VOXER GENERATION IN A RESONATOR-SHAPED MICROFLUIDIC CHAMBER

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Due to low Reynolds number flow, it is always challenging to generate vortex in a microfluidic structure. This paper presents an experimental study on vortex generation in fluid flows in a resonator-shaped micromixer incorporated with piezoelectric (PZT) actuations. The vortex development is visualized by tracing fluorescent dyes in the flow and characterized under various actuation conditions, including the actuation voltage, frequency and flowrate. It is demonstrated that given an actuation frequency and flowrate, the large scale vortices can be generated inside the mixing chamber and fully controlled by the actuation voltage. A frequency window is identified, in which the vortex generation is possible. Bubbles are also observed, but are only associated with strong vortices under high actuation voltages. The results reveal that the mixing enhancement in the micromixer is mainly attributed to the vortex flows by the actuation.

1. Introduction

Nowadays, microfluidic systems have been broadly applied in different fields, such as chemistry, medicine and biology, owing to their advantages of portability, cost-effective, time reduction, less sample consumption, and less contamination. It is always challenging to generate a desirable flow in microfluidic systems for different applications, such as particle sorting and fluid mixing. Among various flow patterns, vortex generation in microchannels has recently become an active research topic. It is known that the Reynolds numbers for flows in microchannels are small, normally in an order less than or equal to one, leading to the creeping flow characteristics with no inertial effect. Vortices are therefore difficult to be formed. Efforts have been made for vortex generation by using some specially arranged flow configurations or externally induced actuations. It was reported that the vortices can be generated in channels with a sudden expansion. Oliveira et al. investigated vortex generation in microchannels by using the hydrodynamic focusing. In their studies, the microchannels formed a cross-junction and the flows were driven onto the junction from three inlets at different flowrates. Symmetric vortices were observed in one of the inlet channels, depending on the driving flowrate ratios. Vortices can also be generated by applying AC electric fields in microfluidic channels, together with laser beams. It was demonstrated that, in a microchannel formed by two plates, the use of an intensive laser irradiation in the presence of electric field can produce strong vortices. The underlying mechanism involved is due to a combina-
tion of electrothermally-induced fluid motion and electrohydrodynamically-induced fluid motion. Wang C et al. developed a technique to generate vortices in a microchannel for particle sorting. In their device, cavities were fabricated along a microchannel to trap and form air bubbles. Under applied PZT actuations, the air bubbles oscillate and interact with flow in the channel, thereby generating vortices near the bubble-flow interfaces.

Recently, a new microfluidic mixer was developed by our group. The mixing enhancement can be achieved in the mixer for the high viscous fluids with viscosities up to 50 times of DI water. The good mixing was attributed to the oscillating bubbles generated in a microfluidic chamber by PZT actuations. However, a further examination of the mixing processes reveals that the mixing enhancement could occur much earlier than the bubble development. Especially the bubbles in the mixing chamber for high viscous fluids are normally small and the bubble oscillations are not strong for mixing enhancement. It is believed that, other than oscillating bubbles, other unsteady flows, such as vortices may also be generated in response to the actuations and hence contribute to the observed mixing enhancement. This motivates the present study. In this paper, flow visualizations are conducted to investigate the flow fields inside the micromixer under various actuation and flow conditions, focusing on the vortex generation and mixing enhancement.

2. Microfluidic mixer and experiment setup

The microfluidic mixer was fabricated using the lamination technology. As shown in Fig. 1(a), the mixer consists of two thick PMMA layers sandwiched with a spacer made of a 300 µm thick dry adhesive layer (Arclad 8102 transfer adhesive, Adhesives Research, Inc.). The upper plate is 1mm in thickness while the lower plate is 2mm thick. The main channel contains two parts, a 16 mm diameter circle chamber, and a nozzle-shape channel with an acoustic resonator profile used for an acoustic resonator. The overall geometric profile of the chamber is given by

\[
y = \begin{cases} 
\sqrt{8^2 - x^2}, & -8 < x \leq 4 \\
0.5e^{0.1011(30-x)}, & 4 < x < 30 
\end{cases}
\]  

