MICROPROPULSION OF AIR AND LIQUID JET BY ACOUSTIC STREAMING

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ABSTRACT

This paper describes an ultrasonic, nozzleless jet propeller that can shoot out jet streams of liquid or air (from a spot of hundreds of micron in diameter) through an acoustic streaming effect. The propelled jet streams of liquid contain atomized liquid particles of 3 to 10 microns in diameter, and move at a rate as high as 37.5 µl/s. In case of air, the speed of the propelled air jet can reach up to 1.2 m/s. This is the first time that acoustic streaming effect is experimentally confirmed in air at such a high frequency of 10.8MHz.

INTRODUCTION

Liquid or air jet can be used as liquid spray and atomization or air propulsion. Liquid spray and atomization are useful for vapor production, drug delivery, and accelerating chemical reaction with increased surface area. The air propulsion produces a reactive backward force through forward moving air stream.

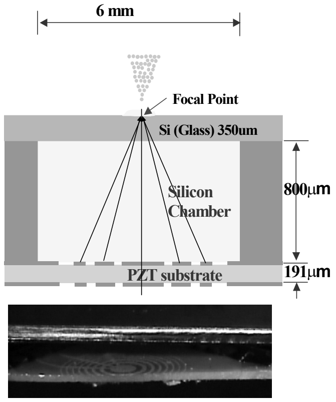
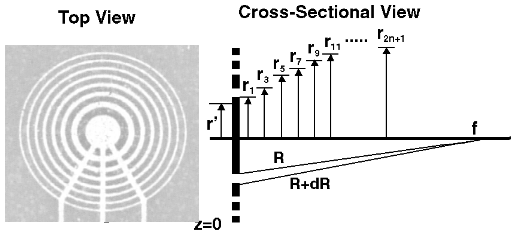


Fig. 1 The cross-sectional view of the liquid and air propeller.

Though microfabrication of a liquid atomizer using a surface acoustic wave has been reported [1], this paper describes for the first time a microfabricated liquid and air propeller that is based on a high frequency acoustic-wave streaming effect, and has high jet density.

THEORY



- **Annular Rings: Half-Wave-Band Sources**

$$r_n = \sqrt{\frac{q\lambda}{2}\left(f + \frac{q\lambda}{8}\right)} \quad (q = n + 1 + 2\cdot\text{offset})$$

- **Acoustic waves interfere.**
  → **Intensity Magnification at Focal Point**

Fig. 2 The electrode pattern of annular rings on both faces of a piezoelectric plate for self-focusing of acoustic waves.

The propeller is built on a PZT sheet (Fig. 1) using Fresnel half-wave-band self-focusing principle (Fig.2 [2]). When the PZT transducer is excited with a burst of sinusoidal waves (of which the frequency corresponds to the thickness resonance of the PZT sheet), it generates strong high frequency acoustic waves. With a proper design of the transducer electrodes, the acoustic waves propagate in the liquid, interfering with each other, and add in-phase at the focal point through a constructive wave interface. Thus intensified acoustic beam is focused onto a tiny spot just above the interface between a solid wafer (Si or glass) and liquid (water or oil) or air.

A high-intensity acoustic wave propagating in a medium is absorbed and scattered by the medium. The wave attenuation with a high intensity wave is nonlinear, and causes the medium itself to move. This nonlinear acoustic effect is called acoustic streaming.

Thus, the high intensity acoustic beam near the focal point produces a steady body force (through the acoustic streaming effect), which atomizes and jets the liquid, or jets the air from the interface.

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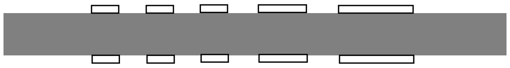
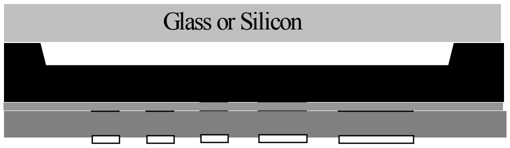
The strong jet force is directed perpendicular to the transducer plane, and is very effective in propelling out either air or liquid (in which case the process is called atomization).

FABRICATION



1. Pattern electrodes on a PZT sheet

2. Microfabricate chamber on a silicon wafer (KOH etching)



3. Bond the PZT sheet, the silicon chamber and a glass/Si cover with epoxy.

Fig. 3 Brief fabrication steps.

