Characteristics of echo signal of pulse ultrasound on boiling two-phase flow

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Pulse ultrasound technique has been applied to measure the reflected echo signals from vapor bubbles in boiling two-phase flow. In this study, an ultrasonic transducer was developed for the ultrasonic measurement in boiling two-phase flow under the atmospheric pressure. Since the Curie point of piezoelements of the transducer is above 250˚C, it has an allowable temperature limit of 120˚C. The basic frequency of the ultrasonic transducer is 2 MHz and the ultrasonic beam diameter is 10 mm. The measured flow has rising vapor bubbles generated by the cartridge heater. The pulse ultrasound transmitted from an ultrasonic transducer travels into a vessel through the carbon steel wall of 1mm thickness. Echo signals are received by the same transducer. So the delay time and strength of a pulse echo are obtained from this measurement, and the distribution of vapor bubbles is obtained from reflected echo signals. Therefore the effect of boiling phenomena is estimated by the ultrasonic echo distribution.

Keywords: Pulse ultrasound, echo signal, boiling two-phase flow, ultrasonic transducer

1 INTRODUCTION

Boiling phenomena are observed in a lot of industrial plants such as nuclear plants and have been investigated by many researchers to clarify its flow structure. Conventionally boiling flow measurements have been done by using such techniques as pressure drop and electrical conductivity [1-4]. However many of these techniques are invasive and have a disadvantage of disturbing flow fields. So the non-invasive and more workable techniques for flow measurements and visualization are required. An Ultrasonic Velocity Profile (UVP) monitor [5,6] is an advanced measurement system on fluid flow, and has been successful in fluid flow measurements. The UVP monitor can obtain flow velocity profiles and visualize flow fields. The chief advantage of the UVP method is a non-invasive measurement. UVP measurement requires a sensor with high sensitivity, which can obtain the ultrasonic echo signals including flow velocity information. However the sensitivity of piezoelements of the sensor attenuates with increasing temperature. There are two approaches available to prevent the decrease in sensitivity of the sensor. One is to put a thermal buffer between a sensor and a high temperature fluid in order to keep the sensor temperature low. In addition, cooling the thermal buffer has a more positive effect. However sufficient knowledge on ultrasonic characteristics of a thermal buffer is essential. Eckert et al. [7] developed an integrated sensor which consists of a buffer rod and piezoelements, and measured velocity profiles of liquid metal flow over 200 ˚C by using the ultrasound Doppler method. Lynnworth et al. [8] have tried to apply the ultrasound to measuring the flow including gas or steam with the temperature up to 600 ˚C or liquid with up to 500 ˚C by using the extensional bundle waveguide. The other is a development of a sensor which can be used at high temperature. It means that the piezoelements with the high Curie point are necessary. This method costs more than thermal buffer method. However it has found a wide range of applications.

The purpose of this study is to measure boiling two-phase flow by using the pulse ultrasound technique. For this purpose, an ultrasonic sensor is developed using the piezoelements with a Curie point above the saturation temperature under the atmospheric pressure. Then by using the sensor, the intensity distributions of the ultrasonic echo signals are obtained in the flow field including bubbles generated by the cartridge heater.

2 HIGH-TEMPERATURE SENSOR

To make the ultrasonic measurement of the high temperature fluid flow fields such as a boiling two-phase flow and a liquid metal flow, the Curie point of piezoelements of an ultrasonic sensor for transmitting and receiving ultrasound is significant. Generally the piezoelectric effect of the element may be destroyed if its temperature exceeds the Curie point. A normal sensor for use at room temperature has an operating temperature limit of about 60 ˚C. So it can not be used at high temperature flow field. As a result, an ultrasonic sensor should be developed for measuring boiling two-phase flow.