(1)

Two 10 mm long and 1 mm wide channels are connected to the main chamber to form Y shape inlets, and one straight channel is connected from another end of the chamber to form one outlet. A piezoelectric disk (Model number BZ21C15NS, AL Goodwell Industries Ltd.) is attached to the circle chamber from the bottom to provide actuations. The piezoelectric actuation is provided by using a 15 mm diameter layer of piezoelectric ceramic disk glued on the top of a 0.1 mm thick, 22 mm diameter brass sheet. Fig. 1(c) shows a picture of the microfluidic mixing device, demonstrating that without actuation of the piezoelectric disk two streams from the upper and lower parts of the channel flow laminarly with no significant broadening of the interface between a DI water-glycerol solution supplied from inlet A and a DI water-glycerol solution with fluorescent dye supplied from inlet B. The fabrication details of such micromixer can be found elsewhere.

In the experiment, a degassed DI water-glycerol (20%) solution was supplied to the microfluidic mixer at inlet A, and the same DI water-glycerol solution with a fluorescent dye was supplied to inlet B, as shown in Fig. 1(c). The flowrates were varied and controlled by two syringe pumps (KD Scientific Inc., USA). The vortex formation and development were visualized through the tracing of the solutions with a fluorescent dye. The piezoelectric disk
was driven by an external signal generator (33120A, Hewlett Packard) and an amplifier (790, PCB Piezotronics) where a sinusoidal signal from the signal generator was amplified 60 times. Both the actuation frequency and the voltage were varied in the experiment. The Reynolds number (Re) in the present study is expressed by

$$\text{Re} = \frac{u L_h}{\nu},$$

(2)

where $u$ is the averaged flow velocity at the straight channel of the mixer, $L_h$ is the hydraulic diameter of the channel (of order $O(10^{-3})$m) and $\nu$ is the kinematic viscosity of the DI water-glycerol solution. The typical Reynolds number in the experiment was of order $O(1)$, and hence a laminar flow should be expected inside the channel in the absence of actuation.

**Figure 1.** Schematic illustration of the microfluidic mixer. (a) a side view of the mixer configuration; (b) a top view of the mixer with channel design and geometric dimensions; (c) a picture of the mixing device used in the study. The image shows that in the absence of the actuation there is no mixing in the fluid. DI water-glycerol solution supplied from inlet A and a DI water-glycerol solution with fluorescent dye supplied from inlet B. The cross line $C'-C$ is chosen to analyse the vortex strength.

The vortex and mixing images were recorded using a CCD camera (Phantom V711, Vision Research, USA). The intensity of grayscale in the recorded images is proportional to the fluorescent dye concentration. When the actuation was switched on, the vortex would be formed inside the chamber to bring the fluorescent dye from the lower portion to the upper half of the chamber where the fluorescent concentration was initially zero. The fluorescent concentration at the upper half of the chamber is therefore an indication associated with the vortical flow and vortex strength. To quantitatively characterize the vortex and mixing quality, a MATLAB code was developed to process the recorded images. A cross line $C'-O-C$ (Fig. 1c) located at the centre of the chamber was chosen to be analyzed. $O-C$ was in the lower half where the fluorescent solution was supplied while $O-C'$ was in the upper half where the fluorescent
concentration was zero before the actuation. The vortex intensity is calculated using the following expression:

\[
Vortex\ Intensity(\%) = \frac{\overline{I}_{OC}}{\bar{I}_{OC}} \times 100\%
\]  

(3)

In equation (3), \(\overline{I}_{OC}\) represents the averaged image intensity along O-C sometime after the actuation, and \(\bar{I}_{OC}\) represents the averaged image intensity along O-C before the actuation. Ideally, this expression will give 0% at the beginning of actuation and 50% for a perfect mixing after long time.

