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PROPAGATION OF A PRESSURE WAVE IN TWO-PHASE FLOW WITH VERY HIGH VOID FRACTION

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Abstract—An experimental and theoretical study of a finite amplitude pressure wave propagating through a two-phase media of about 0.9999–0.99999 void fraction is performed. This two-phase media consists of many parallel liquid films in a gas. The films are perpendicular to the wave propagation direction and result in a two-phase fluid of extremely high void fraction. Experiments are done in a vertical shock tube and show that the shock wave is broken down into an initial sharply rising wave and a second gradually rising wave. The velocity of the first wave agrees well with the theoretical prediction assuming an adiabatic thermal equilibrium change, which approaches the gas sonic velocity in the two-phase flow in the low void fraction region. The second wave is caused by the complex reflection and destruction of the waves.

1. INTRODUCTION

A pressure wave propagating in a gas–liquid two-phase flow shows extremely different behavior from that in a single-phase flow, since the two-phase flow possesses the large compressibility of the gas phase and the large density of the liquid phase. It also shows complicated changes related to the interphase momentum and energy transfer rates. Understanding of the propagation phenomenon of a pressure wave in two-phase flow is needed to assure adequacy of safety margins in machinery utilizing two-phase flows.

Experimental studies of pressure waves in two-phase flow have been performed primarily for low void bubbly flows (Campbell 1958; Hamilton 1968). Due to the sufficiently large weight fraction of the liquid phase, the results show that the propagation velocity of the pressure wave is in good agreement with the sonic velocity in a fluid in isothermal equilibrium.

On the other hand predominantly theoretical studies have been performed for two-phase flow of high void fraction. This is because a homogeneous mist flow of void fraction above 0.99 is not easily produced. However, it is thought that the energy transfer phenomenon between the two phases can be unambiguously observed only in such high void fraction regions.

In the present study, a large number of thin liquid films are produced in a vertical shock tube to generate a two-phase flow of very high void fraction. A pressure wave propagating in this two-phase flow is then studied. The results are compared with a theoretical analysis to quantify the interphase momentum and the energy transfer phenomena in the high void fraction region. The propagation and attenuation of the pressure wave in the two-phase flow and the division of one shock wave into two shock waves are also studied. This kind of two-phase flow is defined as "foam film flow." The part of thin liquid film in the center of the tube is defined as the "liquid film," and the part with significant liquid-tube wall contact, the "liquid-phase ring" (figure 2).

2. THEORETICAL ANALYSIS

The assumption of homogeneous two-phase flow is made for analysis of the propagation velocity of the pressure wave in the foam film flow. When the two phases are not homogeneously distributed in space as in foam film flow, this assumption may be considered inadequate; however observation of the present experiment shows that the foam film is fragmented by the pressure wave into very small droplets to become a well mixed two-phase flow. The gas and the liquid move at the same velocity and are in mechanical equilibrium. With these assumptions, the fundamental equations of mass and momentum conservation laws for the shock wave in the foam flow are,

$$\alpha_1\rho_{g1}u_1 = \alpha_2\rho_{g2}u_2 \qquad \text{(for gas)}, \tag{1}$$

$$(1-\alpha_1)\rho_l u_1 = (1-\alpha_2)\rho_l u_2 \qquad \text{(for liquid)}, \tag{2}$$

$$P_1 + \{\alpha_1\rho_{g1} + (1-\alpha_1)\rho_l\}u_1^2 = P_2 + \{\alpha_2\rho_{g2} + (1-\alpha_2)\rho_l\}u_2^2, \tag{3}$$

where α is the void fraction, ρ_g is the gas density, ρ_l is the liquid density, u is the velocity, P is the pressure. Suffixes 1 and 2 show the states before and after the shock wave. For the equation of state for gas and liquid, that for perfect gas ($P = \rho_g RT$) and constant density (ρ_l = constant) are used, T is the temperature and R the universal gas constant.

For the energy conservation law, the assumption of isothermal equilibrium available in the low void fraction region, mentioned in our previous report (Mori *et al.* 1973), is not always applicable for regions of high void fraction. The following two cases are therefore considered:

In the very high void fraction region, the temperature change of the two-phase medium before and after the shock wave cannot be neglected as the weight fraction of liquid phase in the two-phase flow is low. However it can be considered that in the short time interval when shock wave passes through, the region is adiabatic and the summation of the enthalpy and the kinetic energy of gas and liquid phases is taken as constant. If such a shock wave is called the adiabatic thermal equilibrium wave, the energy equation for the wave is,

$$\begin{aligned}\alpha_1\rho_{g1}u_1(C_pT_1 + u_1^2/2) + (1-\alpha_1)\rho_l u_1(C_lT_1 + u_1^2/2)\\ = \alpha_2\rho_{g2}u_2(C_pT_2 + u_2^2/2) + (1-\alpha_2)\rho_l u_2(C_lT_2 + u_2^2/2).\end{aligned} \tag{4}$$

