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Application of the Through-Transmitted Ultrasonic Signal for the Identification of Two-Phase Flow Patterns in a Simulated High Temperature Vertical Channel

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Abstract

In the present study a new measurement technique has been developed, which uses an ultrasonic transmission signal in order to identify the vertical two phase flow pattern. The ultrasonic measurement system developed in the present study not only provides the information required for the identification of vertical two phase flow patterns but also makes real time identification possible. Various vertical two phase flow patterns such as bubbly, slug, churn, annular flow etc. have been accurately identified with the present ultrasonic measurement system under atmospheric condition. In addition, the present test apparatus can practically simulate the ultrasonic propagation characteristics under high temperature and high pressure systems. Therefore, it is expected that the present ultrasonic flow pattern identification technique could be applicable to the vertical two phase flow systems under high temperature and high pressure conditions.

Key Words : ultrasonic through-transmission technique, flow pattern identification, vertical two-phase flow, real time identification, high temperature system

1. Introduction

Two-phase flow is frequently encountered in various thermal-hydraulic fields. Especially, the characteristics of important two-phase flow phenomena such as two-phase flow heat transfer and pressure drop, etc. strongly depend on the two-phase flow pattern. Current techniques for flow pattern identification include the visual and photographic observation, pressure drop measurement technique [1], radiation based (X-ray or gamma-ray) measurement technique [2], electric conductivity measurement technique [3], electric impedance or conductance measurement techniques [4~6], and the ultrasonic pulse-echo technique for horizontal flow [7]. Ultrasonic techniques can be very effectively applied to two-phase flow pattern identification because the measurement technique is simple and easy as well as it does not disturb the flow.

The present study is the extension of the previous work of Chu and Song [8]. In the previous experiments, the ultrasonic flow pattern identification was performed using transparent vertical acryl channels with inner diameters of 7.5mm and 20mm under atmospheric temperature and pressure condition, and the feasibility of ultrasonic through-transmission technique was confirmed.

In the present work, the same acryl channel with an inner diameter of 20mm has been used, and the experiments have also been carried out under atmospheric temperature and pressure. However a special device, named "buffer cooling rod", is attached to the acryl channel to simulate the ultrasonic propagation characteristics through the channel under high temperature and pressure conditions.

Measurement principle, experimental apparatus, and experimental results are described in the present paper.

2. Measurement Principle

2.1. Characteristics of Ultrasonic Wave

When ultrasonic longitudinal wave is normally incident onto the interface of two different media, part of its energy and sound pressure reflects back at the interface and the rest transmits through the interface as shown in Fig. 1(a). The reflection and transmission ratios of energy and sound pressure are determined by the acoustic impedances of the two media. The reflection ratio (R) and transmission ratio (T) of the sound pressure are as follows when the ultrasonic wave is normally incident onto the interface of the two media:

$$R=\frac{P_r}{P_i}=\frac{\rho_2 c_2-\rho_1 c_1}{\rho_1 c_1+\rho_2 c_2}=\frac{Z_2-Z_1}{Z_1+Z_2} \qquad (1)$$

$$T=\frac{P_t}{P_i}=\frac{2\rho_2 c_2}{\rho_1 c_1+\rho_2 c_2}=\frac{2Z_2}{Z_1+Z_2} \qquad (2)$$

where P_i, P_r, P_t denote sound pressures of the incident wave, reflected wave, and transmitted wave, respectively. ρ is the density of each media and c is the sound speed in each media, and ρc is called the "acoustic impedance" of the media.

As can be seen in eq. (1), incident ultrasonic wave scarcely reflects back when the acoustic impedances of two media are similar. On the other hand, the reflection ratio of the sound pressure becomes close to 1 and very high reflection of the incident ultrasonic wave occurs when the acoustic impedances of the two media are significantly different, such as those of air/vapor and water. The reflection ratio is about 99.9% for air and water interface at room temperature, and it is about 95% for steam and water interface at 300℃ saturation condition.

Such a high percentage reflection of an incident ultrasonic wave at the gas-liquid interface is the phenomenon that makes the identification of the two phase flow pattern with ultrasonic measurement technique possible.