We use a 191μm thick PZT sheet as the transducer substrate, and pattern its silver electrodes on both sides, using 3M HNO_3 at 85°C. Then with epoxy we attach the PZT sheet to the bottom of a silicon wafer with 800 μm deep chamber (microfabricated with KOH wet etching) that contains water. The water chamber is covered with a 350 μm thick silicon or glass wafer (Fig. 3). The dimension of the whole device is 10 x 10 x 1.35 mm^3.

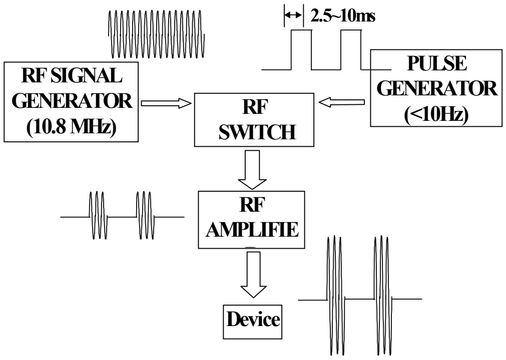


Fig. 4 Applied RF pulses for micropropulsion.

TESTING SETUP

The PZT transducer is driven by a train of pulses of 10.8 MHz sinusoidal wave with its peak-to-peak voltage of 200V (the peak electrical field across the PZT substrate being around 5.2×10^5V/m) (Fig. 4).

To demonstrate the air jet by the transducer, we cover the device surface with smoke from incense (Fig. 5).

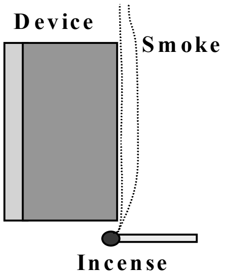


Fig. 5 Set-up to test the air jet.

And to characterize the liquid jet, we use red ink on the device surface (Fig.6), and atomize the ink to produce a jet stream of red liquid droplets. Then we collect the jetted droplets on a glass slide (with transparent oil layer) that is placed above the device. The oil layer on the glass slide holds the jetted liquid droplets, which we view under a microscope to estimate the droplet size.

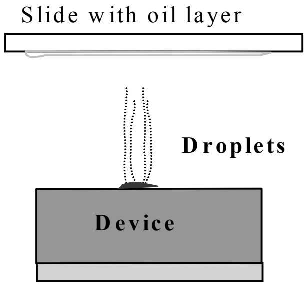


Fig. 6 Set-up to test liquid jet.

RESULTS

The liquid layer placed over the top surface of the device (Fig. 6) is atomized and jetted out by acoustic streaming effect, as shown in Fig. 7. With 1.5 W peak power input ($200V_{\text{peak to peak}}$), the jet speed reaches around 3 m/s with the atomization rate of 37.5 μl/s. Figure 7 shows the liquid jet steam that is 14 mm high and 400 μm in diameter.

Fig. 7 Liquid jet stream produced by the liquid/air propeller.

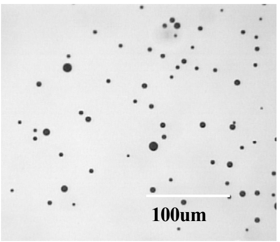


Fig. 8 Jetted Droplets collected on the slide.

Figure 8 shows a photo of the red ink droplets jetted from the device top surface and collected on a glass slide. Upon inspection under a microscope, we find that the most droplet diameters are between 3 and 10 μm with the mean diameter of 5 μm. The droplet size distribution is shown in Fig.9

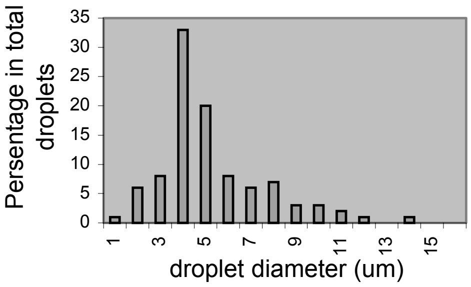


Fig. 9 Droplet size distribution for the jetted water.

To show the effectiveness of the focused acoustic wave in atomizing liquid, we tested the device with high viscosity oil (Table 1). High viscosity liquid requires high energy to break the bonds in the liquid and to overcome the surface tension on the solid surface. The liquid/air propeller produces well-focused high acoustic streaming force, and pushes oil droplets out. Table 1 shows the experimental results on water and oil atomization.

