NOVEL EHD-PUMP DRIVEN MICRO MIXERS

T.-S. Leu * F.-C. Ma **

Institute of Aeronautics and Astronautics
National Cheng Kung University
Tainan, Taiwan 701, R.O.C.

ABSTRACT

Novel electrohydrodynamic (EHD) pump driven micro mixers are fabricated to study fluidic mixing in micro channels experimentally. Microscopic flow visualization experiments are presented to visualize microscale mixing in micro mixers. Mixing is achieved in a laminar flow by perturbing the main flow with EHD pumps in a micro channel. EHD pumps operate in a way to form cross-stream mixing mechanism by using either dc voltage or traveling wave signals. Experimental results show transverse or vortical cross-stream flows are generated within hundreds microns distance in the micro mixers, thereby increasing mixing.

Keywords : Micro mixer; Electrohydrodynamic (EHD) pump.

1. INTRODUCTION

Effective mixing is required in many microfluidic and BioMEMS devices. The low Reynolds number laminar flow missing turbulence eddies that causes microscale mixing very inefficiently. The main mixing mechanism is driven by diffusion only. For diffusion-based micro mixers, intermolecular diffusion of macromolecules is too slow to have effective mixing in small length of time scales. These factors make micro mixing a challenging process to achieve.

Deval et al. [1] have presented a dielectrophoretic chaotic mixer. In their studies, dielectrophoretic force is used to induce chaotic trajectories of embedded particles through electric actuation and local channel geometry. Another chaotic micro mixer approach based on magnetic force for mixing magnetic beads in bio-fluid is developed by Suzuki et al. [2]. It has shown the serpentine channel geometry with perpendicular electrodes arrangement can be used to create the stretching and folding of material lines in 3D flows configurations. Flowler et al. [3] in UCLA has also shown enhancement of mixing using droplet-based microfluidics. In addition to complicated channel geometry change, some of these micro mixers require either dielectrophoretic or magnetic beads to generate pumping force for mixing enhancement. In this paper, a novel EHD-pump driven micro mixer is proposed. This new EHD-pump driven micro mixer doesn’t need geometrical change of the fluid channel and require no extra additives in the fluid. It uses EHD-pumping mechanism to induce charge in the fluids and move the sample fluid in a way to enhance mixing.

2. MICRO MIXER DESIGN AND FABRICATION

In this study, the experiments were performed in a novel electrohydrodynamic (EHD) pump driven micro mixer designed and fabricated in Microfluidic System Laboratory at Department of Aeronautics and Astronautics, National Cheng Kung University in Taiwan. Different from a conventional microchannel design, this device was specially designed for the study of fluidic mixing in a micro device. The design of the micro mixer is sketched in Fig. 1. In Fig. 1, two inlets were shown for liquid A and liquid B entrance. Flows of liquid A and liquid B were supplied by two syringe pumps. The flow rates of the two sample streams could be easily adjusted by different settings of these two pumps. Two parallel sample streams meet and coflow into a main microchannel. It was proved the flow is hydrodynamic stable in the micro channel due to low Reynolds number. No turbulence vortices or eddies are found at the interface of two sample streams. Therefore, very ineffective mixing between two samples occurs in the main microchannel. To enhance mixing, two sets of EHD pumping electrodes are specially designed within a mixing zone of the main microchannel, as shown in Fig. 1. These two sets of EHD pumps can be used to manipulate the flow configuration near two sample interfaces and generate effective mixing in a short distance.

Figure 2 shows the fabrication sequence of the micro mixer. The micro mixer is composed by two different parts: an EHP-pumping electrode plate and a microchannel plate. For the EHP-pumping electrode
plate, thin film Chromium material is first sputtered on a Sodalime glass substrate and then patterned using photolithography to form two sets of EHD-pumping electrodes (Fig. 2a). The width, interspaces and thickness of the electrodes are 100μm, 100μm and 5000Å respectively. The microchannel plate of the micro mixer is fabricated by using milling machine on a plexiglass slide (Fig. 2b). The size of the main channel is 2000μm wide × 200μm deep × 8000μm long. The microchannel plate is drilled with 3 holes for two sample inlets and one outlet before bonding. Finally, EHD-pumping electrodes plate and microchannel plate are silicone bonded together to form micro mixers (Fig. 2c). Figure 3 shows the final package of the micro mixer on a PCB board that houses the micro mixer chip with electrode connections and enables fluidic connections to macroscale connectors.

