Control of Particles in a Standing Wave Field using Ultrasonic Vibration

S. Nomura,* K. Murakami, J. Ochi and Y. Yoshikawa

*Department of Mechanical Engineering, Ehime University, Bunkyo-cho 3, Matuyama, Japan, 790-8577

Abstract: To control the motion of micro machines by acoustic power, the behavior of particles falling in several liquids with a standing wave field was studied experimentally using an ultrasonic vibration of 45kHz. Ultrasonic power effectively acts on a particle as a radiation force when cavitation bubbles do not occur.

INTRODUCTION

Lately, manipulation and levitation using an ultrasonic wave is being studied actively as a non-contact technique. On the other hand, by applying an ultrasonic vibration into liquids, acoustic streaming and cavitation bubbles are generated causing the coefficient of heat transfer on the heating surface in a liquid to increase remarkably. It is considered that ultrasonic vibration is effective for cooling of micro machine since the cavitation bubbles induce very small streaming. For practical applications, this technique may be applied to the control of small heating elements moving in a fluid without contact. In the present study, the behavior of small particles falling in liquids is investigated as the basic research of heat control of micro machines.

EXPERIMENTAL PROCEDURE

A schematic diagram of the apparatus is presented in Fig.1. A PZT transducer with a frequency of 45kHz was fixed to the bottom of a cylinder. The cylinder, with an inner diameter of 50mm and a depth of 370mm, is made of an acrylic resin tube. Ion exchanged water, degassed water and a glycerin aqueous solution (20~100%) were used as the liquids. Several small tubes were inserted in this cylinder and glass particles with a diameter of about 1.5 ~ 3.5mm were dropped into the tubes respectively. The movements of particles were recorded using a high-speed camera.

RESULTS AND DISCUSSION

Falling velocity in standing wave The measurements for the falling velocity of particles in a standing wave field are shown in Fig.2. When the ratio of the tube diameter D to the particle diameter d approaches zero, the ratio of the terminal velocity \( v_t \), obtained from Newton's law of resistance, to the falling velocity \( v \), as measured by high-speed camera, closely approaches unity. As \( d/D \) becomes larger, the velocity ratio \( v/v_t \) becomes smaller due to influence of the cylinder wall. The falling velocities of particles without ultrasonic vibration agree with the
solid line which represents the terminal velocity calculated from the experimental equation for considering the effect of the cylinder wall [1]. The ratio of the falling velocity with ultrasonic vibration $v_u$ is estimated by the averaged velocity through one wavelength. When varying the tube diameter, as the ratio of the diameter of tube to the particle diameter increased, so did the deceleration. All particles were levitated by an ultrasonic radiation force at a ratio of more than 0.6.

**Effect of cavitation** Since cavitation bubbles are observed by applying ultrasonic vibration to a liquid, cavitation intensity as estimated from the erosion loss of an aluminum sheet was measured to investigate the effect of cavitation generation on the radiation pressure. Cavitation intensity in degassed water was weaker than that in ion exchanged water, however, the decrease in velocity of the glass particles by applying ultrasonic vibration exhibited the greatest deceleration in the degassed water as shown in Fig.3. Ultrasonic power effectively acts on a particle as a radiation force when cavitation does not occur. In the case of low ultrasonic power (7W), consequently, there is not a large difference in the average velocity. For the glycerin aqueous solution, the damping effect of ultrasonic wave appeared remarkably.

**Mechanism of deceleration** On the basis of the above study, the falling velocity of a particle was analyzed numerically. The equation for motion of a sphere in a viscous fluid is based on the Basset-Boussinesq-Oseen equation [2], which in addition has to include the acoustic radiation force as follows.

$$m_p \frac{dv}{dt} = -C_D \frac{\rho_f}{2} \frac{\pi}{4} d^2 v^2 + \left( m_p - m_f \right) g - \frac{1}{2} m_f \frac{dv}{dt} + \frac{3}{2} d^2 \sqrt{\frac{\pi}{2} \rho_f \mu} \left( \int_0^t - \frac{dv}{dt} \right) dt - m_f k A^2 \left( Y + 1 \right) \sin 2kx$$

Subscripts: $p$: particle, $f$: liquid

The terms on the right hand side of this equation are the drag force, gravity and buoyancy force, the added mass force, the basset history force, and the acoustic force in the standing wave field [3]. Fig.4 shows the falling velocity as calculated by the above equation. The velocity of a particle is periodically changed due to influence of the radiation force of the standing wave. The particle reaches terminal velocity obtained by Newton's law of resistance after a much larger distance. It is probably because this analysis was made in one dimension that the average falling velocity throughout the cylinder does not agree exactly with experimental results. However, This analysis can explain the deceleration of a particle in standing wave field.

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**REFERENCES**