With regard to the ultrasonic transmission ratio through both sides of the pipe wall as shown in Fig. 1(b), the transmission ratio changes significantly depending on the material of the wall.

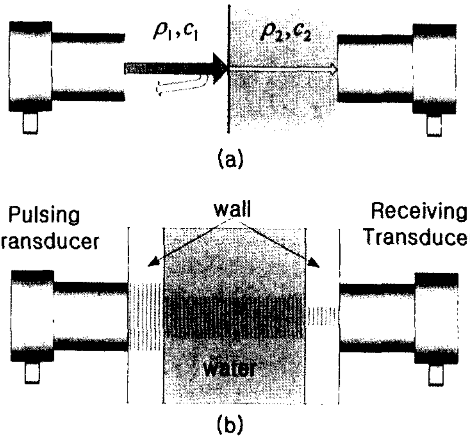

Fig. 1. Characteristic of Ultrasonic Propagation

For example, the transmission ratio is 0.86 for an acryl wall and water at room temperature, 0.12 for a stainless steel wall and water at room temperature, and 0.06 for a stainless steel wall and water at 300℃, respectively.

In addition, the ultrasound has the characteristic to diverge as it travels longitudinally. That is, the sound pressure at the receiving transducer decreases as the distance between pulsing transducer and receiving transducer increases.

2.2. Principle for Identification of Vertical Two-Phase Flow Pattern with Ultrasonic Through Transmission Technique

A two-phase flow pattern identification method using an ultrasonic through transmission technique was first suggested through the previous study of Chu and Song [8] as far as the authors know, and the present study is the refining work of the previous study. The technique is expected to be useful particularly for the identification of the vertical two-phase flow pattern.

The ultrasonic pulse-echo technique uses the time of flight characteristics of received echo signals for the flow pattern identification, on the other hand, the ultrasonic through transmission technique uses the transmission probability and magnitude of transmitted wave for the flow pattern identification. In the case of the pulse-echo technique, loss of echo signal could be unacceptably high unless the interface is fairly perpendicular to the incident angle of ultrasonic beam. For the ultrasonic through transmission technique, on the contrary, all the transmitted ultrasonic signals and the totally reflected ultrasonic signals give the useful information about the flow patterns.

Figure 2 illustrates the ultrasonic propagation characteristics for the ultrasonic through transmission technique depending on the flow patterns and the detailed explanation is as follows: For single-phase liquid flow, all the pulsed or incident ultrasonic waves are transmitted and arrive at the receiving transducer with a maximum