### 3. EXPERIMENTAL SETUP

For a qualitative understanding of the mixing flow field, the flow was visualized by using microscopic flow visualization experimental setup. Figures 4(a) and 4(b) are sketch and image of the experimental setup. The working fluid consists of blue dye in bromobenzene in one half of the main channel cross-section and plain bromobenzene in the other. Two syringe pumps were used to drive the flow in the main channel. Studies were performed for this device which involved flows at Re ≈ 0.33. A flow rate of Q = 0.004mL/min is applied in the main channel (which corresponds to a bulk velocity $U$ is 166.7μm/s). Flow in the main microchannel follows a wake profile and is developing.

![Fig. 1 Sketch of EHD pump driven micro mixer design](image1)

![Fig. 2 Fabrication sequence of the micro mixer. (a) Deposit/Pattern Cr on glass to form EHD pumping electrode plate. (b) Plexiglass-milled microchannel plate (2000μm wide × 2000μm deep). (c) Glue bonding of electrode plate and microchannel plate](image2)

![Fig. 3 Package of the micro mixer on PCB board](image3)

![Fig. 4 (a) Sketch and (b) image of the microscopic flow visualization experimental setup](image4)
by the time it reaches the mixing zone, the area between pairs of EHD pumping electrodes. Experiments are performed by perturbing the interface of two samples through pairs of EHD pumping electrodes operating at a dc or a traveling wave signal. The time evolution of the flow is observed using a NIKON SMZ1000 microscope and a CCD camera. The resulting images are digitized by a frame grabber at 30 frames per second and flow visualization images are used to characterize the mixing in the flow. A high voltage power supply and a control circuit are built to generate either dc signal or traveling wave signal with controllable phase delay in EHD pumps.

4. EXPERIMENTAL RESULTS

Two operation modes of the EHD-pump are investigated in the current micro mixer experiments.

4.1 DC Voltage Operation Mode

In this mode, dc voltage is used in EHD pumps. Crowley [4], Stuetzer [5] and Pickard [6] have studied EHD pumps in this mode. Crowley [4] has shown the maximum pressure $P$ that can be generated in the pump by using dc voltage is

$$P \approx \varepsilon E^2$$

where $\varepsilon$ is dielectric constant of the fluid and $E$ is electrical field.

Equation (1) shows EHD pumping pressure is proportional to the square of electrical field $E$ applied between two electrodes. Before dc voltage is applied to EHD pumping electrodes, flow image is shown in Fig. 5. Figure 5 shows two sample fluids do not mix very effectively in the micro mixer. As soon as the dc voltage is applied to one pair of electrodes, EHD pump generates side force to perturb fluid interface. Mixing is completed in a very short distance. Figure 6(a) and 6(b) shows the sketch and the snapshots of flow pattern when dc voltage $V$ ranging from 70 volt to 280 volt is applied at 12th electrodes from left. The transverse cross-stream flows are generated within the micro mixers. The mixing effect is gradually enhanced with

![Fig. 5 Micro mixer before EHD pump actuation](image1)

![Fig. 6](image2) (a) The sketch and (b) the snapshots of flow pattern after dc voltage $V$ ranging from 70 volt to 280 volt is applied at 12th electrodes from left
the increase of dc voltage. Figure 7 shows the sequence images of mixing process when a dc voltage \( V = 280 \) volt is suddenly applied. In Fig. 7, the time difference between each image in sequence is \( 1/3 \) sec. The cross-stream mixing process is established within 1 second.

### 4.2 Traveling Wave Operation Mode

In traveling wave operation mode, traveling wave signals with a fixed phase delay are applied to a series of EHD pumping electrodes. Melcher [7], Fuhr [8] and Choi [9] have studied micro electro-hydrodynamic pump driven by traveling electric fields. In traveling wave mode, liquid motion is generated by the interactions between charged induced in the fluid and applied electric fields. For our case, a dielectric liquid, bromobenzene, is used and a six phase, 60 degree delayed, square traveling wave voltages are applied, as shown in Fig. 8(a). In this case, the time delay \( t_0 \) for each phase of the traveling wave signal is

\[
t_0 = T \frac{f}{6} = \frac{1}{6f}
\]

where \( T \) and \( f \) are the period and the frequency of the traveling electric field, respectively.

The instantaneous charge density \( \rho(x, y, t) \) can be expressed by

\[
\rho(x, y, t) = \rho_0 \left( 1 - e^{-\frac{t}{\tau}} \right), \quad 0 < t \leq t_0
\]

\[
\rho(x, y, t) = \rho(t_0) e^{-\frac{t-t_0}{\tau}}, \quad t_0 < t < 2t_0
\]

where \( x, y \) as shown in Fig. 1, are Cartesian coordinates in streamwise and transverse directions. \( \rho_0 \) describes the steady state charge density as time \( t \rightarrow \infty \). \( \tau = \varepsilon / \sigma \) is the charge relaxation time determined from the electrical conductivity \( \sigma \) and the dielectric constant \( \varepsilon \). \( \rho(t_0) \) is the instantaneous charge density at \( t = t_0 \).