On the other hand, when the heat capacity of the liquid phase is large, or when there is little resistance to heat transfer to or from the region, a wave is considered in an isothermal condition; the gas and liquid are at an equal and constant temperature before and after passage of the shock wave. Such a shock wave is called an isothermal equilibrium wave in this paper and the energy equation for this wave is

$$T_{g1} = T_{g2} = T_{l1} = T_{l2}. \tag{5}$$

By use of [1–5], the propagating velocities D for the adiabatic thermal equilibrium and the isothermal equilibrium waves are given as follows as functions of the void fraction α of the two-phase flow, pressure P, densities ρ_g, ρ_l, specific heats C_p, C_l and intensity of the shock wave (P_2/P_1):

Adiabatic thermal equilibrium wave:

$$D^2 = \frac{P_2 - \dfrac{\alpha_1\rho_{g1}R(P_2-P_1)}{2\{\alpha_1\rho_{g1}C_p + (1-\alpha_1)\rho_lC_l\}}}{\alpha_1\left\{1 - \dfrac{\rho_{g1}R}{\alpha_1\rho_{g1}C_p + (1-\alpha_1)\rho_lC_l}\right\}\{\alpha_1\rho_{g1} + (1-\alpha_1)\rho_l\}}. \tag{6}$$

Isothermal equilibrium wave:

$$D^2 = \frac{P_2}{\alpha_1\{\alpha_1\rho_{g1} + (1-\alpha_1)\rho_l\}}. \tag{7}$$

The propagation velocity of the adiabatic thermal equilibrium wave coincides with that of the isothermal equilibrium wave when the void fraction is small and the specific heat of the liquid is large. That is, when $\alpha_1\rho_{g1}C_p \ll (1-\alpha_1)\rho_lC_l$, [6] becomes equal to [7]. In such a small void fraction region [6] and [7] agree well; in a large void fraction region the difference cannot be neglected. For example, if the extreme limit of $\alpha = 1$ is considered, [6] and [7] are respectively given as follows:

$$D^2 = \frac{P_2}{\rho_{g1}}\left(\frac{\kappa+1}{2}+\frac{\kappa-1}{2}\frac{P_1}{P_2}\right), \qquad [8]$$

$$D^2 = \frac{P_2}{\rho_{g1}}, \qquad [9]$$

where κ is the adiabatic index. Equation [8] is the adiabatic propagating velocity of the pressure wave in gas, and [9] is the isothermal progagation velocity of the pressure wave in gas. The two equations are significantly different. From this consideration the energy transfer phenomenon between gas and liquid phases in the two-phase flow can be evaluated from studies for phenomena near $\alpha \approx 1$.

3. EXPERIMENTAL APPARATUS AND METHOD

As shown in figure 1, the experimental apparatus consists of a vertical shock tube, a foam generator and semiconductor pressure gauges. The vertical shock tube consists of two sections; the upper part a high-pressure tank and the lower part a measurement section made of a transparent acryl pipe 2000 mm in length, 11 mm in inner diameter and 27 mm in outer diameter permitting good observation of the foam generated in the measurement section. The initial pressure P_1 was atmospheric and by use of an adequate diaphragm a shock wave of intensity of $(P_2/P_1) = 1.1$–2.0 was generated. Several means including mist flow were tried unsuccessfully to make two-phase flows of void fraction over 0.99. After several trials, we came to the conclusion that the foam flow containing numerous thin liquid films in gas was most successful. The thin film can be made as foam of materials such as soap. The foam generator for this purpose is set at the bottom of the shock tube and is connected with a liquid soapy container. The air flowing in from the side of the foam generator generates bubbles in the soapy liquid and intermittently flowed into the measurement section, forming a foam flow consisting of many parallel thin films. Upon production of the required number of film foams, the generation was stopped and the foams were kept motionless in the tube. By changing the air velocity we could change the interval, d, of the

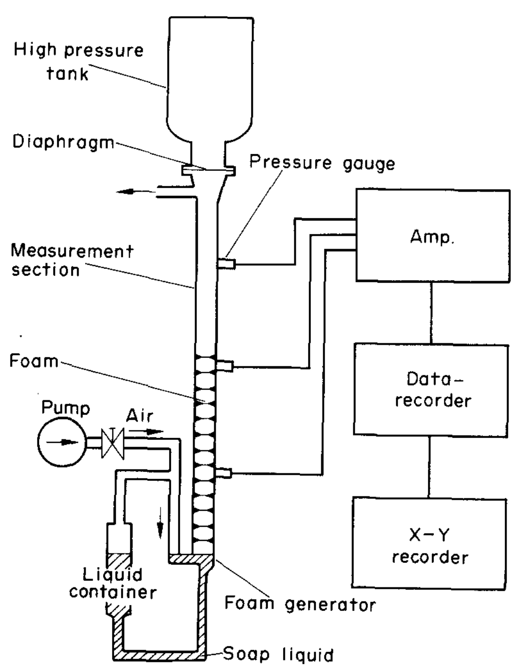

Figure 1. Experimental apparatus.

foam between about 3–60 mm. The surface tension of this solution was 35 dyn/cm, measured by the dropping liquid method.

