Study on ultrasonic velocity profile measurement in vapor-water two-phase flow

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In the gas-liquid two-phase flow measurement, a number of measuring techniques have been developed and applied to the flow monitoring of the two-phase flow structure. The ultrasonic velocity profile (UVP) measurement is one of the successful measuring techniques, since it is a non-invasive measurement and can obtain the velocity profiles along the measuring line. For the on-site flow monitoring, the clamp-on UVP measurement is required. However a solid wedge is necessary for the installation of an ultrasonic transducer on the pipe without a machining process of the pipe. Because of the use of the wedge, the transmitted sound field in fluid gets complicated, so it is important to clarify the ultrasonic transmission behavior when a wedge is used. Thus the transmission characteristics of the pulse ultrasound transmitted to the flow were investigated using the radiation angle of the ultrasonic beam and the ultrasonic transmission intensity obtained by the sound pressure distribution measurement, and then the optimal incident angle of the ultrasonic pulse was decided. Using the optimal ultrasonic incident condition, the applicability of the UVP measurement to boiling two-phase flow was investigated.

Keywords: Boiling two-phase flow, Velocity profile measurement, Ultrasonic transmission characteristics, Sound pressure distribution, Clamp-on type

1 INTRODUCTION

Gas-liquid two-phase pipe flow is one of the important phenomena for safety operation of industrial plants. They require two-phase flow measuring techniques for monitoring the flow structures (e.g. void fraction distribution, velocity profile, flow rate etc.) in real-time. The ultrasonic velocity profiler (UVP) [1] can measure the flow velocity profiles in opaque pipes. So it can be a very effective tool for on-site flow observation. Furthermore, as an application of UVP technique to gas-liquid two-phase flow, the multi-wave ultrasonic velocity profiling method [2] can measure the velocity profiles of both gas and liquid phases simultaneously. The conventional ultrasonic measurement of gas-liquid two-phase flow has had little applicability to the boiling two-phase flow. The ultrasonic measuring technique to boiling flow has the capability of on-site two-phase flow monitoring. In addition, in the installation of ultrasonic measuring instruments, the clamp-on type is suitable for the two-phase flow monitoring in the plants in operation, because it is not necessary to machine the existing pipes. However the transmitted ultrasonic sound fields get complicated due to the effect of metallic pipes. Hence the transmission characteristics of pulse ultrasound should be examined in detail before the ultrasonic measurement.

In this study, for the purpose of UVP measurement of boiling two-phase flow at high temperatures, the ultrasonic transmission characteristics are clarified by measuring the transmitted sound pressure distributions and comparing them with theoretical analysis, and then the optimal incident angle for ultrasonic velocity profile measurement is decided. Using the optimal incident angle, the velocity profiles of vapor bubbles in a circular pipe are measured by UVP.

2 ULTRASONIC TRANSMISSION CHARACTERISTICS

2.1 Ultrasonic transmission in clamp-on type

In the clamp-on ultrasonic measurement, an ultrasonic transducer (TDX) is installed on the solid wedge fixed on the pipe wall. So ultrasonic waves emitted from the TDX transmit to the wedge. When the waves pass through the wedge, the wave mode is the longitudinal wave. The reflection, refraction

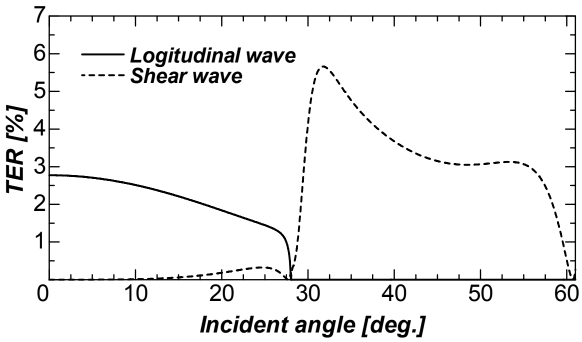


Figure 1: Transmission energy ratio in a case of the transmission between acrylic wedge, stainless steel plate and water.