3. Vortex generation and characterization

By using the fluorescent dye as flow tracers, the vortices are observed inside the microfluidic chamber after the actuation is switched on under various voltages and frequencies. Figure 2 shows a typical vortex development at different times with the actuation. The experimental conditions include: a flowrate of 6ml/hr at both inlets A and B, an actuation voltage of 80V and a driving frequency of 2500Hz. Before the actuation (Figure 2(a)), the upper fluid (without fluorescent dye from inlet A) and the lower fluid (with fluorescent dye from inlet B) are separately flowing through the chamber, indicating no mixing and vortices. However, as shown in Figure 2(b), 5 seconds after the actuation the fluorescent dye fluid has been rotated up and obviously a vortex pattern can be observed. The fluorescent fluid is continuously rotated into the upper-half chamber (see Figures 2(c-e)). Finally at 25 seconds (Figure 2(e)), a big vortex is found to be occupying almost the whole chamber and a small one is located at the upper-left.

![Figure 2](image-url)

**Figure 2.** Recorded images in time sequence to show the development of the vortex under the actuation. The actuation voltage and frequency were 80V and 2.5KHz respectively, and the flowrate was 6ml/hr.
Since our vortex experiment is observed by tracing the fluorescent dye, the time scale shown in experimental image results is dependent on the fluorescent dye transport in flow with actuation effects. In fact, the actual vortex development corresponding to the actuation should be much faster and it is mainly characterized by the actuation frequency. To justify these arguments, scaling analysis suggests that the characteristic time for vortex development is of order $\tau_{\text{vortex}} = O(1/f)$. Using the actuation frequency $f = 2.5$ KHz, we can obtain the vortex development time of order $\tau_{\text{vortex}} = O(10^{-3})$ s. On the other hand, there are two time scales associated with the fluorescent dye transport. One is by the molecular diffusion estimated by $\tau_{\text{dye, diff}} = O(L_h^2/D)$. Taking $D_n$ as $10^{-10}$ m$^2$/s for the dye diffusivity$^{12}$, we can obtain $\tau_{\text{dye, diff}} \sim O(10^5)$ s, which is too slow to be taken into account here. The other time scale is by convective transport estimated by $\tau_{\text{dye, conv}} = L_h/U$ with $U$ being the vortex flow velocity. By taking $U$ to be in the same order of the mean flow velocity $u$ that is used in calculating the Reynolds number, we can find $\tau_{\text{dye, conv}} \sim O(1)$ s, which is in agreement with our experimental observation shown in Figure 2.

By using the vortex strength defined in Equation (3), the vortex generation and development are further characterized in terms of the actuation voltage, frequency and the flowrate. We take 30% as a criterion to determine whether the vortex is formed or not inside the chamber. Such criterion, though it is a bit arbitrary, can be used as an indicator for describing the vortex generation at different flow and actuation conditions.

Figure 3 shows the vortex strength versus time for different actuation voltages, with the frequency and flowrate being fixed at 2.5 KHz and 4 ml/hr, respectively. It is seen that, at the low actuation voltage 50V, the vortex cannot be properly formed and the vortex strength is remained below 30%. As the voltage is increased to 60V, the vortex strength is above 30% after 9 seconds. The higher voltage applied, the shorter time taken to bring the vortex strength above 30%, indicating a stronger vortex formed by the actuation. However, at very high actuation voltages, gas bubbles are generated in addition to the strong vortex flow. This can be seen in Figure 3 for the actuation at 120V, a small bubble is found at the upper-left corner (indicated by a dashed circle in the photo). The bubbles generation in this type of mixer was reported previously$^{4-5}$, in which flow mixing enhancement was attributed to the bubble oscillations without mentioning the vortices.

