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SHORT COMMUNICATION

Acoustically induced bubbles in a microfluidic channel for mixing enhancement

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Abstract Due to small dimensions and low fluid velocity, mixing in microfluidic systems is usually poor. In this study, we report a method of enhancing microfluidic mixing using acoustically induced gas bubbles. The effect of applied frequency on mixing was investigated over the range 0.5–10 kHz. Under either low frequency 0.5 kHz or high frequency 10 kHz, no noticeable improvement in the present mixer was observed. However, a significant increase in the mixing efficiency was achieved within a window of the frequencies between 1.0 and 5.0 kHz. It was found in our present microfluidic structure, single (or multi-) bubble(s) could be acoustically generated under the frequency ranging from 1.0 to 5.0 kHz by a piezoelectric disc. The interaction between bubble and acoustic field causes bubble oscillation which in turn could disturb local flow field to result in mixing enhancement.

Keywords Microfluidics · Mixing · Acoustic cavitation

1 Introduction

Microfluidic devices promise to offer a viable microfluidic platform for miniature chemical, medical, environmental and security diagnostic kits as well as well controlled fundamental chemistry and biology research (Erickson and Li 2004). The main advantages of microfluidic systems include portability, cost-effective, time reduction, little sample consumption, and less contamination (Tudos et al. 2001). Micromixing is one of important functions of microfluidic systems; for example the processes such as DNA hybridization, cell activation, enzyme reactions, and protein folding require fast reactions that involve mixing of the regents or/and reactants. However, due to small dimensions, the Reynolds number is usually quite low, and flow in microfluidic systems is absolutely laminar. As a result, the mixing is mainly based on molecular diffusion, and hence long mixing length/time is required and the mixing efficiency is poor (Beebe et al. 2002).

In order to achieve complete mixing within a reasonable time and channel length scale, numerous mixing techniques have been developed, and mixing devices can be categorized as either passive mixers or active mixers (Nguyen and Wu 2005; Hessel et al. 2005). Passive mixers utilize geometrical advantages to enhance mixing and they do not require external forces. Approaches such as lamination with zig-zag paths (Liau et al. 2005) and splitting and recombining streams (He et al. 2001) can increase the interfacial area for diffusion. Using a 3D-serpentine microchannel can generate chaotic advection to stretch and fold volumes of fluids to be mixed over the cross-section of channel (Liu et al. 2000; Stroock et al. 2002). A droplet based microfluidic system was also reported to achieve fast mixing by inducing chaotic flow inside droplets moving through winding microchannels (Song et al. 2006). Active mixers utilize external driving forces to disturb the flow to enhance mixing. Examples are the mixing devices using oscillating pressure (Glasgow and Aubry 2003), magnetohydrodynamic (Bau et al. 2001), electrohydrodynamic (El Moctar et al. 2003), and electrokinetic instability (Oddy et al. 2001) and electrokinetic heterogeneity (Biddiss et al. 2004). In the literature, several studies on acoustic field enhanced microfluidic mixing were reported. Yang et al.

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(2001) designed an ultrasonic micromixer based on ultrasonic vibration produced by a PZT diaphragm excited with 60 kHz and 50 V_{pp}. The mixer chamber was fabricated using silicon wafer covered with glass. However, it still needs long time to achieve complete mixing in this device. Another drawback is that the rate of mixing could not be increased with input power and there is a problem associated with temperature rise induced by high-frequency ultrasonic irradiation. Liu et al. (2002) developed an acoustic micromixer relying on bubble oscillation to induce secondary flow similar to a sink-source flow pattern. It was demonstrated that complete mixing can be achieved within several tens of seconds, with a significant improvement compared to the mixing time reported by Yang et al. (2001). Low energy was consumed with 2.0 kHz and 5 V_{pp}. However, foreign gas bubbles were needed to be introduced and trapped on the mixer chamber wall.

In this communication, we report a technique to enhance mixing in a polymer based microfluidic structure using acoustically induced gas bubbles by a piezoelectric unit. It will be demonstrated that in the present microfluidic structure, enhanced mixing can be achieved under a window of applied acoustic actuation frequencies. Different from Yang et al. (2001)'s work where no gas bubble was present, the mixing enhancement is achieved through acoustically generated gas bubbles, and the required frequency is much lower so that the problem associated with temperature rise due to acoustic irradiation can be reduced. Compared to Liu et al. (2002)'s study where a foreign bubble is needed to be trapped on the mixer chamber wall, the gas bubble in our case is automatically generated by acoustic field so that we can have a better control. Experiments were conducted to study the effect of applied frequency on the mixing processes over the frequency range 0.5–10 kHz.