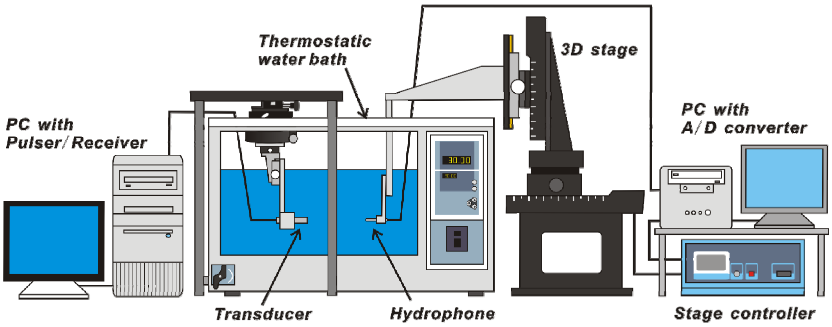


Figure 2: Schematic diagram of three-dimensional automatic USPD measuring system

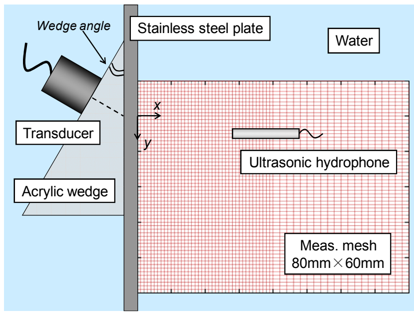


Figure 3: Test section of USPD measurement

and mode conversion occur at the interface between the wedge and the pipe wall, and then, in addition, the shear wave and the plate wave are generated in the pipe wall. These waves are converted into the longitudinal wave again at the interface between the pipe wall and the water. Since each wave mode has a different propagating velocity, the ultrasonic sound field in water contains multiple waves and gets complicated.

2.2 Ultrasonic transmission energy ratio

The transmission energy ratio (TER) [3] of the ultrasonic wave was used to compare the intensity of transmitted ultrasonic wave with the results of the sound field measurement. The TER of the ultrasonic wave transmitted between two mediums can be calculated from the amplitude ratio of displacement potential of each reflection and refraction wave to that of the incident wave. Thus the TERs from acrylic resin to stainless steel and from stainless steel to water were estimated. And then the TER between a wedge, plate and water was obtained from the product of TERs for the longitudinal and shear waves, and the calculated results in the case of transmission between an acrylic wedge, a stainless steel plate and water are shown in Figure 1. The TERs of each wave mode are varied by the incident angle. At an incident angle above 28 degrees, there is no longitudinal wave, since 28 28.02 degrees is the critical angle of the wave at the interface from acrylic resin to stainless steel. This figure shows the TER has a maximum value at the incident angle of around 30-35 degrees. In this case, the TER is not more than 6 % of the incident wave, so most waves are reflected.

2.3 Sound field measuring method

The ultrasonic sound pressure distributions (USPDs) of transmitted pulse ultrasound were measured by an ultrasonic hydrophone. The measurement system of the USPD and the test section are illustrated in Figure 2 and Figure 3, respectively, and the measurement conditions are shown in Table 1. The pulse signal sent from the pulser/receiver (TB-1000: Matec Inc.) built in a PC was transmitted to the wedge by the TDX. The

Table 1: Measurement conditions of USPDs.

