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PHYSICAL ACOUSTICS

Fluid Mixing Enhanced by Surface Acoustic Waves in a Micro-Cavity

Sheng Jin[a], He Zhang[a], Ren-Hao Ma[a], Xiao-Dong Xu[a], Li-Ping Cheng[a, *], and Shu-Yi Zhang[a]

[a]Lab of Modern Acoustics, Institute of Acoustics, Nanjing University, Nanjing, 210093 China

*e-mail: chenglp@nju.edu.cn

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Abstract— One big challenge in micro-fluidic systems is that the mixing efficiency by molecular free diffusion is too low, especially when the viscosity of the fluids is high. In this paper, we designed two types of inter-digital transducers that can generate surface acoustic waves (SAWs), and then performed a series of experiments, where streamings driven by SAWs accelerate the mixing of different fluids. It is found that when the driving voltage exceeds a threshold, an Eckart streaming is excited, and the Eckart streaming can effectively enhance the mixing efficiency of different fluids by almost one order of magnitude. The mixing efficiency increases with the driving voltage. The results also demonstrate that the mixing efficiency is high even in the high-viscosity fluids where the free diffusion is extremely slow.

Keywords: acoustic streaming, Eckart flow, fluid mixing

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INTRODUCION

Microfluidic systems have a wide range of applications due to their small size and portability [1] hence they have become a hot research topic in recent years [2–4]. One application is the mixture of different fluids. The mixing of different fluids within microchannel has been used in many fields, such as biochemical research [5], medical analysis [6], chemical reactions [7]. The mixture of different fluids in microchannels can increase the efficient volume in the flow system, significantly reduce energy consumption and reagent usage in chemical reactions [8]. However, owing to the low Reynolds number of the fluid in the microchannels, rapid and homogeneous mixing of the fluids is difficult. Therefore, it is imperative to increase the mixing efficiency of different fluids in the microchannels [9].

Several methods have been proposed, where the external driving force is based on dielectrophoresis [10], electrokinetics [11], magnetics [12], and acoustics [13]. Among them, ultrasonic waves, which can drive acoustic streamings in the fluids, have many advantages, such as their nice biocompatibility and label-free nature [3, 14]. In particular, the acoustic streaming induced by surface acoustic waves (SAWs) attracted more and more attention since SAWs possess some unique characteristics, such as their low loss rate, low power consumption, and ease of integration. As a result, SAW-based acoustic streaming effect has been widely used not only in ultrasonic motors [15–17], but also in fluid mixing [14, 18–21] or even plant transpiration.

Owing to the nonlinear effect, strong acoustic waves propagating in the fluid would drive the fluid to move globally, which is called acoustic streaming [22]. The acoustic streaming includes boundary-driven streaming and Eckart acoustic streaming [23, 24], and the boundary-driven streaming can be further classified into Schlichting streaming and Rayleigh streaming [25], which excite vortices inside and outside of the boundary layer, respectively. In a real case, the three kinds of acoustic streaming patterns often co-exist or may be converted from one to the other. In this paper, we use Eckart acoustic streaming to improve the fluid mixing efficiency. The effect of various parameters on the mixing efficiency is investigated by experiments.

EXPERIMENT SETUP

In our experiments, the SAWs are generated by an inter-digital transducer (IDT) on a substrate, which is made of 128° YX-$LiNbO_3$. As shown by Fig. 1, two types of IDTs are manufactured, the first is a classical one with parallel electrodes (*panel a*), and the other is a focused IDT with arc-shaped electrodes (*panel b*). The energy of the surface acoustic waves excited by the IDTs is concentrated on the surface of the $LiNbO_3$ substrate. A cylindrical container is put on the substrate, with the substrate being the bottom. The inner radius of the cylinder is 6 mm, and its height is 2 mm. The ultrasonic waves, whose amplitude is controlled by the driving voltage of the IDT, become leaky SAWs propagating on the substrate under the fluid. The leaky SAWs would excite longitudinal waves in the fluid, leading to acoustic streaming. In our experiments, each IDT is composed of 15 pairs of aluminum