The charge density as a function of time from 0 to \( 2t_0 \) can be shown in Fig. 8(b). In Fig. 8(b), dielectric fluid is first charged from 0 to \( 2t_0 \) when the electrical field is applied between electrode 1 and electrode 2, the accumulated charge \( \rho(t_0) \) from 0 to \( t_0 \) starts to relax following Eq. (4) and charged fluid is dragged at the same time by the electrical field applied between electrode 1 and electrode 2. The force density induced by the interactions between the induced charge and the traveling electrical field \( E(x, y) \) can be easily derived from Coulomb force \( = \text{Charge} \times \text{Electrical field} \) and is described as

\[
F(x, y, t) = \rho(t_0) e^{-\frac{t-t_0}{\tau}} E(x-x_p, y)
\]

where \( x_p \) is the pitch of the electrode.

Following similar analysis in Choi’s paper [9], the
generating instantaneous pressure $P(t)$ per one wavelength to the flow direction (positive $x$-direction) of the fluid is calculated by integrating the $x$-component of the force density

$$P(t) = \frac{1}{d} \int_0^\lambda \int_0^\delta F_x(x, y, t) \, dx \, dy$$

where $\lambda$ is the wavelength of the traveling electric field and $d$ is the height of the channel.

Since the instantaneous maximum pressure value $P_{\text{max}}$ occurs at $t = t_0, t = 2t_0, t = 3t_0, t = 4t_0, \ldots, nt_0$, $P_{\text{max}}$ could be described as (6).

$$P_{\text{max}} = (1 - e^{-\frac{t}{t_0}}) \int_0^\delta \int_0^\lambda \rho_0 E_x(x-x_p, y) \, dx \, dy$$

The integral term in Eq. (7) can be regarded as a constant. Therefore, Eq. (7) becomes

$$P_{\text{max}} \propto (1 - e^{-\frac{t}{t_0}})$$

The time average of the force density can be derived by integrating Eq. (5) from $t_0$ to $2t_0$.

$$< F_x(x, y, t) > = \frac{t_0}{t_0} (1 - e^{-\frac{t}{t_0}}) \rho_0 E(x-x_p, y)$$

The relationship between force density and the electrical stress tensor in the channel is expressed as

$$F_x(x, y, t) = \frac{\partial \mathbf{T}_y}{\partial y}$$

The velocity of the fluid can be calculated from (11).

$$\mu \frac{d\nu}{dy} + \{T_y(x, y, t)\} = 0$$

From Choi [9], the average velocity of the fluid is obtained as

$$v_{x,\text{avg}} \propto 6 \pi (1 - e^{-\frac{t}{t_0}})^2$$

and the flow rate $Q$ is described as

$$Q = v_{x,\text{avg}} \cdot w \cdot d \propto 6 \pi (1 - e^{-\frac{t}{t_0}})^2$$

where $w$ and $d$ are the width and the height of the channel, respectively.

Figure 9 shows the theoretical relations of pressure and flow rate to the function of $ft$. In Fig. 9, the maximum pressure decreases as $ft$ increases. The flow rate increases as $ft$ increases and has a maximum near $ft = 0.133$. Therefore, a theoretical maximum flow rate frequency exists when $ft = 0.133$.

Table 1 listed the maximum flow rate frequencies for different working fluids. From Table 1, some working fluid will not be feasible for traveling wave EHD pumps. For examples, the maximum flow rate frequencies of kerosene and Freon R133 are 1.09E−4Hz and 6.25E−5Hz respectively. These frequencies are so low that they are similar to dc voltage EHD operation mode. The maximum flow rate frequency for water is about 714Hz. In previous dc voltage EHD operation mode, the dc voltage amplitude for water is limited to 3 ~ 5 volt since water is going to hydrolyze above this limit. By using traveling wave mode EHD-pumps, it is possible to use high frequency ac traveling waveform signal to pump water. Fuhr [8] has demonstrated the traveling wave mode EHD-pumps for water in their experiments. For convenience of operation and flow visualization, dielectric fluid bromobenzene is used as working fluid in the current experiments. The maximum flow rate frequency for bromobenzene is about 2.78Hz.