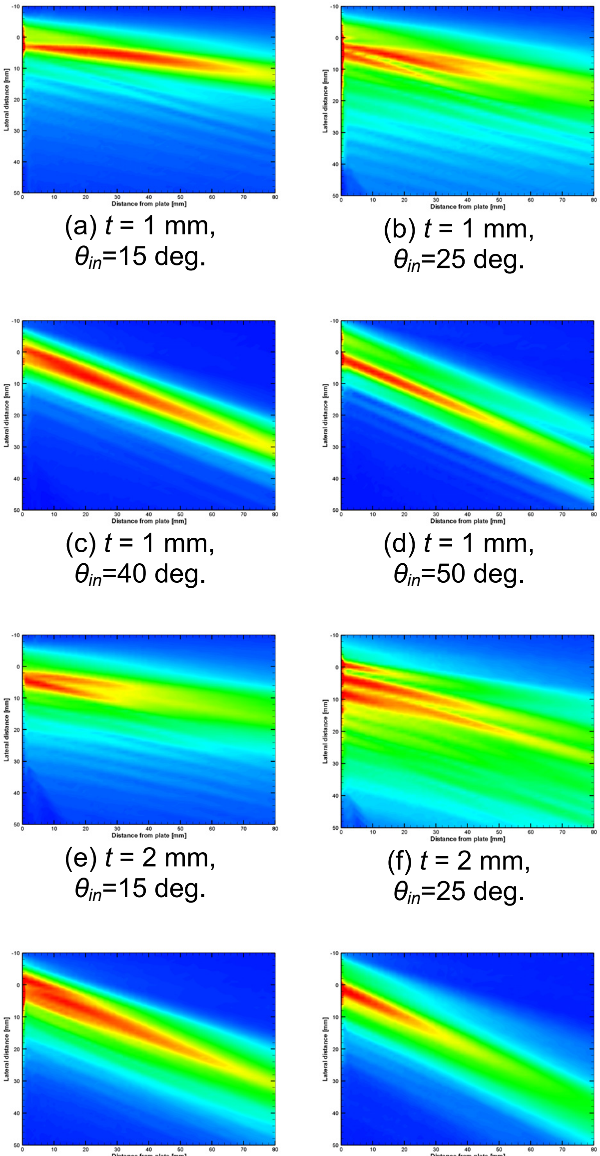
Ultrasonic basic frequency	2 MHz
Ultrasonic beam diameter	10 mm
Wedge material	Acrylic resin
Wedge angle θ_{in}	8-50 degrees
Plate material	Stainless steel
Plate thickness t	1 mm, 2 mm
Water temperature	30°C
Detectable area of hydrophone	1mm x 1mm
Measuring area	80mm x 60mm

signals transmitted into water were received by a movable ultrasonic hydrophone with a detectable area of 1 mm^2, and the transmitted sound pressure was stored by an A/D converter (NI PCI-5112: National Instruments) in a PC. Then the USPD in the measuring area was obtained.

In the USPD measurement, water temperature was maintained at 30°C by using a thermostatic water bath. The sound velocity in water under such conditions was 1510 m/s. 2 stainless steel plates with 1 and 2 mm thickness were used to estimate the effect of the plate thickness. Through the theoretical analysis, 10 types of wedges whose angles range from 8 to 50 degrees were selected and used to measure the USPDs. A high-temperature TDX (2K10I-H: Japan Probe) with a basic frequency of 2 MHz and an allowable temperature limit of 120°C was used.

2.4 Results of USPD measurement

The typical USPDs are shown in Figure 4. Figures 4(a), (c), (d), (g) and (h) have a single linear beam. On the other hand, there are some different beams in Figures 4(b), (e) and (f) because of the appearance of multiple wave modes. Furthermore, in Figures 4(a), (b) and (e), striped waves are found at different direction from a strong beam. These waves are the leaky plate wave, which is caused by the plate wave generated in the plate. From these figures, the beam formation in fluid can be easily understood, and it is found that the ultrasonic beam



(a) t = 1 mm, θ_{in}=15 deg.
(b) t = 1 mm, θ_{in}=25 deg.
(c) t = 1 mm, θ_{in}=40 deg.
(d) t = 1 mm, θ_{in}=50 deg.
(e) t = 2 mm, θ_{in}=15 deg.
(f) t = 2 mm, θ_{in}=25 deg.
(g) t = 2 mm, θ_{in}=40 deg.
(h) t = 2 mm, θ_{in}=50 deg.