The pressure change through the shock wave was measured by three semiconductor pressure gauges set along the tube axis, the signal from which was recorded by a data-recorder and then reproduced by an X–Y recorder. Deformation and break of foam due to the pressure wave were photographed for detailed investigation.

4. EXPERIMENTAL RESULTS

4.1 *Construction of foam*

General foam flows exist in air in the form of many thin films of liquid phase with complicated patterns. In the present study, foams were arranged with a constant interval and perpendicular to the shock tube axis, as shown in figure 2 as to make a theoretical analysis feasible. In this case one foam consists of a thin liquid film part and the liquid ring adhering to the tube wall which occupies the most part of liquid contained in the foam.

The volume, V, of liquid contained in the foam was found constant regardless of foam interval. This foam flow therefore is quantified by the form interval, d, or the film number per unit length, m.

As the liquid film in the center part of the foam was considered to have an important effect on the performance of the pressure wave propagating in the foam flow mentioned above, the thickness of this liquid film was measured by a Mach–Zender interferometer using a He–Ne laser. Assuming the displacement of the fringe S by introduction of a film in the optical path, the index of refraction of liquid, n, and the wave length of light λ, the thickness of the liquid film δ (Jenkins & White 1957) is given by

$$\delta = \lambda S/(n-1). \qquad [10]$$

The measurement of the absolute value of S was done by changing the film number. The thickness of the liquid film, δ, was found to be 0.73 μm.

4.2 *Shock wave in the foam film*

An example of the results of pressure measurement obtained at points 730, 1130 and 1530 mm from the diaphragm when the shock wave propagates in the foam flow is shown in figure 3. By comparison, it is found that one shock wave is separated into 2 waves and the first wave and the second wave are propagated. The first wave is attenuated with the propagation distance. In the present work, the propagating velocity of the first wave, its attenuation and the cause of the generation of the second wave are studied.

In order to clarify the relation of such characteristic pressure changes and the deformation of the foam as mentioned above, the geometry of the foam when the pressure wave was propagating through it was photographed. One example is shown in figure 4. As the signal of the pressure

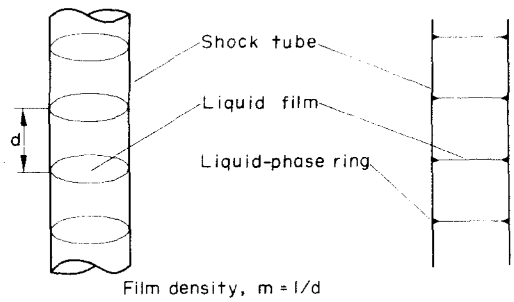

Figure 2. Model of foam film flow.

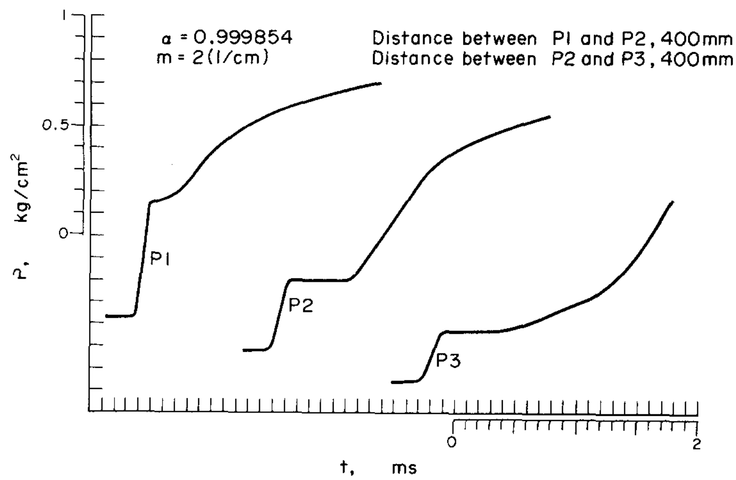

Figure 3. Typical pressure wave in foam film flow.

