Mechanism of ultrasonic atomization using a multi-pinhole plate

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Modifying ink-jet techniques used for character displays, an atomizer with a multi-pinhole plate is trial-made. The pinhole plate with seven pinholes of $80\text{ }\mu\text{m}$ in diameter is piezoelectrically driven at 34.4 kHz by a bimorph structure. Due to the intrinsic nature of the technique, important merits such as the uniform diameter of the atomized droplets, easiness of changing the diameter and of control of the atomizing rate may be expected. Employing the trial-made atomizer, the principle and physical properties of the ultrasonic atomization are experimentally studied. The displacement amplitude distribution of the plate, threshold pressure of atomization, phase of ejection, diameter and amount of droplets as a function of applied voltage are measured to make clear the physical properties of the technique. As a result of experiments, it is made clear that the surface tension of the liquid acts as a valve and that the atomizer has a self-acting liquid supply itself and does not need any pumping apparatus.

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1. INTRODUCTION

Ultrasonic atomizations of a liquid in a layer and in a fountain have been experimentally and theoretically studied of their physical properties by many researchers.¹⁻⁸⁾ The diameters of ultrasonically atomized droplets have been proved to be mainly determined by the frequency, vibration displacement amplitude and surface tension of the liquid used, and its histogram usually shows that the diameter distributes around the mean diameter.^{1,3)} If both the diameter and the amount of atomization can be controlled deterministically, further applications may be expected.

For the purpose a piezoelectrically energized ink-jet technique employed as means of the character displays⁹⁻¹²⁾ has been tried to be modified as a new atomization technique.¹³⁾ Due to the intrinsic nature of the technique, important merits such as the uni-

form diameter of the atomized droplets, easiness of changing the diameter and of control of the atomizing rate may be expected.

In this paper the principle and physical properties of the technique is studied.

2. PRINCIPLE

Consider the case where a tank with a multi-pinhole plate is filled with liquid as shown in Fig. 1 (a). If the liquid is pressure by certain means and if the surface tension of the liquid is strong enough to block the air coming into the tank through the pinholes, the liquid is ejected from the pinholes like a water pistol. If the pressure with proper amplitude changes alternately and the tank is kept filled with an adequate apparatus, droplets of the liquid continuously come out from the pinholes, that is, the liquid is atomized.

Using an idealized geometry shown in Fig. 2, let

Fig. 1 Schemes of multi-pinhole plate atomizer.

Fig. 2 Simplified model of the atomizer for considering the force equilibrium between the inside and outside of the cavity ($F_t = 2T/R$, force due to surface tension).

us treat the phenomenon qualitatively to some extent and consider the equilibrium among surface tension of liquid, pressures inside and outside of the cavity. If no additional pressure is applied, the force equilibrium can be written as

$$\frac{2T}{R} + P_0 - \rho gh = P_0, \quad (1)$$

where P_0 denotes the sea-level pressure and T , R , ρ , g and h are the surface tension of liquid, the radius of curvature, the density of liquid, the gravitational acceleration and the distance measured downward from the center of the pinhole to the liquid surface, respectively.

In this case the force F_t due to surface tension

directs outward as shown in Fig. 2 (a). If negative pressure P_a is applied, the equation

$$\frac{2T}{R} \geq p_a + \rho gh \quad (2)$$

must be satisfied to make the air not to come into the cavity. If additional positive pressure P_a is applied as shown in Fig. 2 (b) and

$$\frac{2T}{R} + P_0 \leq P_0 - \rho gh + p_a \quad (3)$$

is satisfied, the liquid is ejected to form a droplet. Then the threshold of the atomization must be expressed as

$$p_a = \frac{2T}{r} + \rho gh, \quad (4)$$

where r is the radius of pinhole and the minimum value of R .

Another configuration which is shown in Fig. 1 (b) is possible. In this configuration atomized droplets falling down to pinhole plate may interfere the continuous atomization and bubbles generated by alternating pressure may also interfere the continuous atomization. In the former case, however, the bubbles go upward automatically to keep continuous atomization and no atomized droplets fall down to the pinhole plate. Therefore the former configuration may be superior to the latter.

3. CONFIGURATION OF A TRIAL-MADE ATOMIZER AND ITS VIBRATION CHARACTERISTICS

3.1 Configuration of a Trial-Made Atomizer

In order to obtain alternating pressure, two simple methods are possible. One method is to displace the bottom or side wall piezoelectrically as in the ink-jet technology¹¹⁾ and the other one is to vibrate the pinhole plate itself.¹²⁾ Comparing the two methods with each other, there is no difference between two method if the liquid to be atomized is incompressible. If the liquid is compressible, however, the pressure generated by the displacement of the wall does not transfer to the pinhole plate and the former does not work well. On the other hand the latter works well also in this case, because the vibration of plate generates sound pressure just at the vicinity of the plate. Therefore the latter method may be superior to the former and is employed in this experiment.