2.1 Development of a sensor

Since the ultrasonic transducer developed in this study has an allowable temperature limit of 120 ˚C, so it can be used in boiling two-phase flow measurement under the atmospheric pressure. The

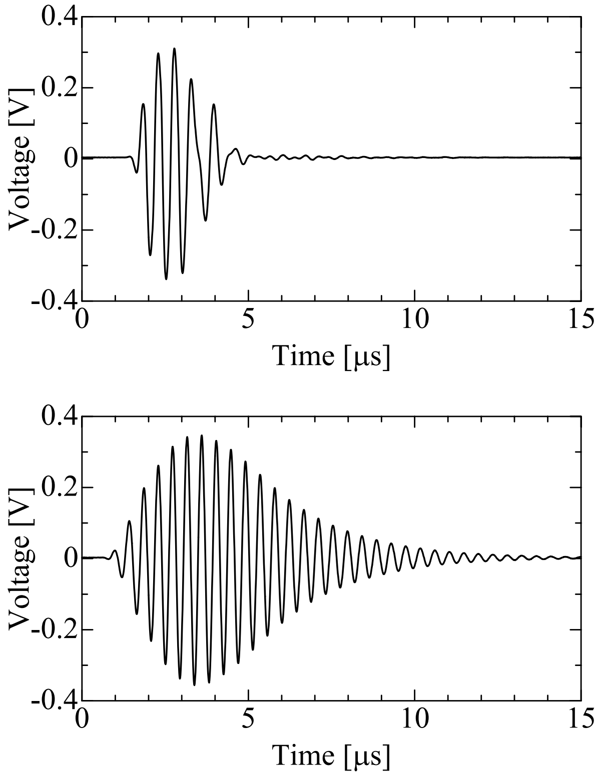


Figure 1: Typical echo signal reflected from a flat plate in water, Upper: Normal transducer, Lower: High-temperature transducer.

piezoelements are 1-3 composite vibrators. The Curie point of this element is above 250˚C. The heat resistance of resin surrounding the piezoelement column is taken into consideration. Furthermore, this sensor is fabricated with the operating temperature limit of an adhesive in mind.

2.2 Comparison of sensors

The typical echo signals of normal and high temperature transducers are shown in Figure 1, respectively. The basic frequency and beam diameter of each transducer are 2 MHz and 10 mm, respectively. These signals are measured in water of 23 ˚C and reflected from a flat steel plate. An output pulse wave from a pulser has two bursts. In the signal of a normal transducer, a clear burst wave is obtained. Two reflected signals compared, the echo signal of a high temperature transducer is widely trailed and wave number increases as shown in Figure 1. This shows that there is a significant decrease in the sensor sensitivity.

3 EXPERIMENTAL SET-UP AND METHOD

3.1 Experimental set-up

Figure 2 shows a schematic diagram of the experimental set-up. A rectangular vessel has a size of 80×80×200 mm and made of carbon steel. Tap water is filled in the vessel, and a cylindrical cartridge heater, which is made of stainless steel, is inserted into the middle of the bottom. The heater has a diameter of 9.4 mm and a length of 100 mm.