Next, the traveling wave mode EHD-pumps is applied in the micro mixer. For the electrodes in upper half of the channel, the traveling wave signal is applied in the downstream direction that accelerates the fluid. For the electrodes in lower half of the channel, the traveling wave signal is applied in the upstream direction.
Table 1 The maximum flow rate frequency for different working fluid

<table>
<thead>
<tr>
<th>Working Fluid</th>
<th>Dielectric Constant $\varepsilon_r$</th>
<th>Conductivity $\sigma$ (1/Ω·m)</th>
<th>Relaxation Time $\tau$ (sec)</th>
<th>Maximum Flow Rate Frequency $f$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>80</td>
<td>0.0001</td>
<td>1.86E–4</td>
<td>714</td>
</tr>
<tr>
<td>corn oil</td>
<td>3.1</td>
<td>5.00E–11</td>
<td>5.49E–1</td>
<td>0.24</td>
</tr>
<tr>
<td>acetone</td>
<td>21</td>
<td>5.00E–06</td>
<td>3.72E–5</td>
<td>3580</td>
</tr>
<tr>
<td>kerosene</td>
<td>2.2</td>
<td>1.60E–14</td>
<td>1220</td>
<td>1.09E–4</td>
</tr>
<tr>
<td>bromobenzene</td>
<td>5.4</td>
<td>1.00E–09</td>
<td>4.78E–2</td>
<td>2.78</td>
</tr>
<tr>
<td>Freon R113</td>
<td>2.12E3</td>
<td>6.26E–5</td>
<td>2.13E3</td>
<td>6.25E–5</td>
</tr>
</tbody>
</table>

Note: $\varepsilon = \varepsilon_r \cdot \varepsilon_0$ where $\varepsilon_0$ is the electric permittivity of free space, which equals to 8.85E–12 F/m

Fig. 9  Plot of Eq. (8) and Eq. (13) as function of $f\tau$

that decelerates the fluid. Figure 10 shows the trace of debris when only the traveling wave signals are applied in the mixing region. The opposite directions in traveling wave signals at upper and lower EHD pumping electrodes make one side of the fluids move forward and the other side backward to generate vortical flow structure, as shown in debris images Fig. 10. Figure 11 shows sequence of flow images when traveling wave signal with frequency $f = 2.78$Hz and voltage amplitude $V = 280$volt is suddenly applied in the micro mixer. In Fig. 11, the time different between each image in sequence is 1/15sec. The cross-stream mixing process is established less than 1/3 second. Flow visualization image sequence movie also shows unsteady perturbation in the mixing zone generate cross-stream mechanism which enhancing mixing in a very effective way.

To maximize mixing effects, the optimized traveling wave frequency for mixing enhancement is investigated. In Fig. 12, traveling wave signals with frequency $f = 2.78$, 10, and 20Hz and voltage amplitude $V = 280$volt are used. These three frequencies is marked as (a) $f\tau = 0.133$, (b) $f\tau = 0.48$ and (c) $f\tau = 0.96$ in Fig. 9 respectively. It is easy to identify in Fig. 12 that mixing is enhanced more effectively when traveling wave signal with frequency $f = 2.78$Hz is applied.

In Table 1, frequency $f = 2.78$Hz happened to be the maximum flow rate frequency of bromobenzene calculated by using theoretical result $f\tau = 0.133$, where $\tau$ is the relaxation time scale of bromobenzene, obtained from dielectric constant $\varepsilon$ and conductivity $\sigma$ of bromobenzene.

It is surprised to find that the quantitative theoretical results in Figs. 8 and 9, as well as the equation in Section 4 can be applied in the present problem even the mean flow effect is not included in the analysis. The main reason is that the mechanism of EHD pump is related to how well the working fluid being charged by one electrode and being moved by electric field between two electrodes. The relaxation time $\tau$ responsible for charging time scale of a dielectric fluid is not relevant to mean flow condition since it is determined by its dielectric constant $\varepsilon$ and conductivity $\sigma$. The mean flow effect will be minimized as long as the charged fluid does not displace away from the charging electrode by mean flow during the charging time of the signal. The displacement $x_0$ of the charged fluid by mean flow is about 10μm estimated from the average velocity (166.7 μm/sec for the current flow rate) and charging time $t_0$ (0.06sec for the maximum flow rate traveling wave
signal of bromobezene). The displacement $x_m$ is only $1/10$ of the electrode width. Therefore, the mean flow effect on the EHD pumping mechanism is very limited. The quantitative theoretical results could be applied in the present problem. Of course, it is expected that the maximum flow rate frequency may not be an appropriate value if the mean flow (or Reynolds number) is too high. Therefore, the optimized frequency is proven to be the same as the maximum flow rate frequency which produce the maximum amplitude of perturbation for mixing enhancement in the present EHD micro mixer.

**5. CONCLUSION**

We have designed and fabricated a simple efficient EHD-pump driven micro mixer that can be easily integrated in a microfluidic system. No additives and no geometrical change in the microfluidic systems are required for the micro mixers. Both the experiments and the theoretical analytical revealed the operation principles of the EHD-pump in micro mixer applications. When EHD pumps appropriately operate, transverse or vortical motion can be generated near the interface of two fluids. Efficient mixing can be achieved within a short distance and time scale.

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