2 Experimental

Figure 1a depicts a side view of the microfluidic mixer that was constructed by two 2-mm thick PMMA layers sandwiched with a spacer made of a 300-µm thick dry adhesive layer (Adhesives Research, Inc., Arclad 8102 transfer adhesive). A CO_2 laser was used to cut the adhesive layer to form a Y-channel for introducing mixing liquids from two inlets and a chamber for acoustic actuation. The height of the actuation chamber and the Y-channel is 300-µm, and other dimensions are indicated in Fig. 1b. As shown in Fig. 1b, the actuation chamber consisted of two parts, a circle chamber to accommodate a piezoelectric disc and an exponentially expanded nozzle. A similar design of the chamber was used for an acoustic resonator by Luo et al. (2007). A 10-mm long and 1-mm wide straight channel

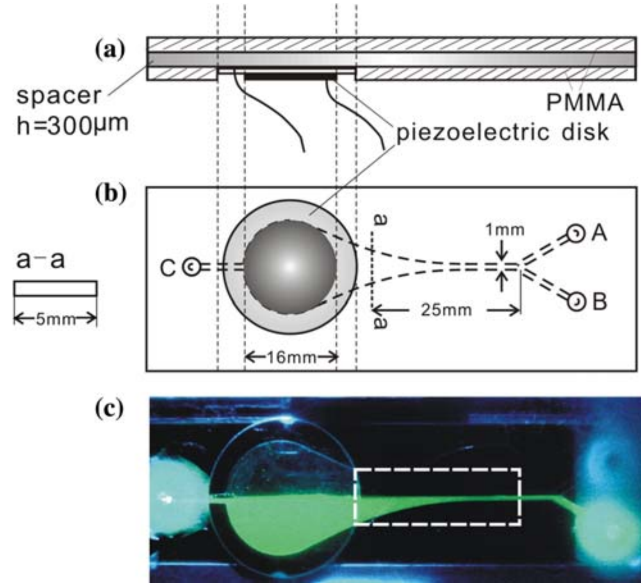


Fig. 1 Schematic illustration of the acoustic microfluidic mixer. **a** Side view of the mixer configuration, **b** top view of the mixer, **c** visualization of fluorescent dye in mixing experiment before powering on the piezoelectric disc

was connected from another end of the nozzle to form the outlet *C* of the mixer. A piezoelectric disc of 10-mm diameter (Model number BZ21C15NS, purchased from AL Goodwell Industries Ltd) attached to a 0.0995-mm thick, 16-mm diameter brass sheet was assembled underneath the circular part of the chamber. The brass sheet is directly in contact with the mixing liquid in the chamber, while the nozzle was sandwiched between the two PMMA layers. The piezoelectric disc 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 20 times by the amplifier.

In the mixing experiments, DI water was supplied to the inlet *A*, and fluorescent dye dissolved in DI water was supplied to the inlet *B*. Two syringe pumps were used and the same flow rate was set for two streams of mixing liquids at 5 ml/h, respectively. Six different frequencyies were applied including 0.5, 1.0, 1.5, 2.0, 5.0, and 10.0 kHz. The input voltage was fixed at 5 V_{pp}. The intensity of the fluorescent dye was recorded using a CCD camera (DCR-DVD803E, SONY), and the results were used to assess the quality of the mixing processes in the microfluidic structure decribed above.

3 Results and discussion

When the piezoelectric disc was not actuated, there was almost no occurrence of mixing throughout the mixer, as can be seen from a clear interface between the two streams of liquids shown in Fig. 1c. This should be expected because the characteristic Reynolds number is of order $O(1)$ (estimated from the characteristic velocity, 10-mm/s, the characteristic hydraulic diameter, 0.46-mm, and the kinetic viscosity, 1-mm^2/s), suggesting that the mixing in this laminar flow case is dominated by molecular diffusion only. However, once the piezoelectric disc was actuated, an enhancement in the mixing was observed, as shown in Fig. 2 which depicts the effect of applied frequency on the mixing in the present microfluidic structure.