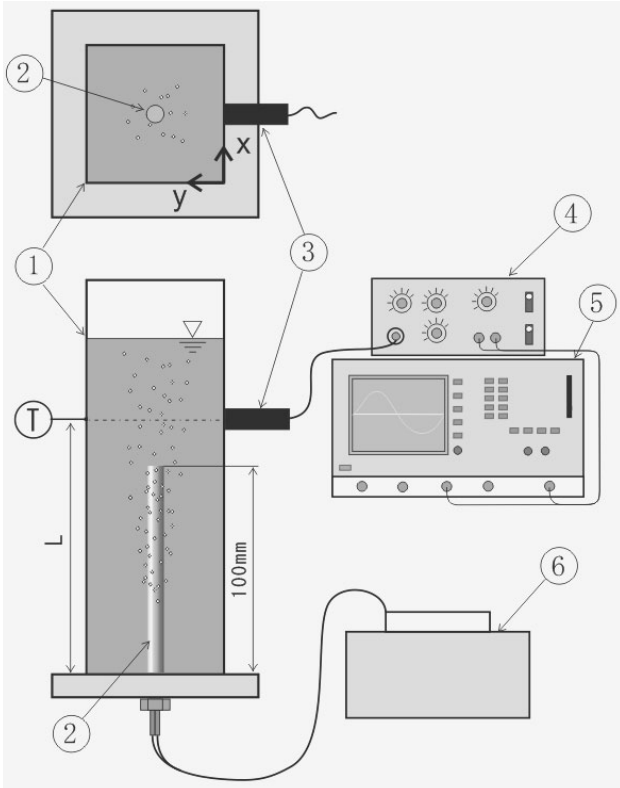


Figure 2: Schematic diagram of experimental set-up; 1. Vessel, 2. Heater, 3. Ultrasonic transducer, 4. Pulser/receiver, 5. Digital oscilloscope, 6. Slidax.

Table 1: Specifications of ultrasound and pulser/receiver.

Basic frequency	2 MHz
Beam diameter	10 mm
Pulse width	1.0 μs
Burst per pulse	2 burst
Input voltage	300 V
Pulse repetition frequency	2 kHz
Gain	32 dB
High pass filter	1 MHz
Low pass filter	2.25 MHz

The ultrasonic transducer is attached to the side surface of the vessel. The ultrasonic couplant (50A4084: Staveley Sensors Inc.) is filled between the transducer and the vessel wall surface for transferring the ultrasound into the vessel. This couplant, which is designed for high temperatures, provides the high coupling efficiency and can transmit an ultrasound at the temperature up to about 350 ˚C. The distance from the bottom to the central axis of the transducer is L [mm]. The coordinate system of the top surface of the vessel seen from above is represented by x [mm] and y [mm] as shown in Figure 2.

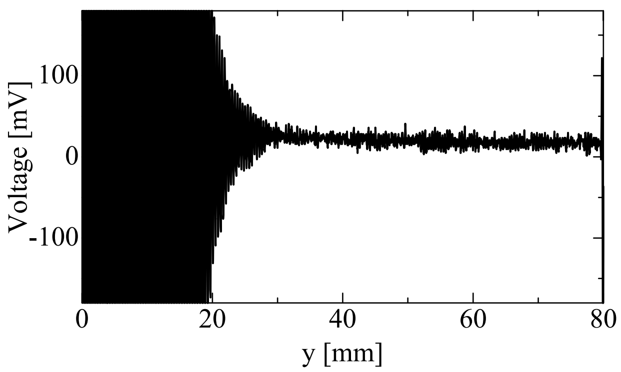
3.2 Experimental method

A pulse wave sent from a Pulser/receiver (TB-1000: Matec Inc.) is emitted by an ultrasonic transducer into the vessel through the wall, which is made of 1 mm thick carbon steel plate. The echo signal of pulse ultrasound reflected from vapor bubbles or the vessel wall is received by the same transducer. The waveform of echo signals is loaded on the digital oscilloscope (C547AL: LeCroy Corp.). The specifications of the ultrasound and the pulser/receiver are shown in Table 1. The ultrasonic basic frequency of the high temperature transducer is 2 MHz, and the beam diameter is 10mm. The pulse repetition frequency is 2 kHz because it should be fast enough to understand the boiling phenomena. The sound velocity in water at 95 ˚C is about 1540 m/s.

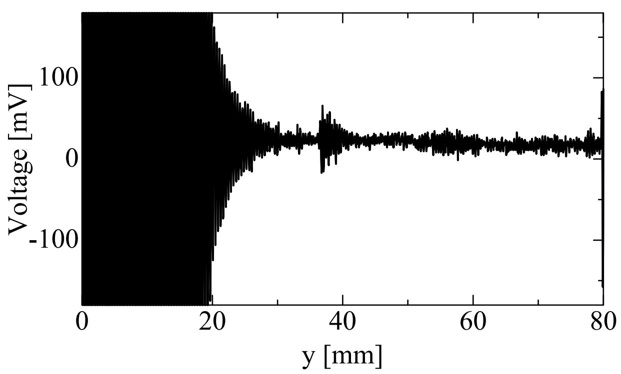
The temperature of the vessel was measured by a thermocouple. During the ultrasonic measurement, the temperature of the outer surface of the vessel was about 92 ˚C, which can be thought to be the temperature of the transducer itself.