Employing a bimorph structure where a ring disk

Fig. 3 Schematic diagram and dimensions of a trial-made atomizer (a, bimorph vibrator; b, c, body and arrangement of pinholes).

vibrator is bonded to the pinhole plate, a multi-pinhole plate atomizer is trial-made as shown in Fig. 3. The circular plate clamped at the periphery and the circular ceramic ring vibrator bonded on it are used as a bimorph vibrator shown in Fig. 3 (a).

The geometry of the atomizer is shown in Figs. 3 (b) and (c). The membrane is $50\text{ }\mu\text{m}$ in thickness and has seven pinholes of $80\text{ }\mu\text{m}$ in diameter, and the pinholes are arranged at equal interval of $250\text{ }\mu\text{m}$. The thickness and the inner and outer diameters of the ceramic vibrator are 1 mm, 3.5 mm, and 10 mm, respectively. The membrane is made of steel and the body made of brass.

3.2 Vibration Characteristics of the Atomizer

When no liquid fills the cavity, the atomizer resonates at two frequencies of 38.5 kHz and 45.3 kHz. If the cavity is filled with liquid, the vibration at the lower resonance frequency is severely damped and the upper one goes down to 34.41 kHz. The atomization at the lower one is unstable and intermittently stopped due to bubbles caused by the vibration of liquid. On the other hand the atomization at upper one is stable although bubbles are generated also in this case. Then the upper frequency is employed as the operating frequency of this atomizer.

Fig. 4 Measured and calculated distributions of the bimorph vibrator. A nodal line is found just inside the ceramic vibrator.

The vibration amplitude distribution of the atomizer with and without liquid are measured by using an optical heterodyne technique¹⁴⁾ and are shown in Fig. 4. Since the vibration amplitude distribution of the bimorph vibrator can be calculated in accordance with the reference,¹⁵⁾ the calculated distribution is also shown in Fig. 4. The maximum value of the calculated distribution is set to coincide with that of the measured one at an applied voltage of 1 volt without liquid. The calculation is carried out assuming that the outer periphery of ceramic vibrator is supported, because the pinhole plate is much thinner than the ceramic vibrator.

As is clear from the figure, the calculated distribution agrees well with the measured one without liquid. A nodal line is just inside the ceramic vibrator and this corresponds to a second vibration mode of a circular membrane. The displacement of the plate with liquid measured at 1 volt is smaller than that without liquid, but the vibration pattern is the same in spite of the frequency shift due to the liquid. The lower resonance frequency mentioned above corresponds to a fundamental mode of circular membrane.

The equivalent mass of the bimorph vibrator is calculated by using the displacement distribution and is 3.82×10^{-4} (g), where the mechanical terminal is assumed to be the center of the plate. The force factor of the bimorph vibrator is about 0.02 (N/volt).

4. EXPERIMENT

4.1 The Extreme Values of h

To examine the minimum pressure p_a necessary for ejecting droplets and the available maximum pressure difference between inside and outside of the liquid surface in the pinhole, the atomizer is set as shown in Fig. 5 and the value of h is changed employing water as liquid. As a result, the maximum and minimum values of h are 33.26 and -20 cm respectively, where h is measured downward from the center of the plate. These values correspond to the pressure ρgh as listed in Table 1. Corresponding curvatures of the surface calculated in accordance with Eqs. (2) and (3) are also listed in Table 1, where the surface tension of water is 72.8×10^{-3} (N/m) and $p_a = 0$.

The calculated radius of $74 \mu\text{m}$ is nearly twice of the radius r and $F_t = 2T/R = 1.96 \times 10^3$ N/m².

In order to apply DC pressure the mean value $h = (33.26 - 20)/2 = 6.63$ cm may be appropriate as a value of h . However the radiation pressure due to the sound may be also applied as DC pressure, and $h = 8$ cm is employed in this experiment. In this case the threshold of atomization p_a is estimated to be 2.47×10^3 N/m², because the value of ρgh is 0.78×10^3 N/m² for $h = 8$ cm.

4.2 Displacement

The displacement amplitude at the center of the membrane is measured as a function of input voltage with a laser doppler method¹⁶⁾ and the result is plotted in Fig. 6. The atomization begins at about 15 volt and becomes steady above 30 volt. The displacement amplitude is proportional to input voltage from 30 to 50 volt.