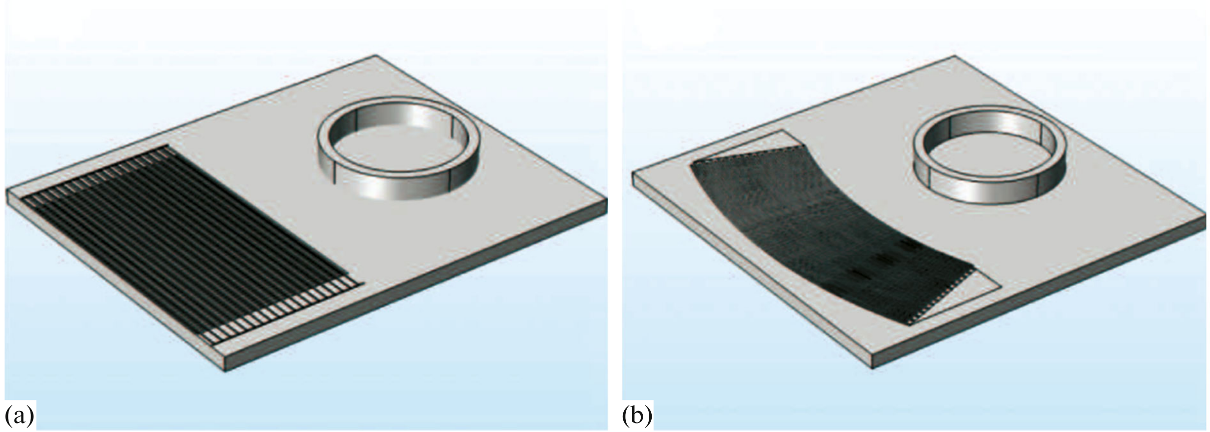

Fig. 1. Schematics of the device: (a)—with parallel IDT; (b)—with focused IDT.

electrodes. For the parallel IDT, both the width and the pitch of the electrodes are 50 μm, the aperture is 8 mm, and the resulting resonant frequency is 19.64 MHz. For the focused IDT, both the width and the pitch of the electrodes are 40 μm, and the resulting resonant frequency is 24.45 MHz. The container is centered at the focus of the IDT.

2. RESULTS

We first use the parallel IDT for experiments. The fluid is water mixed with red ink. The ink is added in order to display any motion of the fluid. When the peak-to-peak amplitude of the driving voltage is set to be 2.5 V, the top view of the fluid inside the container is displayed in Fig. 2a. Note that the SAWs propagate from the left to the right. It is seen that a stationary wave pattern appears at the surface of the fluid, where the dark and bright stripes correspond to the wave crests and the troughs, respectively. As the driving voltage is increased to 5.0 V, the stationary wave fronts remain almost parallel, but slightly shifted along the SAWs direction, as revealed by Fig. 2b. In particular, the bright stripe on the right moves much closer to the inner wall of the container, and becomes much more elongated than other wave fronts. A careful observation indicates that there is very slow flow inside the fluid.

When the driving voltage is further increased to 7.5 V, as shown in Fig. 2c, the wave fronts are not straight anymore, and are disturbed into "S"-shaped structures, implying that the harmonic stationary waves are excited in the transverse direction. Although the flow in the fluid become stronger than in Fig. 2b, the stationary wave pattern is still quasi-stable. However, when the driving voltage is increased to 10 V, the stationary wave pattern disappears, and the fluid begins to circulate symmetrically, as depicted by Fig. 2d. The circulation pattern with two symmetric vortices reminds us of the Eckart streaming.

In order to investigate how the Eckart streaming can accelerate the fluid mixing, we put a drop of 3 μL red ink at the surface center of the 250 μL pure water. In the case without SAWs, i.e., no driving voltage is imposed on the IDT, the red ink spot diffuses very slowly. As revealed by Fig. 3a, the red spot expands gradually but uniformly in every direction. The expansion is so slow that even after 78 seconds the red spot covers only ~64% of the surface area. It is found that the red ink finally covers the whole water surface at $t = 100$ seconds. Then, we set the driving voltage of the IDT to be 10.0 V so as to excite Eckart streaming. As illustrated by Fig. 3b, the induced acoustic streaming destroys the regular shape of the red spot, and drives the red ink to flow quickly. After 8 seconds, the red ink occupies almost the whole surface, although the red ink is not so much uniformly distributed on the water surface. At $t = 78$ seconds, the red ink is distributed on the water surface homogeneously.