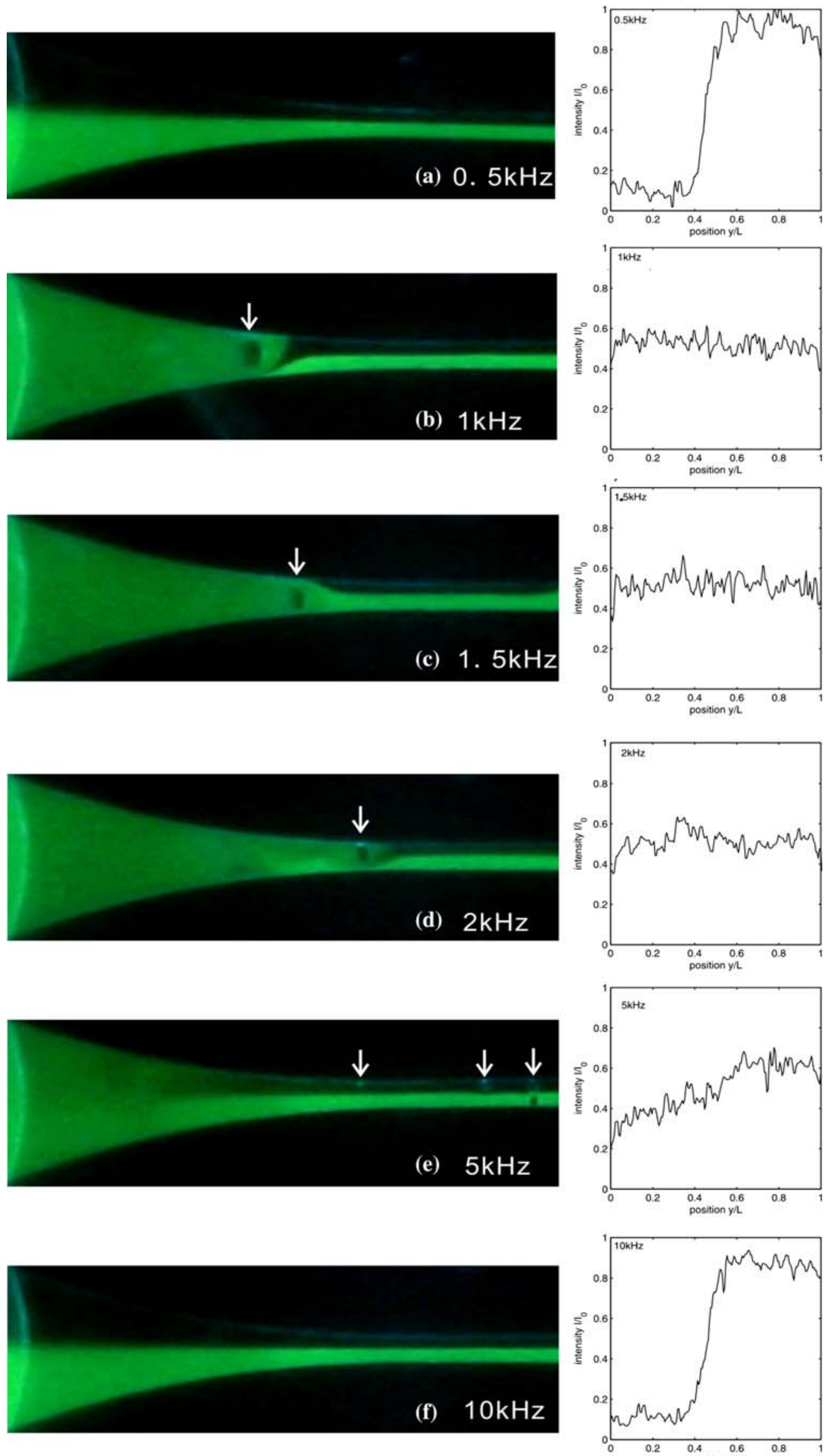
To quantitatively characterize the mixing quality, we wrote a MATLAB code to process the captured fluorescent images. It is assumed that for a certain point in an image, the fluorescent dye concentration c_i is related to the image intensity I_{i}. For analyses, we choose a cross-section located in the nozzle channel (as indicated by the line *a*–*a* in Fig. 1b). The results of the normalized fluorescent intensity distributions along such cross-section are also displayed in Fig. 2. Furthermore, we calculated the mixing efficiency using the following expression:

$$\sigma = 1 - \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\bar{I}_{\mathrm{i}} - \bar{I}_{\infty}\right)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\bar{I}_{0\mathrm{i}} - \bar{I}_{\infty}\right)^2}}$$