![Figure 3](image)

**Figure 3.** Vortex formation and development under different actuation voltages. The fluorescent intensity along the line C'-O-C (shown in Figure 1) was calculated and 30% was taken as an indicator to evaluate the vortex strength. The actuation frequency and flowrate were fixed at 2.5 KHz and 4 ml/hr respectively.
The present study reveals that the vortices generated by the actuation may play a major role in the mixing enhancement. The results presented in Figure 3 show that the vortex strength can be controlled by the actuation voltage, and the bubbles are generated only at higher actuation voltages and are associated with the strong vortices.

Figure 4. Vortex formation and development under different actuation frequencies. The fluorescent intensity along the line C'-O-C (shown in Figure 1) was calculated and 30% was taken as an indicator to evaluate the vortex strength. The actuation voltage and flowrate were fixed at 80V and 4ml/hr respectively. (a) Development of the vortex strength versus time after the actuation. (b) The vortex strength calculated at 25 seconds after the actuation versus the actuation frequency.

Figure 4 shows the vortex strength versus time for different actuation frequencies, with the actuation voltage and flowrate being fixed at 80V and 4ml/hr respectively. The results show that, at 2KHz and 2.5KHz, the vortex generations are quite strong, indicated by the short times (~5s) for the vortex strength to reach above 30%. At either higher frequencies of 3.5KHz or a lower frequency of 1.5KHz, the vortices are found to become weaker as it takes longer time (>20s) to achieve the vortex strength above 30%. Further increasing the frequency to 4KHz or reduces it to 1KHz, there is no vortex formed. By calculating and plotting the vortex strength at 25 seconds for these frequencies, as depicted in Figure 4(b), it shows that there is an actuation frequency window centered around 2-2.5 KHz with about 2 KHz in width. The vortex generation is only observed inside this frequency window. Such actuation frequency window is found to depend on the actuation voltage and flowrate. Figure 5 shows the vortex strength...
versus time for different flowrates, with the actuation voltage and frequency being fixed at 80V and 2.5KHz respectively. It can be seen clearly from Figure 5 that at low flowrates the vortices are relatively easy to be generated and the strengths are strong, while the vortices are relatively weak at high flowrates, even unable to be generated if the flowrate is equal to or higher than 20ml/hr. These vortex generation results indicate strong interactions of the hydrodynamic driving of the incoming flows and PZT actuations inside the chamber. The hydrodynamic force from the syringe pump is to maintain the flowrate and laminar flows in the channel, while the actuation is to impose an external force on the flow for the vortex generation. It is believed that relatively higher pressures, corresponding to high flowrates, can counterbalance low pressures produced by the actuations so that the vortex becomes weak, is suppressed, or even completely vanishes.

![Figure 5](image)

**Figure 5.** Vortex formation and development for different flowrate through the channel. The fluorescent intensity along the line C’-O-C (shown in Figure 1) was calculated and 30% was taken as an indicator to evaluate the vortex strength. The actuation frequency and voltage were fixed at 2.5KHz and 80V respectively.

4. **Conclusions**

Experimental studies have been conducted with focus on vortex generation for liquid flows in a micromixer with PZT actuations. The vortices under the actuation have been visualized and characterized in terms of the actuation voltage, frequency and flowrate. The following conclusions are drawn from this research.

- A novel method to generate vortices in a specially designed micromixer has been demonstrated. By applying PZT actuations, large scale vortices can be generated inside the micromixer, in which only laminar flows would exist otherwise. The vortex strength can be fully controlled by the actuation voltage, depending on the actuation frequency and flowrate. This feature is quite unique and may have advantages in various applications.

- Bubbles can be induced in the fluids at high actuation voltages which generate strong vortices. The mixing enhancement is mainly attributed to the vortex flows, apart from the oscillating bubbles.

Further studies are needed to explore the mechanisms of the vortex generation demonstrated in this study, the actuation frequency windows observed in our experiments, and the effect of mi-
cromixer configurations. It is also necessary to examine the detailed flow field under the actuations through both direct flow experimental measurements and numerical simulations.

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REFERENCES