Since free diffusion is extremely slow in high-viscosity fluids, it is of great interest to check whether the acoustic streamings work well in mixing fluids with high viscosity. In order to change the viscosity of the fluid, we use glycerol-water solution as the fluid in the container, with the volume ratio between the glycerol and the water being 30, 40, 50, and 60%. The corresponding dynamic viscosity is 2.57 mPa s, 4.04, 6.86, and 12.76 mPa s, respectively [26]. In comparison, the dynamic viscosity of pure water at 25°C is 0.89 mPa s. We define the time at which the red ink covers the whole fluid surface as the mixture time, though the red ink is not yet uniformly distributed. Therefore, as described in the previous paragraph, the mixture for the pure water is 8 seconds when the driving voltage is 10 V. With the same driving voltage, the mixture time

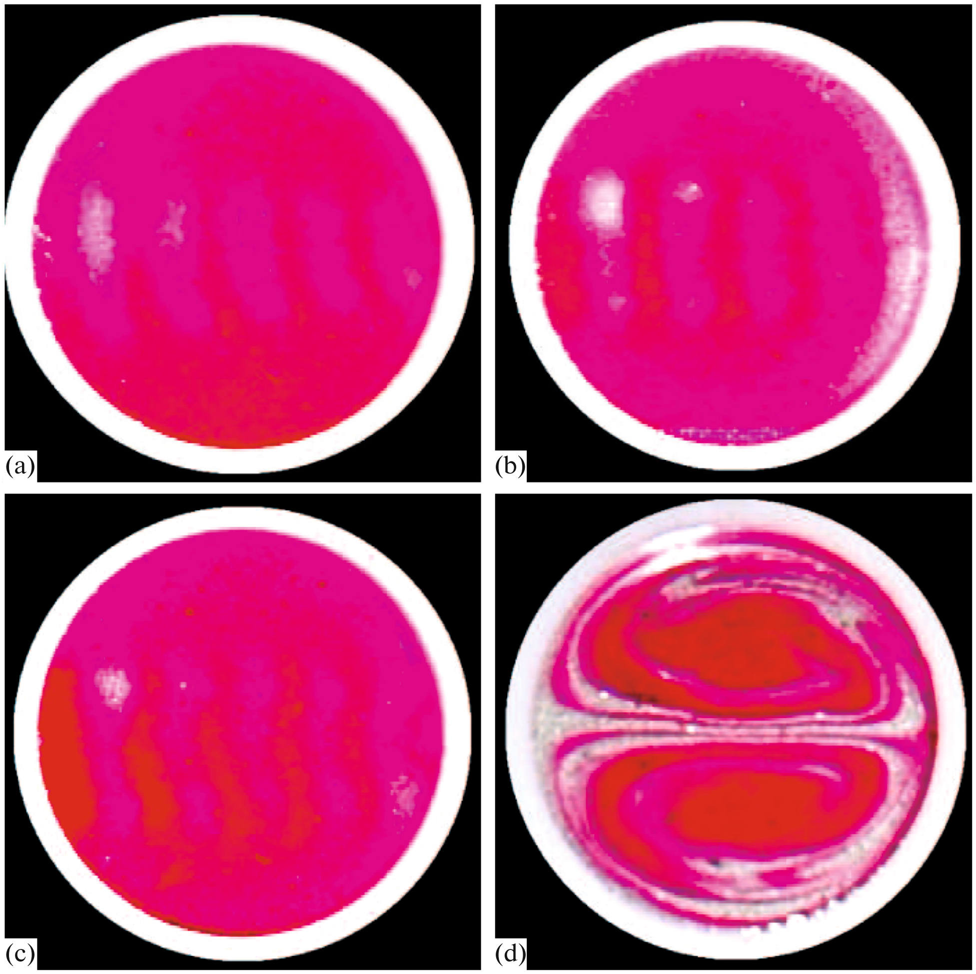

Fig. 2. Top views of the fluid in the steady state in different cases with the driving voltage of the IDT is (a)—2.5, (b)—5.0, (c)—7.5, and (d)—10.0 V.

of the four types of glycerol-water solution is 14, 20, 23, and 39 seconds, respectively. The variation of the mixture time with the viscosity is plotted in Fig. 4 as the squares connected by the solid line. It is seen that the mixture time increases with the fluid viscosity monotonically, which is expected. For comparison, the triangles connected by the dotted line in Fig. 4 correspond to the mixture time of the different types of fluid in the case of free diffusion, i.e., there are no SAWs. It is seen that the mixture time can be shortened by ~92% when Eckart streaming is excited with the 10 V driving voltage. Therefore, we can see that the acoustic streaming can improve the mixing efficiency of two fluids significantly.