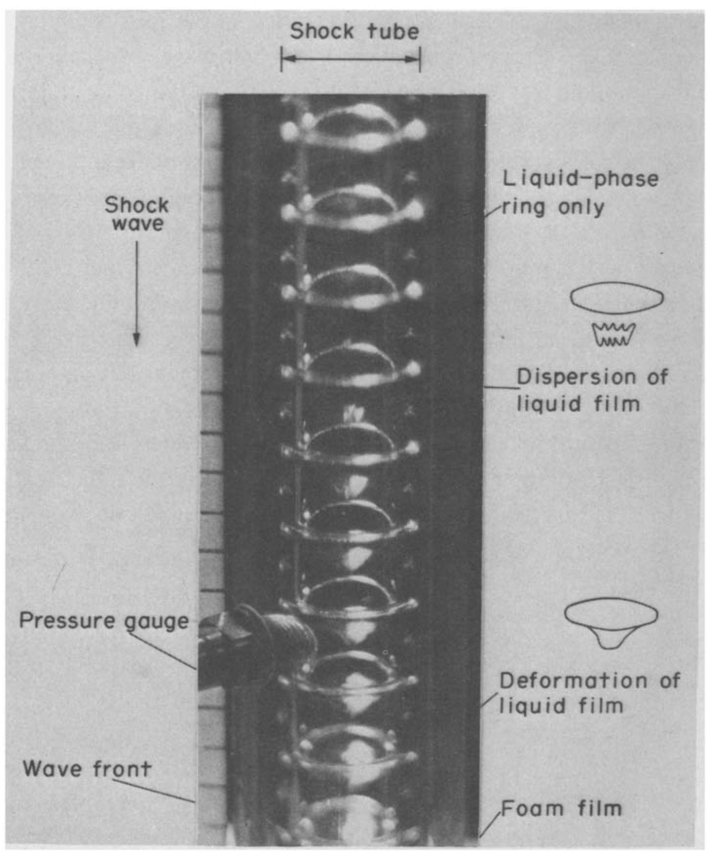

Figure 4. Aspect of foams in shock front.

transducer in the figure was used as the trigger signal for the camera, it may be appropriate to consider the leading edge of the first wave at the position of the pressure transducer. In this case the second wave is located above the area photographed and is not shown. As seen from the photograph, the liquid film is increasingly deformed as the shock wave travels through it, then is fragmented and dispersed. During this time, the liquid phase ring adhering to the tube wall has not experienced any deformation. It is considered from this observation that only part of the liquid film is deformed by the first wave, and that the void fraction which is important for investigation of the propagation phenomenon of the first wave is given by the thin liquid film of thickness 0.73 μm and film density m.

The frequency response of the present measuring electronic system is DC-7 KHz, and assuming the propagation velocity of the pressure wave to be 350 m/s, the minimum resolving distance is about 5 cm. As seen from figure 4, within the rise time of the pressure wave of the first wave, the breakdown of the liquid film and fragmentation into tiny droplets is perfectly carried out, and a uniform two-phase flow is considered to be realized. Therefore a comparison of the measured propagating velocity of the first wave and the predicted value based on the assumption that the two-phase flow is a uniform medium, may be possible. Further study using smaller pressure transducers and measuring devices with higher frequency response is required for research at times after the time constructions of the shock wave in the foam flow such as deformation and breakdown of the liquid film due to the first wave.

4.3 *Propagation velocity of the first wave*

The change of the propagating velocity of the first wave due to the intensity of the shock wave is seen in figure 5, with void fraction as parameter. The vertical axis is the propagation velocity, the horizontal axis is the mean value of the pressure ratio before and after the first wave, $P_{21} = P_2/P_1$, in the measuring section and the experimental value of the same sign in the figure is the one for a constant film density, that is, void fraction. Considering the liquid contained only in the film part as concerned with the propagation of the first wave, the theoretical values of the adiabatic thermal equilibrium wave given by [6] for the void fraction, obtained from the thickness of the liquid film δ and the film density m, are shown by solid lines in the figure. It is found from the good agreement in the wide pressure region that the liquid phase affecting the propagating velocity of the first wave is the liquid film part only. The good agreement proves the accuracy of the mechanical equilibrium ($u_g = u_l$) and, the thermal equilibrium ($T_g = T_l$) before and after the shock wave, assumed in the analysis. The reason for the agreement may be that the relaxation time of momentum and energy transfers between the two phases is sufficiently short, due to the extremely small diameter of the tiny droplets generated by the fragmentation of the liquid film.

