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On the propagation velocity of finite amplitude pressure wave in bubbly waters

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1. Introduction

Wave propagation characteristics in two-phase mixtures are remarkably changed by the state of contained gas phase, even if their void fractions are the same value. Therefore a lot of research works have been carried out and many works have been reported. Wave propagation characteristics in bubbly water has been examined mainly on the infinitesimal pressure waves (acoustic waves), and the effect of the bubble diameters to their propagation characteristics has also been reported.¹⁻⁴⁾ On the other hand, wave propagation characteristics of finite amplitude pressure waves has been examined on the effects of the void fraction and on the amplitude of the pressure wave,⁵⁻⁷⁾ and the effect of the bubble diameter to the propagation velocity of finite amplitude waves has not been examined.

In this work, two kinds of bubbly waters, whose void fractions are almost the same but the mean diameters of bubble contained in the bubbly waters are very much different, are prepared, and compressive pressure waves are propagated in them containing in a shock tube. Thus the effect of bubble diameter in the bubbly water to the wave propagation characteristics is clarified.

2. Experiment

Blockdiagram of the experimental apparatus is shown in Fig. 1(a), (b). In this experiment, a liquid-filled shock tube is composed of two kinds of tubes. A brass tube, 24 mm in inner diameter, is used for the high pressure chamber and for a part of the low pressure chamber of the shock tube. A Lucite rectangular tube, 20 mm × 28 mm in inner sizes, is used for the low pressure chamber and the test section and they are joined by a stainless steel adapting tube.

Compressed air is led to the high pressure chamber of the shock tube, however, the pressure of the low pressure chamber is maintained to be the atmospheric one. When the pressure difference (ΔP) is reached a previously set value, the separating diaphragm set between the pressure chambers is broken by a knife edge

and a compressive pressure wave propagates through the test section.

In the test section of the shock tube, bubbly water is previously filled in the test section and is circulated between the shock tube and outer tanks by three pumps, and just before breaking the diaphragm the circulation is stopped by the electromagnetic valves.

The pressure waves propagating in the test section is detected by transducers (PCB Model 111A24), which are set 350 mm apart each other on the shock tube wall and their outputs are recorded by a Digital Memory.

In this experiment two kinds of bubble formation methods are adopted. The one is a Rotary Atomizer method⁸⁾ and the other one is a common porous plate method. In the former method, a rotor, 150 mm in diameter is rotated about 700 to 1,000 rpm in a bubbly water jacket and a lot of bubbly water containing very small bubbles is obtained. In this method homogeneous bubbly water of 3×10^{-4} to 2×10^{-2} in void fraction is obtained and the mean diameter contained in it is about 50 μm . In the latter method, a porous plate of AS-resin, 5 mm in thickness, whose nominal void diameter is 30 to 50 μm , is used, and it is set in the center of the bottom flange of the test section of the shock tube. In this case compressed air is sent through the plate to the test section and bubbly water containing rather large bubbles is obtained. In this method homogeneous bubbly water of 10^{-3} to 10^{-1} in void fraction is obtained and the mean diameter contained in it is about 0.5 mm.

In these experiment some surface active agent of about 0.4 vol% is added in the bubbly water to prevent the bubbles from their coagulation.

3. Results and Discussion

3.1 Propagation velocities

Theoretical propagation velocity (C) of a finite amplitude pressure wave in the bubbly water is obtained by the following equation⁹⁾:

$$C^2 = \left(\frac{\Delta P}{P_0} + 1 \right) \cdot \left[\left\{ \frac{\frac{1-a}{\rho_l C_l^2} + \frac{a}{P_0} + \frac{\Delta P}{P_0} \frac{1}{\rho_l C_l^2}}{1 + \left(\frac{1-a}{P_0} + \frac{a}{\rho_l C_l^2} \right) \Delta P} + f(E) \right\} \cdot \{ a \rho_g + (1-a) \rho_l \} \right]^{-1}$$

where ΔP is the amplitude of compressive pressure

Fig. 1 (a) Block diagram of experimental apparatus.

Fig. 1 (b) Detail sizes of liquid-filled shock tube.