4 RESULTS AND DISCUSSION

Figure 3 shows the ultrasonic echo signals reflected from the boiling flow field. The horizontal axis is the distance from the transducer, y, and the vertical axis is the detected voltage. The position of the transducer is L=120 mm and x=40 mm. The ultrasonic beam travels above the heater. Figure 3(a) and 3(b) show the echo signals which involve no bubbles and a bubble inside an ultrasonic beam, respectively. These figures indicate that the echo signals from bubbles cannot be obtained over 20 mm away from the transducer, because of the ringing of pulse waves inside the vessel wall. In Figure 3(a), there are no visible signals from bubbles. In Figure 3(b), however, it is found that the echo signal reflected from vapor bubbles appears around 40 mm.

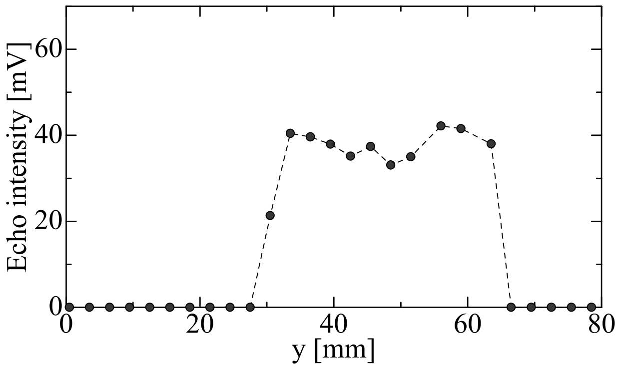


(a)

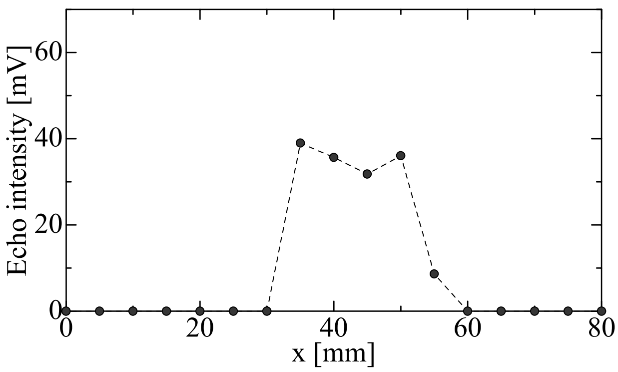


(b)

Figure 3: Typical echo signals from the boiling two-phase flow field at L=120mm, x=40mm, (a) Flow field has no bubbles inside ultrasonic beam, (b) Flow field has a bubble around y=40mm.



(a)



(b)

Figure 4: Averaged distribution of echo intensity from boiling flow field at L=120mm, (a) distribution on y axis, x=40, (b) distribution on x axis, y=40.

Because the position estimated from the delay time of the echo signals from a bubble is equal to the position of the bubble, the strength of the echo signals and the bubble position can provide the distribution of bubbles passing through the ultrasonic beam. The strength is defined as an echo intensity which is a peak to peak value of detected voltage at a certain position. Figure 4 shows the distribution of the echo intensity from the boiling flow. These distributions were cleared off the standing wave and averaged by time series for about 3 seconds. The horizontal axis means the position of the reflection along the ultrasonic beam in Figure 4(a) or the position of the transducer in Figure 4(b) and the vertical axis means the average value of the