From figure 5, the sonic velocity for the respective void fraction is obtained by making P_{21} approach unity, the result of which is shown in figure 6. This result however shows the sonic velocity propagating in the broken liquid film existing as particles and careful observation is required to distinguish the difference from the sonic velocity in the intact liquid film flow. The elasticity and rigidity of the liquid film may have an effect on the sonic velocity in the liquid film flow

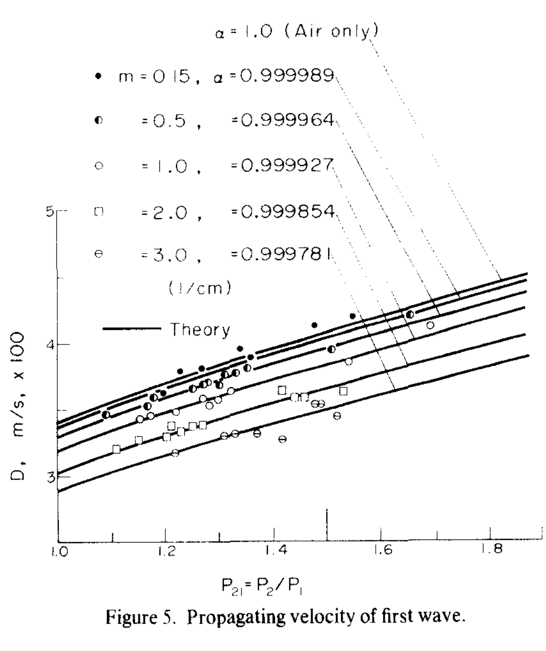

Figure 5. Propagating velocity of first wave.

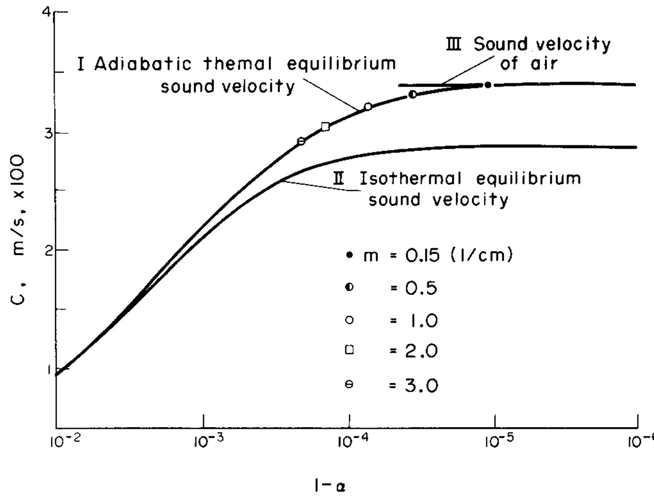

Figure 6. Sonic velocity in two-phase flow.

when the liquid film is intact. When the liquid film fragments even for such a very weak shock wave as in the present experiment, the effect may be neglected. The solid lines in figure 6 show the adiabatic thermal equilibrium sonic velocity I given by [6], the isothermal equilibrium sonic velocity II by [7] and the sonic velocity of air III by [8], respectively. The adiabatic thermal equilibrium sonic velocity approaches the isothermal equilibrium sonic velocity below 0.996 void fraction and approaches the sonic velocity of air above 0.999991. This experimental value shows that in the void fraction region from 0.9998 to 0.99999 the sonic velocity is definitely not isothermal but adiabatic and satisfies the thermal equilibrium condition ($T_g = T_l$).

Regardless of the entirely different condition from the film geometry and the droplet geometry before and after the shock wave, the experimental results can be explained by use of a void fraction defined macroscopically. This might be due to the fact that the void fraction, a macroscopical physical quantity, has a significant effect on two-phase flow.

4.4 *Attenuation of the first wave and generation of the second wave*

When the pressure wave in the foam flow as shown in figure 3 is observed, it seems that the attenuation of the first wave and the generation of the second wave are closely connected. There is no doubt that the liquid phase ring occupying the most part of liquid volume of the foam has some effects on these phenomena. An investigation was made therefore on the effect of the liquid phase ring.

A thread was stretched in the axial direction along the inside wall of the the shock tube, then the liquid of the liquid phase ring went down along this thread and the two-phase flow of a liquid film only (liquid film flow) was made. The pressure wave pattern propagating in this flow is shown in figure 7. The pressure change is the same with that in the air and shows no attenuation performance. In the case of the liquid film flow however, the film was more apt to break than in the foam flow. However, the results of the sonic velocity in the film flow are in good agreement with those shown in figure 6.

As understood from the experimental results explained above, it is considered that the pressure change characteristic of the foam flow is closely related with the liquid phase ring. A liquid phase ring was imitated with a wire ring to clearly understand the phenomenon. A spiral wire of a diameter of 0.65 mm was inserted in the shock tube, contacting the inside wall, and changes of the wave form were examined.