4.3 Phase of Ejection and Initial Velocity of Droplet

To study the phase of ejection of droplets, stroboscopic observations are carried out shifting the timing of illumination. A schematic diagram of stroboscopic observation is shown in Fig. 7. The duration of light pulse is $1 \mu\text{sec}$. As is shown in Fig. 8, the water is pushed out to form a hemisphere at $\phi = 48^\circ$ and a droplet is formed and ejected at $\phi = 144^\circ$, where the ϕ denotes the phase of pressure. The signal of pressure is obtained by using an electrostrictive thin film of PVDF bonded to the bottom of the cavity. Figure 8 also shows that only

Table 1 Measured maximum and minimum pressures which are determined by the surface tension.

h (cm)	-20	33.26
Pressure (N/m ²)	1.96×10^3	3.26×10^3
Radius curvature	$74 \mu\text{m}$	$45 \mu\text{m}$

Fig. 5 Setting of the atomizer.

Fig. 6 Displacement as a function of the applied voltage.

Fig. 7 Schematic diagram for stroboscopic observations of droplet.

one droplet is ejected from one pinhole a period.

Figure 9 shows the initial velocity of droplet plotted as a function of vibration velocity, where the velocity of the droplet is calculated using the interval of droplet observed with the stroboscope. The velocity of the droplet seems to be a square root function of vibration velocity.

Fig. 8 Phase of ejection of droplet. (a) and (b); photographed at $\phi = 48^\circ$, and $\phi = 144^\circ$ respectively.

4.4 The Performance and the Geometric Mean Diameter of Droplet

The performance of the atomizer is measured as a function of applied voltage, where the performance is defined as a atomization rate. The result is shown in Fig. 10 together with the geometric mean diameter of droplet. The atomization rate gradually increases up to $4.4 \text{ cm}^3/\text{min}$ and saturates at about 47 volt while at this input voltage the vibration velocity is still proportional to the input voltage. Bubbles are observed in the plastic outlet tube when higher voltage is applied. This may be caused by ultrasonic cavitation.

5. DISCUSSION

To verify the role of surface tension, inner pressure of the cavity is calculated using Bernoulli's theorem

$$P = \frac{1}{2} \rho V^2 \quad (5)$$

Fig. 9 Initial velocity of droplet as a function of vibration velocity.

Fig. 10 Performance of the atomizer and the geometrical mean diameter (GMD) of droplet measured as a function of input voltage.

and the measured velocity of droplet V , where P denotes the pressure difference and may be written as

$$P = p_a - \rho gh. \quad (6)$$

If a vibration velocity of 2.1 m/sec is picked up from Fig. 9, for example, the corresponding velocity of droplet is 6.8 m/sec and the pressure P can be calculated as $23.12 \times 10^3 \text{ N/m}^2$ in accordance with Eq. (5) and the corresponding value of P_a becomes $23.9 \times 10^3 \text{ N/m}^2$ from Eq. (6). If a vibration velocity of 0.54 m/sec, which corresponds to the threshold of atomization as shown in Fig. 6, is employed in place of 6.8 m/sec, the corresponding pressure is calculated as $1.9 \times 10^3 \text{ N/m}^2$ in the same way, where p_a is assumed to be proportional to the vibration velocity.

This value is smaller than the value of $2.4 \times 10^3 \text{ N/m}^2$ estimated in the previous chapter, and this difference may be due to the radiation pressure. But the fact that the surface tension acts as the valve of the atomizer is concluded to be reasonable.

Fig. 11 Schematic sequence of ejection of droplet.

As for the sequence of atomization, it may be concluded as follows; When the plate displaces outward as shown in Fig. 11, the water in the cavity is also accelerated outward due to the surface tension and the lack of volume corresponding to the droplet. As the plate moves inward, the positive pressure is generated and accelerates the water outward. Then a water rod is formed until the pressure cease to accelerate the rod. The accelerated water rod goes outward apart from the cavity before the plate reaches at the maximum. The water rod changes its form to a sphere shape due to the surface tension. These processes are repeated.

6. CONCLUSION

The principle and physical properties of an ultrasonic atomization using a multi-pinhole plate are studied experimentally, employing a trial-made atomizer.

As one droplet is ejected from one pinhole a period, the amount of atomized liquid is expected to depend on the frequency, number of pinholes and pressure amplitude used. Fine droplets may be produce if pinhole plate with small pinholes is vibrated at high frequency.

If the configuration proposed here is employed, no pumping apparatus may be necessary and this fact is very important for making a compact atomizer in practice.

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