where N represents the total number of points examined along the cross-section *a*–*a*, $\bar{I}_{\mathrm{i}}$ is the normalized intensity at each point, $\bar{I}_{0\mathrm{i}}$ is the normalized minimum intensity at each point without mixing taking place (e.g., value 0 or 1 in this study), and $\bar{I}_{\infty}$ is the normalized maximum intensity in complete mixing states (e.g., value 0.5 in this study). Figure 3 shows the mixing efficiency versus applied frequency. Under the experimental conditions studied, it can be noted that when the frequency was below 1 kHz or above 5 kHz, the mixing was still poor (indicated by the low mixing efficiency less than 10%). This suggests that the acoustically induced vibration does not make noticeable contribution to the mixing in our case. However, significant mixing was occurred within a window of the frequencies ranging from 1 to 5 kHz; for instance, at the driving frequency of 1.5 kHz the mixing efficiency could reach as high as near 90%. To interpret this scenario, a close examination of Fig. 2 indicates that gas bubble(s) were generated within this window of the frequency applied. After the power that drives the piezoelectric disc was turned on, bubble(s) could be generated within 1–2 s. As indicated by the arrows in Fig. 2, higher frequency shifted the occurrence of the bubble generation towards the Y-channel side because under a higher frequency, the size of bubbles became smaller so that the bubbles were present in a region to accommodate the channel size so that they could be more stable. At the high driving frequency of 5 kHz, several small bubbles were found to be trapped on the channel wall. From the recorded images, we could roughly estimate that corresponding to the frequencies of 1, 1.5, 2, and 5 kHz, the induced bubbles sizes are about 0.71, 0.47, 0.35, and 0.29 mm, respectively. Under flow conditions, the induced gas bubble suffered strong interaction between the bubble and the acoustic field, and it appeared in a dynamically stable situation. The presence of bubble(s) not only altered the flow path that could exhibit some geometry effect on mixing, but most importantly caused a churning motion of mixing liquids around the bubble due to the bubble oscillation resulted from the interaction between the applied acoustic field and the bubble. Vortex motion in the liquid was observed in the vicinity of the individual bubble, and thus the chaotic flow might occur, giving rise to dramatic increase in the mixing efficiency. At 5 kHz, though multi bubbles were observed, the interaction between the bubble and the flow field trended to be weak duo to smaller bubble size, giving rise to a lower mixing quality compared to that at 2 kHz. Interestingly, when the power was switched off, the acoustically induced bubble(s) were still present in the channel, but the mixing enhancement phenomenon was disappeared, suggesting that a change of flow path due to the presence of bubble(s) had insignificant geometry effect on the mixing in this case. To further explain why the occurrence of mixing enhancement, according to the acoustic theory a simple acoustic theory that gives a correlation between the bubble size and the resonant frequency can be estimated to be $f \sim 1/R_0$. By varying the bubble size from 0.2 mm to 1 mm, we can estimate the corresponding resonant frequencies ranging from 5 to 1 kHz, respectively. It however, should be pointed out here this simple theoretical formula is for bubbles in stationary water within unbounded domain. As for our case where acoustically induced bubble is in a fluid flow bounded by microchannel walls, modification is needed to take into account of the wall and flow effects.

The occurrence of acoustically induced gas bubble(s) in the present microfluidic structure is likely due to acoustic cavitation. To support this argument, we used a probe (ADE technologies Microsense Probe 5130) to measure the transient displacement of the piezoelectric disc under various applied frequencies, and we thus were able to estimate the vibration velocity of the piezoelectric disc versus the frequency as shown in Fig. 4. Under the experimental conditions, the sound wave length is related to the sound speed, c and the frequency, f and can be approximated as $\lambda = c/f = 0.15$–3 m which is much larger the characteristic dimension of the microfluidic structure. Hence the acoustic field itself effect on the liquid flow structure is insignificant here. In view of the fact that the area ratio of the brass sheet to the cross-section of Y-channel is nearly about 1,000, using the mass conservation under assumption of incompressible fluid we estimated that the acoustically

Fig. 2 Visualization and intensity distribution of fluorescent dye in the mixer for various applied frequencies. The experimental images (*left*) used for assessing mixing quality are taken from the region indicated by the dashed-line rectangle in Fig. 1c. *Arrows* show the location of acoustically induced gas bubbles. The fluorescent intensity distribution (*right*) are obtained by digitized the fluorescent images along the cross-section, *a–a* shown in Fig. 1b