Table 1 The device's atomization

Liquid	Viscosity	Droplet Mean Diameter	Pulse Width	Maximum Atomization Rate
Water	1 cSt	5 μm	>1.5 ms	37.5 μl/s
Oil	55 cSt	15~20 μm	>7 ms	2.2 μl/s

Since the liquid/air propeller is based on self-focusing of acoustic waves onto a focal spot, we can choose the spot where we desire to jet by design. Thus, with an array of such propellers, we can control liquid jetting spots. For instance, a 2 x 2 jet array shown in Fig. 10 can produce liquid jets from any of the four spots at the centers of the transducers. Figure 11a and 11b show the liquid jets from the 4 spots and the 2 spots, respectively.

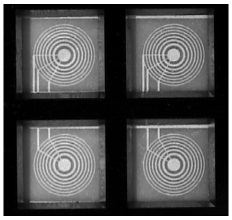
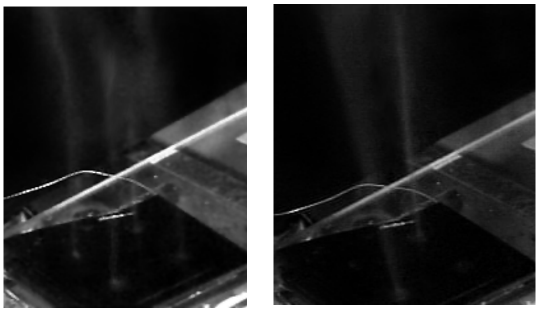


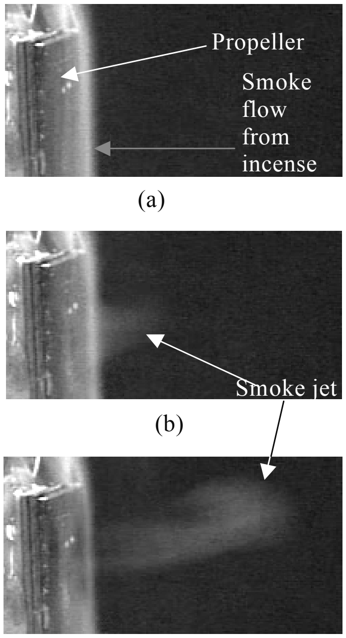
Fig. 10 A 2 x 2 jet array for micropropulsion.



(a) (b)

Fig. 11 2 x 2 jet array for controllable micropropulsion (a) photo of liquid jets when all four devices are actuated, (b) when only two devices are actuated.

In air, the propeller is tested with a smoke from incense (Fig. 5), and shown to produce an air jet. When we apply a burst of RF signal, the smoke is jetted out from the surface with the jet speed of up to 1.2m/s. Fig. 12 shows pictures taken at different times when the propeller is actuated: (a) before any electrical voltage is applied, when incense smoke covers the device surface (the smoke is around 1 mm thick); (b) right when an RF pulse is applied to the device (the air jetted out pushes the smoke out of the device surface); (c) 33 ms after a 5 ms wide RF pulse is applied, showing the fast progress of the smoke jet.



(a)

(b)

(c)

Fig.12 Pictures showing the air jets produced by the propeller.

DISCUSSION

When acoustic wave is conventionally used to atomize liquid, the atomization takes place through the surface vibration on the interface between a solid plate and liquid. However, in case of the liquid/air propeller described in this paper, the liquid jet stream is due to acoustic streaming effect, as evidenced by the air jet. Without acoustic streaming effect, the longitudinal acoustic wave will not produce a net body force to produce an air jet. And the air jet experiment confirms the strong enough acoustic streaming effect at 10.8 MHz in air to produce the air jet.

CONCLUTION

This nozzleless and heatless transducer uses high-frequency acoustic-steaming effect to jet out liquid or air. A powerful liquid jetting has been demonstrated with water and oil. The transducer can atomize very small amount (as small as tens of μl) at a specific spot of hundreds micron in diameter. Moreover, the transducer does not have to be in contact with the liquid and air to be jetted out.

ACKNOWLEDGEMENT

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REFERENCES

1. Minoru Kurosawa, Akira Futami, and Toshiro Higuchi, “Characteristics of Liquids Atomization Using Surface Acoustic Wave”, Transducers ’97, 1997 International Conference on Solid-State Sensors and Actuators, p 801-804.

2. X. Zhu and E.S. Kim, "Microfluidic Motion Generation with Acoustic Waves," Sensors and Actuators: A. Physical, vol. 66/1-3, pp. 355-360, April 1998.