ranged from 0.001mM to 0.01mM. Table 1 tabulates the cases of study with parameters of the channel height and electrolyte concentration. The channel height is non-dimensionalized by the Debye length ($K = d / 2\lambda_D$) and Debye length is calculated by Eq. (1). The range of $d / 2\lambda_D$ is ranged from 3.3 to 10.3. The measured pressure drop was increased with flow rate for the same microchannel, but was decreased with channel depth decreased (Fig. 4). The output streaming potential and current versus flow rate was plotted in Fig. 5a and 5b. For the same flow rate, the output streaming potential and current were increased as $d / 2\lambda_D$ was decreased. The energy transfer efficiency was increased from 0.0003% to 0.0008% as $d / 2\lambda_D$ decreased from 10.3 to 3.3 (Fig 6). The energy transfer efficiency should be increased tremendously if the channel depth approached to $d / 2\lambda_D \sim 1$ or even smaller.

For the channel depth of 2um, $K(= d / 2\lambda_D)$ is 10.3 for 0.001mM and 3.3 for 0.01mM KCl electrolyte concentration. The electroviscous effect [6] is significant as seen from Fig. 4. In addition, from eqs. (3) and (4), the streaming current and potential are proportional to concentration, but inversely proportional to $K^2$. These are the reasons the output streaming potential and current are higher for concentration of 0.01mM than that of 0.001mM KCl electrolyte.

<table>
<thead>
<tr>
<th>$d$ ($\mu$m)</th>
<th>$n_a$ (mM)</th>
<th>$\lambda_D$ (nm)</th>
<th>$d / 2\lambda_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.01</td>
<td>97</td>
<td>10.3</td>
</tr>
<tr>
<td>2</td>
<td>0.001</td>
<td>307</td>
<td>3.3</td>
</tr>
<tr>
<td>4</td>
<td>0.001</td>
<td>307</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>0.001</td>
<td>307</td>
<td>9.8</td>
</tr>
</tbody>
</table>

![Fig. 4: The pressure drop versus flow rate at various channel heights $K(= d / 2\lambda_D)$](image)

![Fig. 5: (a) Streaming potential, and (b) streaming current vs. flow rate at various channel heights $K(= d / 2\lambda_D)$](image)
3.3 The Planar Channel Chip with a Stack of Microchannels

The output streaming potential and streaming current by using planar channel chip with a stack of parallel microchannels were plotted in Fig.7. Both of the streaming voltage and current were increased sharply as flow rate was increased. The maximum streaming voltage and current were ~3.5 V and 46 nA for flow rate near 0.5 ml/min. Comparing the result with single channel case (Fig.4), the increase is about ten folds in streaming potential and fifty folds in streaming current.

From Eq. (4), the streaming voltage is a function of pressure gradient, zeta potential (surface charge), ionic concentration, and channel depth to Debye length. The zeta potential (surface charge), ionic concentration, and channel depth to Debye length of planar channel are the same as the single channel in Section 3.2. According to theoretical analysis, there is no reason to get high potential in using planar channel. A possible reason for the remarkable streaming potential is that the multiplicity of the electrokinetic effect by the stack design of parallel microchannels. The maximum energy conversion efficiency reached 0.08% which was much higher than the efficiency of the single channel (near 15 to 100 folds). The planar channel with stacked microchannels was demonstrated as a successful design for electrokinetic microchannel battery.

4. CONCLUSION

For single channel, lower ratio of channel depth to Debye length promotes the better performance of the electrokinetic microchannel battery. For the planar channel with stack microchannels, the streaming potential is as high as 3.5 V at 0.52 ml/min flow rate. Comparing to the single channel, the energy conversion efficiency is increased from 15 to 100 folds. A possible reason for the remarkable streaming potential is that the stack microchannel enhances streaming potential and current effectively.

Fig.7: Streaming potential and current versus given flow rate for planar channel with gates.

ACKNOWLEDGEMENT

The authors highly appreciate the supports from Industrial Technology Research Institute and National Science Council, Taiwan under contract NSC94-2218-E-007-017.

REFERENCES