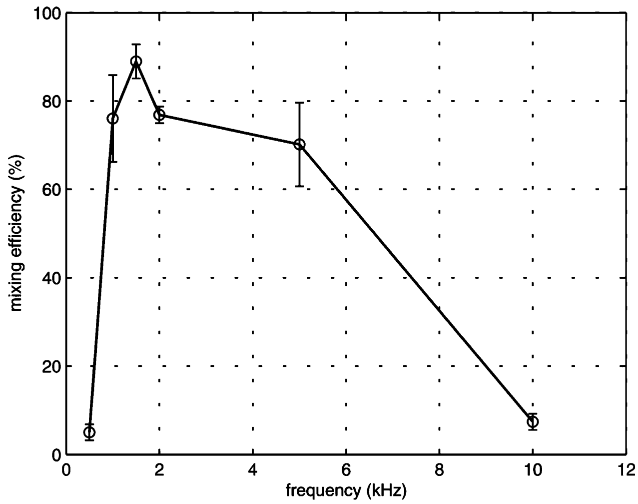


Fig. 3 Variation of the mixing efficiency with applied frequency

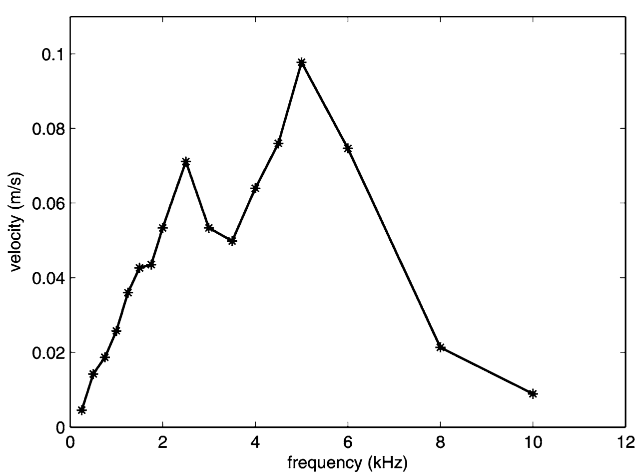


Fig. 4 Vibrating velocity of the piezoelectric disc versus various applied frequency

induced liquid mean velocity in the narrow Y-channel is about 40–100 m/s within the frequency range of 1.0–5.0 kHz, by vibrating the brass sheet at the same speed as the piezoelectric disc. With such high induced vibrating velocity in the narrow Y-channel, the vibrating pressure likely could reach the cavitation threshold (i.e., the amount of negative pressure needed) (Herbert et al. 2006). In other words, gas bubble(s) can be generated within this acoustic frequency range. Further increasing frequency can result in the suppression of the cavitation (Madan and Sameer 2005). This explains why no bubble generation was observed in our microfluidic mixing device once the frequency was above 10 kHz. However, no theory is available for predicting the acoustic cavitation threshold in a microchannle structure because acoustic cavitation is a complex process. According to Herbert et al. (2006), the acoustic cavitation is related to local pressure, surrounding temperature, and other factors. The basic requirement for acoustic cavitation occurrence is that the local pressure is below its saturated pressure under a given temperature. Moreover, some factors that determine cavitation nuclei are also important; impurities, dissolved gas, surfactants, etc., are such parameters relevant to the cavitation nuclei and thus the cavitation pressure. After the cavitation occurs, bubble growth is dependent on surface tension, local flow and geometric structure etc.

In summary, we have presented a technique for mixing enhancement in a microfluidic structure using acoustically induced gas bubbles. Experiments were carried out to study the mixing processes under the effect of various applied frequencies ranging from 0.5–10 kHz driven by a piezoelectric disc unit. It was found gas bubble(s) could be generated within a window of the frequencies between 1.0 and 5.0 kHz. We observed that the interaction between the bubble and the acoustic field caused the bubble oscillation which in turn could generate chaotic flow in the neighborhood of the bubble, thereby achieving significant enhancement in mixing. We demonstrated that in the present microfluidic structure, due to the acoustically induced gas bubble(s) the mixing efficiency could reach about 80% within such frequency range. We also found no bubble generation occurred either decreasing (e.g., 0.5 kHz) or increasing (e.g., 10 kHz) frequency and thus low mixing efficiency was obtained (less than 10%). The occurrence of bubble generation was attributed to the acoustic cavitation. However, further studies in model development and thorough experimental investigations are needed to explore more for this interesting phenomenon.

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