Figure 4: Typical USPDs measured by ultrasonic hydrophone

shapes in the USPDs change depending on the incident angle and plate thickness.

2.5 Ultrasonic transmission characteristics

For the clarification of ultrasonic transmission characteristics when a wedge is used, the radiation angle and the transmission intensity are estimated by using the measured USPDs.

The radiation angles of transmitted beams were evaluated by connecting the beam in USPD, as is shown in Figure 5. Several beams appear at the wedge angles from 15 to 30 degrees, and the radiation angles of each beam were obtained. Under these conditions, these radiation angles show large variations, because the beam characteristics are changed by the overlapping of multiple waves. The

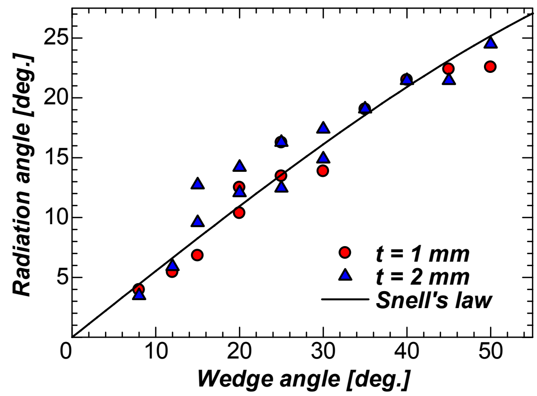


Figure 5: Radiation angle of the ultrasonic beam transmitted to water.

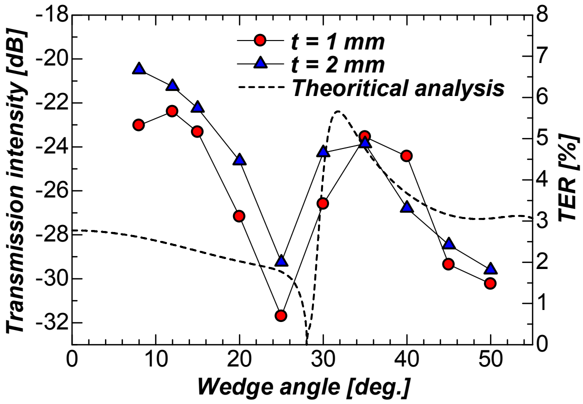


Figure 6: Transmission intensity of the transmitted ultrasonic beam.

radiation angles at the wedge angles of 8, 12, 35 and 40 degrees give close agreement with that of Snell's law, which is calculated by the incident angle and the sound velocity in theory.

The transmission intensity I_T was calculated by the following equation.

$$I_T = 20\log\left(\frac{V}{V_0\cos\theta_r}\right) \qquad (1)$$

where V is the voltage value detected by the hydrophone, and V_0 is the reference voltage of this TDX. θ_r is the radiation angle of transmitted beam estimated from USPDs. Figure 6 shows the transmission intensity and TER based on by theoretical analysis. The transmission intensity as well as the TER decreases near 25 degrees, because it is the critical angle.

For the velocity profile measurement, the single linear beam with high intensity is better. From the USPD measurement, estimation and comparison with theoretical analysis, it is found that the incident angle (wedge angle) of 40 degrees is well suited for flow measurement in pipe with 1mm thick wall.

3 VAPOR BUBBLE VELOCITY PROFILE MEASUREMENT

3.1 Experimental set-up and method

The experimental set-up for boiling two-phase flow measurement is shown in Figure 7. Water pre-heated by a pre-heater in the storage tank flowed into test pipe by a pump. The flow rate of water was adjusted by the control valve and measured by the orifice flowmeter. The cartridge heater was inserted in the inlet of the test channel and vapor bubbles were generated in the pipe. This heater has a diameter of 12.7 mm, a length of 300 mm and a maximum heat flux of 400kW/m^2. The heater powers were individually set by the temperature controllers. The overflowed water returned to the storage tank again. The test channel consists of circular pipes made of PYREX glass and stainless steel. PYREX glass pipe was used to visualize the flow field, and stainless steel pipe was used to simulate the ultrasonic measurement in the operating plants. These pipes have an inner diameter *D* of 50 mm.