To make the observation of phenomenon easy, two rolls of spiral wire were located between the pressure transducers P_2 and P_3. An example of the pressure change determined in the shock tube is shown in figure 8. The shock wave, having propagated from the upper part was detected in transducers P_1 and P_2, and passing through the section where the spiral wire was inserted, was

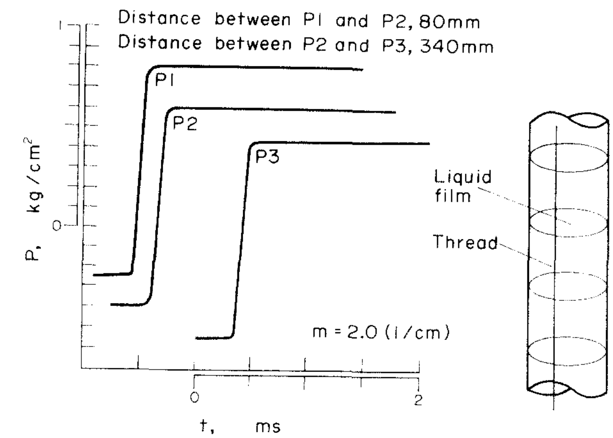

Figure 7. Pressure wave in two-phase flow of liquid film only.

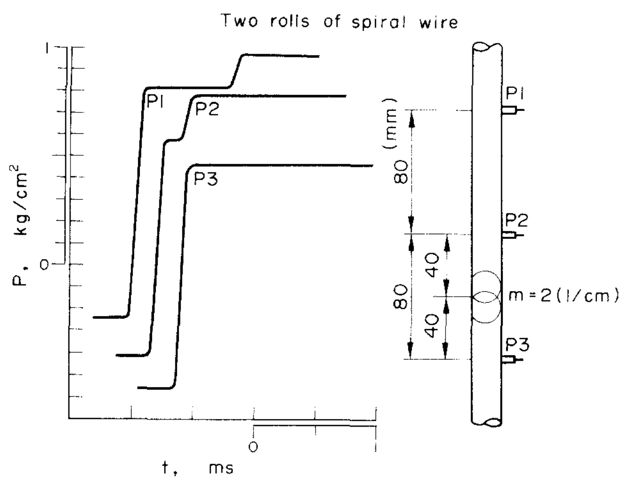

Figure 8. Pressure wave through two rolls of spiral wire.

detected by P_3. The pressure changes at P_1 and P_2 are seen to consist of the initial rise and the second rise. The initial rise occurs in order of P_1 and P_2, while the second one is in order of P_2 and P_1, and at P_3 this second pressure rise is not observed. This fact means that a reflected shock wave propagating upward was generated by the spiral wire. On the other hand, the pressure wave passing through the spiral wire and detected at P_3 is seen to be weaker than those at P_1, P_2.

To compare the pressure change shown in figure 8 with those in the foam flow, two foams were set at the same location as the spiral wire and a shock wave was propagated. An example of the pressure change thus obtained is shown in figure 9. In this case, as in figure 8, a reflected wave is formed, but being different from the case of the spiral wire, the reflected wave is gradually attenuated. It may be because the water of the liquid phase ring was dispersed in the air by the particle velocity of air after the shock wave passed and did not continue generation of the reflected wave.

It is considered that the pressure wave propagating in the foam flow with many films in the shock tube and the pressure wave propagating in the spiral wire evenly placed in the tube are affected by the accumulation of the effects mentioned above. In order to make this point clearer, an experiment was made on the pressure wave propagating in the long spiral wire or in the foam flow of many films of the interval of 5 mm between P_1 and P_3. The results are shown in figures 10 and 11. In figure 10, at P_1 a short time after the incidence of the shock wave, the first reflection wave arrives and then the pressure gradually rises due to the reflection wave made by the respective spiral wire. On the other hand at P_2, set in the spiral wire, the pressure rise by the

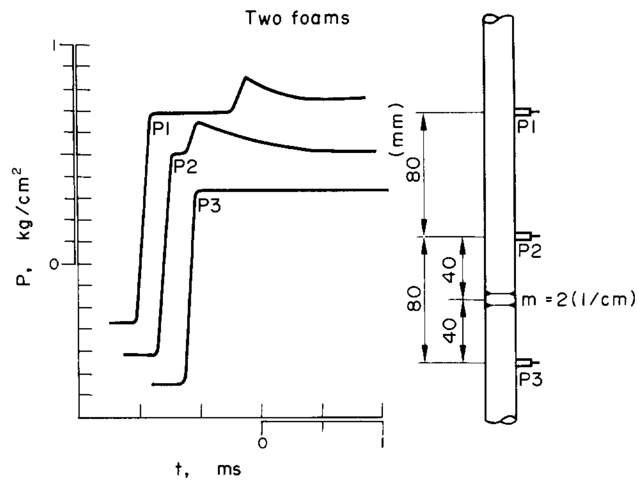

Figure 9. Pressure wave through two foam films.