- A: Circular brass tube, $\phi 24$, $t=3$,
 B: stainless steel adapting tube, $\phi 24$, $t=13$
 (circular to rectangular cross section),
 C: Lucite rectangular tube, 28×20 , $t=10$.
 Ti: Barium titanate transducer, Tr1: pressure
 transducer, Tr2: pressure transducer.

wave, P_0 is the ambient pressure, α is the void fraction and C_i is sound velocity in water. ρ_g , ρ_l are densities of gas contained in the bubbles and water, respectively. The term $f(E)$ is a function, expressing the effect of the elastic property and deformation of the cross section of the shock tube to the propagation velocity of pressure wave.

Unknown function, $f(E)$, is determined by the

measurement of the propagation velocity of the compressive pressure wave in the shock tube, filled with degassed water.

In this experiment, the propagation velocities of finite amplitude pressure waves are determined by the time lapse of output waveforms of pressure transducers, set on the shock tube wall (cf. Fig. 1).

Experimental results are shown in Figs. 2 and 3. The data shown in Fig. 2 are obtained in the bubbly water, made by the Rotary Atomizer, and those shown in Fig. 3 are obtained in the one by the porous plate. Some numerical results of the above-mentioned equation are also shown in these figures as a parameter of ΔP .

In the experimental results, propagation velocities are tend to be greater, as the increase of amplitude of the compressive pressure wave for the same void fraction of bubbly water and this tendency is coincide with the theoretical results shown in Figs. 2 and 3. Decreasing the void fraction of bubbly water, made by the Rotary Atomizer, propagation velocities tend to coincide with the theoretical ones of infinitesimal pressure waves at the void fraction of about 10^{-3} . On the other hand, velocities in bubbly water obtained by the porous plate do not tend to approach the theoretical value of the infinitesimal wave, even if the void fraction becomes to be small value.

The reason, why the different tendency of the propagation velocity of pressure wave has been observed in the two kinds of bubbly waters, might be explained by the consideration of the cut-off frequency of a shock tube and bubbly water system. The cut-off frequency is changeable with the elasticity of material and cross section of the shock tube as well as with the void frac-

Fig. 2 Relations between propagation velocity and void fraction, in bubbly water obtained by a Rotary Atomizer.

Fig. 3 Relations between propagation velocity and void fraction, in bubbly water obtained by a porous plate.

tion of bubbly water and bubble radius, contained in the shock tube. The velocity of infinitesimal pressure wave in bubbly water changes at the resonance frequency of the bubble contained in it, because of its dispersive characteristics, and when the frequency of the infinitesimal wave is above the bubble resonance one the propagation velocity is greater than the one below the resonance frequency. Therefore the cut-off frequency of the shock tube and bubbly water system, obtained by the porous plate in this experiment, is supposed to be larger than the frequency of bubble resonance in the bubbly water. For the strict and detailed explanation of the cause, however, some theoretical formulations of the propagation velocity for a finite amplitude wave, considered the effect of

Fig. 4 An example of pressure waveforms.
(a) Bubbly water obtained by a Rotary Atomizer. $a=2.0 \times 10^{-2}$, $\Delta P=2.9$ bar.
(b) Bubbly water obtained by a porous plate. $a=2.1 \times 10^{-2}$, $\Delta P=2.9$ bar.

the bubble radius and the material and shape of the shock tube, should be necessary.

3.2 Waveforms

Waveforms of the pressure waves, propagating in the previously stated two kinds of bubbly waters and being detected by the pressure transducers set on the shock tube wall, are somewhat different and the typical examples are shown in Fig. 4(a), (b). The upper and lower traces in the figures are the output waveforms of the upper and lower transducers shown in Fig. 1, respectively.

The waveforms in the bubbly water, obtained by the Rotary Atomizer, are stepping up sharply like a step function and this tendency does not depend on the void fraction. The reason might be considered as follows; In the bubbly water, containing very small bubbles, the cut-off frequency of the liquid-filled shock tube system might be higher than the one in the bubbly water, containing rather large bubbles. For the strict explanation, however, some theoretical formulations stated in the previous section should be necessary, too.

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