The UVP monitor (UVP-Duo, Met-Flow) was used for the velocity profile measurement of vapor bubbles in vertical upward flow. The test section of the UVP measurement was placed at 27*D* from the top of the cartridge heater. The TDX was connected to the UVP monitor and fixed on the surface of the acrylic wedge, which has an incident angle of 40 degrees. The ultrasonic couplant was poured between the TDX and the wedge and between the wedge and the pipe wall surface for transferring the ultrasound into the pipe. This couplant, which is designed for high temperatures, provides the high coupling efficiency and can transmit ultrasound at the temperature up to about 350°C.

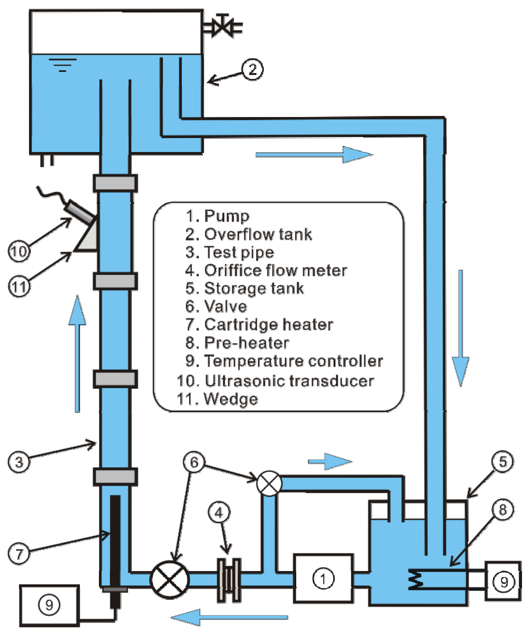


Figure 7: Schematic diagram of experimental loop for boiling two-phase flow measurement

Table 2: Experimental conditions.

Working fluid	Water, vapor
System pressure	Atmosphere
Inlet heat flux	300 kW/m^2
Inlet subcooling temperature	5 K

3.2 Velocity profiles of small vapor bubbles

The velocity profiles were measured using the small bubbles generated by the heater, as is shown in Figure 8. From this result, it is found that the velocity profiles changed depending on the difference of the liquid flow rate. So the velocity profile of flow field at around 100°C can be obtained by the estimation of the ultrasonic transmission characteristics. However there is a little velocity drop due to the ultrasonic reflection in the wedge. It will be possible to eliminate it by improving the shape of the wedge.

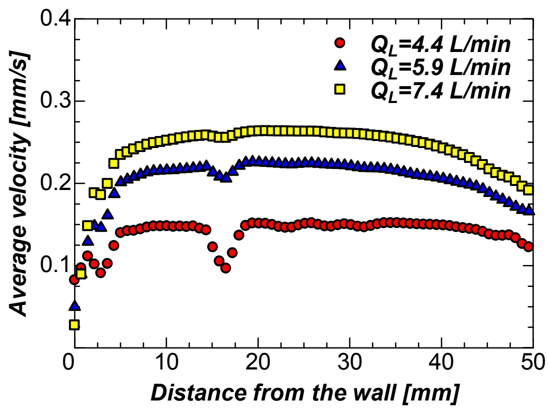


Figure 8: Velocity profiles of small vapor bubbles generated by the heater.

4 SUMMARY

For the clamp-on ultrasonic velocity profile measurement of the vapor-water boiling two-phase flow, the ultrasonic transmission characteristics were investigated experimentally by the ultrasonic sound pressure distribution measurement using the ultrasonic hydrophone. And the possibility of the ultrasonic velocity profile measurement of boiling two-phase flow at high temperatures was verified.

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