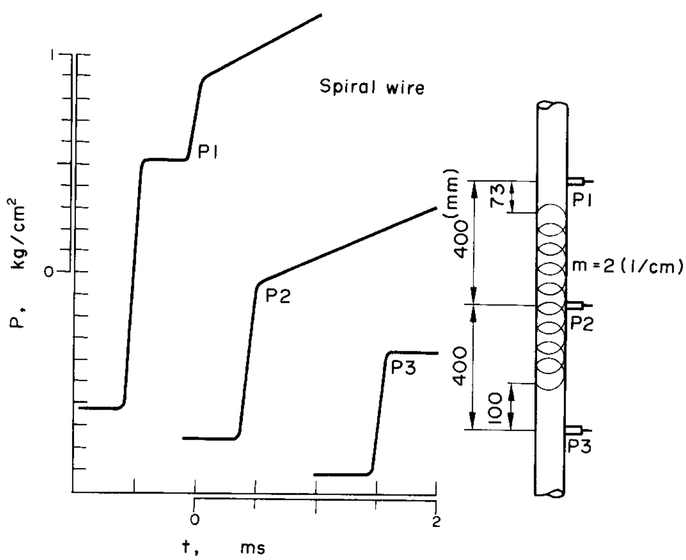

Figure 10. Pressure wave through spiral wire.

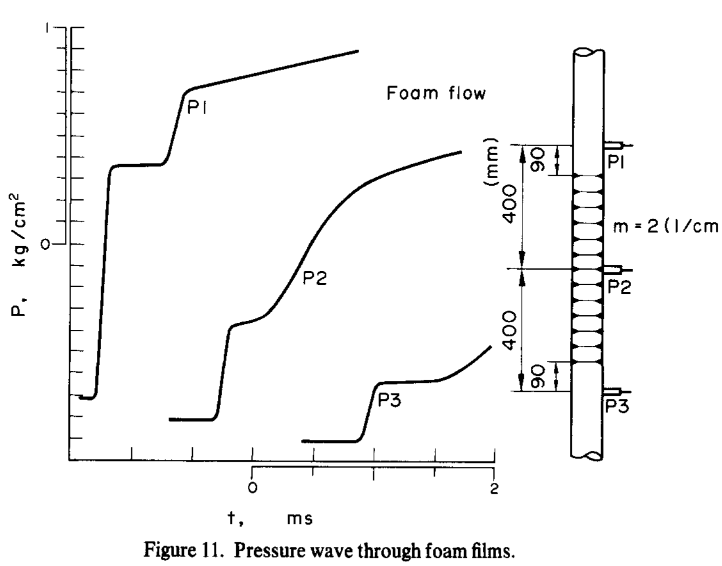

Figure 11. Pressure wave through foam films.

reflection wave begins simultaneously with the incidence of the shock wave. As the shock wave that arrives at P_2 has emitted reflection waves by many spiral wires, the shock wave intensity is decreased from the value of P_1. At P_3 a more weakened pressure wave is detected, and a constant pressure is detected after the initial rise as there is no spiral wire downward of P_3.

Figure 11 shows the result of a same experiment made on the foam flow. The shock wave attenuates due to the reflection wave by the liquid ring, and the liquid ring is dispersed after the passage of the first wave. The dispersion of the liquid ring is the cause of the formation of the second wave and causes the discrepancies of wave forms between figures 10 and 11. If the attenuation rate, a, of the first wave per one sheet of foam film or one role of spiral wire is defined by the following equation, the value of a is considered to be constant along the flow direction within the accuracy of 10%.

$$a = -\mathrm{d} \cdot \ln (P_2 - P_1)/\mathrm{d} \cdot (mx). \qquad [11]$$

The variation of a with m is shown in figure 12. The height of the liquid ring is about 1 mm and the diameter of wire is 0.65 mm. It is not possible to explain quantitatively the difference of both by the present experiment. However the attenuation rate per one sheet or one roll is seen to decrease with the increase of roll number per unit length, and the reflection waves from the adjacent liquid phase ring or the spiral wire are considered to be mutually interferring.

In order to clarify the generation mechanism of the second wave by the liquid phase ring, the photograph in connection with the generation of the second wave is shown in figure 13. The very top of the second wave is the point of the initiation of turbulence of the liquid ring. As the second wave is a wave propagating in a lower void fraction than the first wave, its propagation velocity is smaller than that of the first wave. It is considered that the second wave is generated as a result of a complicated mechanism accompanied by the change of reflection performance by the liquid phase ring, change of the void fraction, and change of the propagating velocity due to the dispersion of the liquid phase ring into the air. Further study is required for an exact understanding of this mechanism.