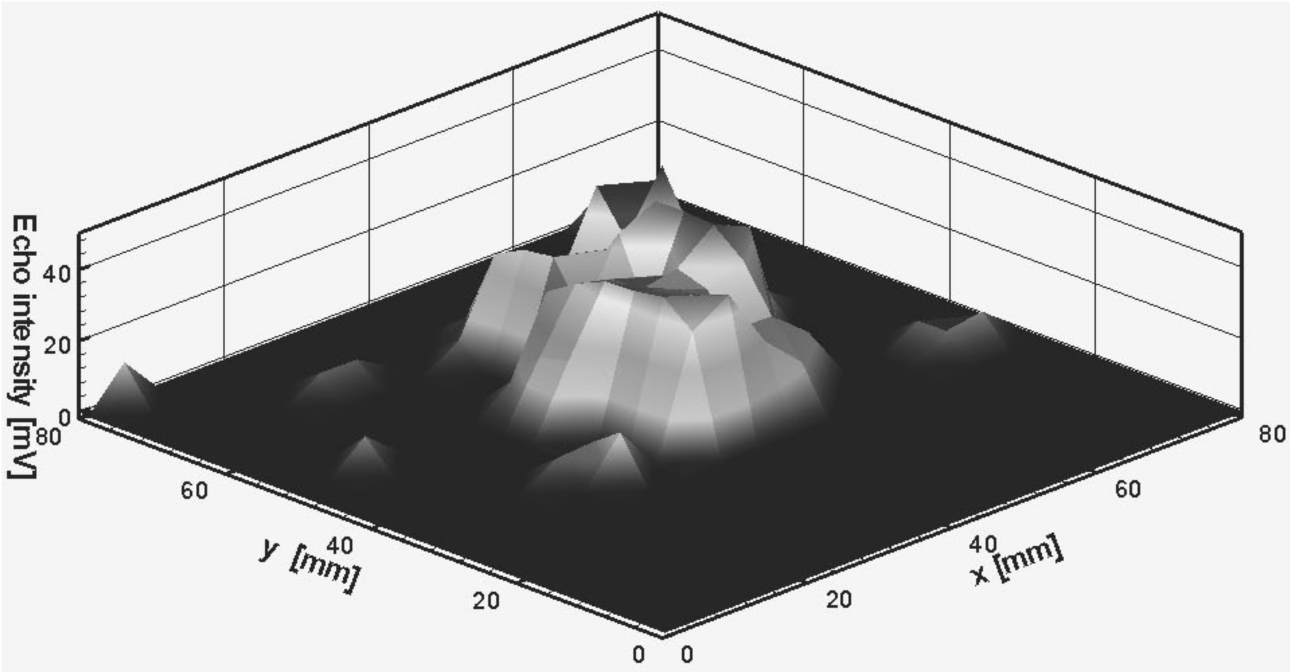


Figure 5: Cross-sectional distribution of echo intensity reflected from boiling flow field at L = 120 mm.

echo intensities. Figure 4(a) shows an echo distribution along the ultrasonic beam direction at x=40 mm. The echo intensity is stronger around the middle of the vessel. Thus the bubbles rise near the heater at L=120. The echo intensity distribution, which is measured by laterally traveled transducer on x axis, at y=40 is shown in Figure 4(b). It is also shown that the echo is obtained in the middle region. The region where the bubbles exist can be given by distributions on the line.

It would appear that the structure of the flow field is easy to understand by using the echo distribution in a cut plane. Figure 5 shows the cross-sectional distribution of the echo intensity at L=120. The averaged echo intensity at each point is plotted and drawn by the color density. In Figure 5, the vapor bubbles exist only near the upper part of the heater, and the bubble distribution is available to understand the boiling flow structure.

From these results, the flow field of the boiling two-phase flow could be visualized by the reflected echo signal and the cross-sectional distribution of the echo intensities.

5 CONCLUSION

An ultrasonic transducer has been developed for the ultrasonic measurement of the boiling two-phase flow under the atmospheric pressure, and the distribution of the echo intensity of rising bubbles generated by a cartridge heater has been obtained. The present work shows that the boiling two-phase flow field has been visualized by using the pulse ultrasound technique.

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