We reproduced the above experiments with the focused IDT. It is expected that since the SAWs excited by the focused IDT are concentrated at the container, the streaming velocity inside the fluid becomes larger compared to the parallel IDT in the case of the same driving voltage. The enhanced streaming favor the mixing of the fluids. As indicated by the diamonds connected by the dashed line in Fig. 4, the mixture time is further reduced with the focused IDT. In the low viscosity cases, the mixing efficiency is enhanced by 100% compared to the parallel IDT.

3. SUMMARY

From our experiments, we can see that when the driving voltage is low, the excited SAWs are so weak that only stationary waves are excited in the fluid. Only when the driving voltage exceed a threshold, e.g., 10 V in our device, an Eckart streaming is formed, with two vortices are formed symmetrically. The circulation of the vortices can efficiently accelerate the mixture of the two fluids. With the 10 V driving voltage, a drop of red ink at the middle of the water surface can expand to cover the whole surface within 8 seconds, which is about 12 times faster than the free diffusion. We also investigated the mixture efficiency when the fluids has

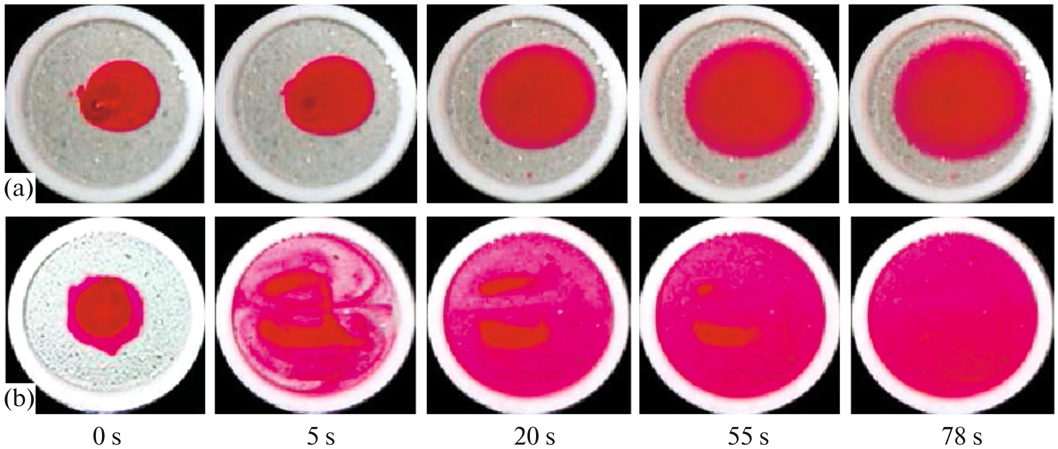

Fig. 3. Evolution of the red ink on the fluid surface.

different viscosity. As expected, the mixture time increases monotonically with the fluid viscosity.

However, it should be noted that although the red ink drop expands to the whole water surface in 8 seconds, the ink distribution is not homogeneous, with two patches of strong concentration near the surface center even until $t = 55$ seconds. This is due to that the excited Eckart streaming is a regular laminar flow, and the red ink tends to be concentrated at the centers of the two vortices. The red ink is homogeneously distributed on the surface only after 78 seconds, which is moderately smaller than the free diffusion time, which is 100 seconds. It is expected that only many smaller vortices are excited, e.g., the acoustic waves are excited in orthogonal directions, the efficiency of uniform mixture can then be significantly enhanced. Future devices which can excite smaller vortices are strongly desired.

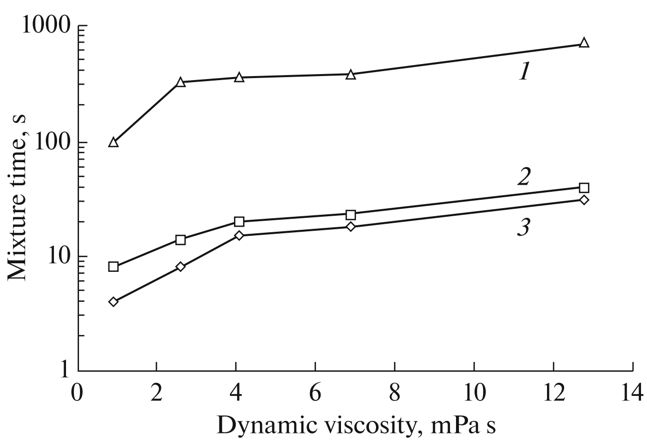

Fig. 4. Variation of the mixture time with the viscosity of the fluid in three cases: (*1*) corresponds to the free diffusion, (*2*) corresponds to the acoustic streaming driven by the parallel IDT, whereas (*3*) corresponds to the acoustic streaming driven by the focused IDT.

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