5. CONCLUSION

A theoretical and experimental study is made on the finite amplitude pressure wave propagation in the foam flow consisting of many thin liquid films and the following conclusions are obtained.

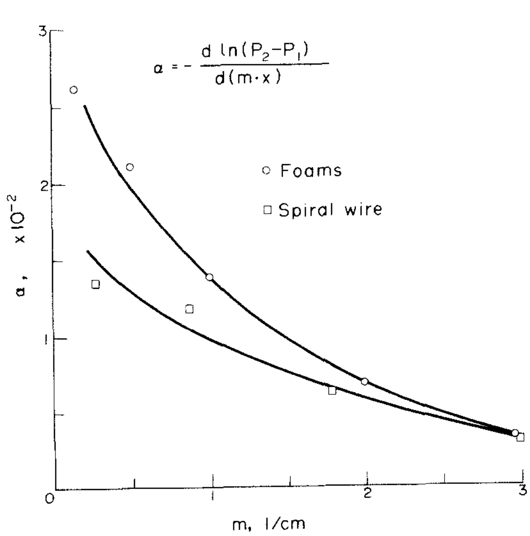

Figure 12. Attenuation rate of first wave.

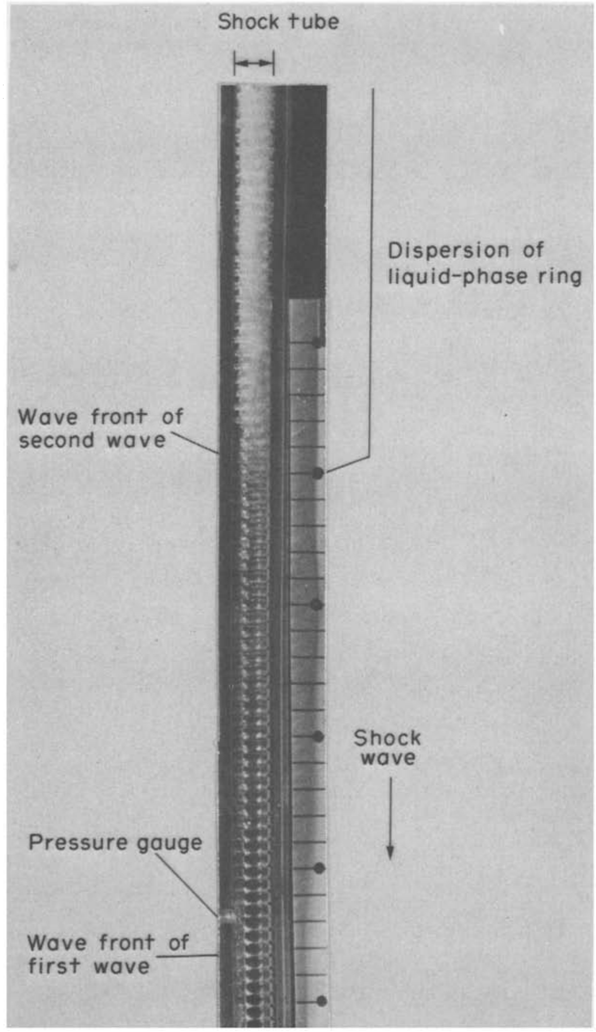

Figure 13. Behavior of liquid-phase ring after shock wave.

(1) The shock wave propagation in the foam flow is broken into two waves; the first wave at the very top and the second wave downstream of it.

(2) The first wave is the pressure wave propagating in the two-phase flow which fragments liquid film to form tiny droplets. The second wave is located downstream and propagates more slowly than the first wave, dispersing the liquid ring adhering to the shock tube wall.

(3) The void fraction of the two-phase flow generated by breaking the liquid film in which the first wave is propagating is 0.9998–0.99999, and this propagation velocity agrees very well with the theoretical prediction assuming a homogeneous flow and an adiabatic thermal equilibrium. It may be because droplets generated by dispersion of the liquid film are very small and the temperature relaxation time between the two phases is sufficiently short.

(4) According to the theoretical analysis, propagation velocity of the adiabatic thermal equilibrium wave approaches the sonic velocity of the isothermal equilibrium wave at void fractions below 0.9 and approaches the adiabatic sonic velocity in gas above the void fraction of 0.99999. It is made clear that the sonic velocity obtained from the experimental value of the first wave exists between these two sonic velocities.

(5) The attenuation of the first wave is caused by the reflection by the liquid phase ring, and the attenuation rate per one sheet of foam varies with the film interval.

(6) The second wave is the wave propagating in the mist flow generated by the dispersion of the liquid ring. The separation of the first wave and the second wave is due to the difference of the

propagation velocities caused by the increase of the void fraction due to the atomization of liquid ring into the air.

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