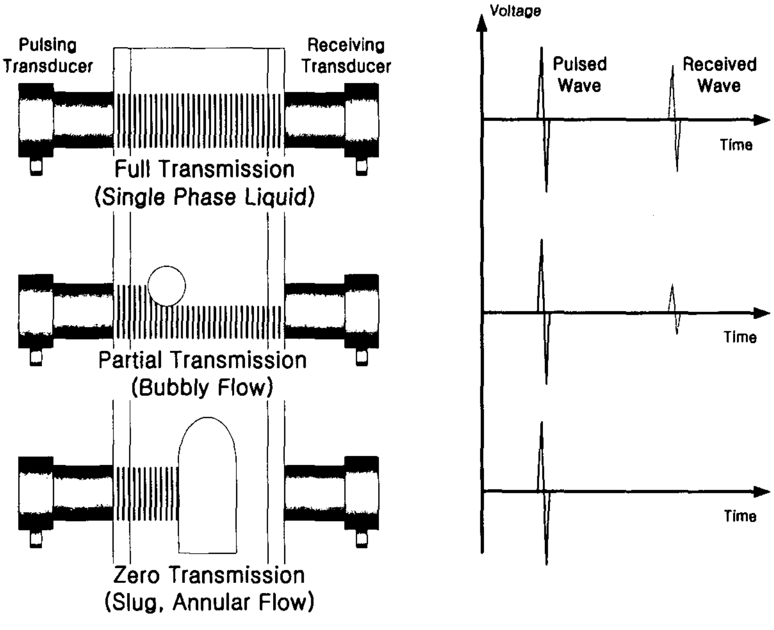

Fig. 2 Principle of Ultrasonic Flow Pattern Identification

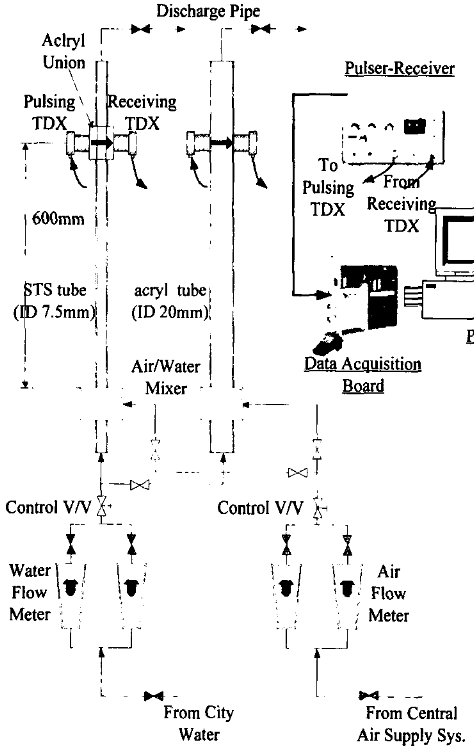

Fig. 3. Schematic of Test Apparatus

amplitude because there is no gas-liquid interface. As the temperature of the stainless steel wall and water increase, the maximum amplitude or the voltage of the transmitted ultrasonic signal decreases. That is because the acoustic impedance difference between the wall and water increases. For example, the maximum amplitude of the transmitted ultrasonic signal through single phase liquid at 300°C saturation condition would drops to the about half value of the amplitude at room temperature condition.

For bubbly flow, there can be single bubbles smaller than the ultrasonic beam diameter and a cluster of bubbles larger than the ultrasonic beam diameter. Partial reflection of incident ultrasonic wave occurs when ultrasonic wave collides with a single bubble, and partial or total reflection can occur when an ultrasonic wave collides with a cluster of bubbles. Therefore, the transmitted ultrasonic waves for bubbly flow have the characteristics of a decreased transmission probability and amplitude. The transmission probability and amplitude are dependent on the void fraction.

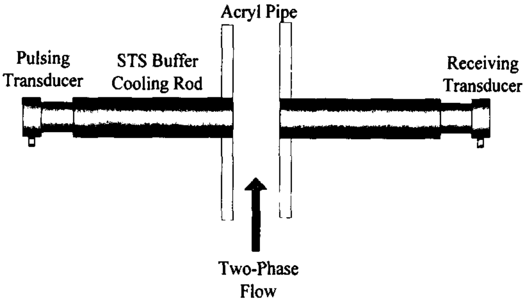

Fig. 4. Modification of Test Channel to Simulate the Actual Pipe Condition

In the case of slug/churn flow, it consists of a slug/churn bubble larger than the ultrasonic beam diameter and a liquid tail/bulk. When the slug/churn bubble passes the ultrasonic beam path, pulsed or incident ultrasonic waves totally reflect back at the bubble interface. As a result, the transmitted ultrasonic signal level at the receiving transducer is zero or negligibly small depending on the temperature-dependent acoustic impedances of air/steam and water, as described above. When the liquid tail/bulk, which accompanies small bubbles, passes the ultrasonic beam path, part of the pulsed or incident ultrasonic waves arrive at the receiving transducer. Due to the inherent periodicity of the slug/churn flow, the received ultrasonic signal shows periodic characteristics.

In the case of an annular flow, a gas core larger than the ultrasonic beam diameter is established in the center of the flow channel. Therefore, all the pulsed or incident ultrasonic waves reflect back at the gas core-liquid film interface, and zero or negligibly small ultrasonic signal arrives at the receiving transducer.

3. Experiments

Figure 3 shows the test apparatus for the identification of a vertical two-phase flow pattern using an ultrasonic through transmission technique. It consists of (1) test section where the vertical upward cocurrent two-phase flow occurs, (2) ultrasonic pulser/receiver and transducers which generate the ultrasonic waves and receive the transmitted ultrasonic waves, and (3) data acquisition system which measures and saves the high frequency received ultrasonic waveform, and processes the received ultrasonic signals.

The test section has two vertical channels with a height of 1.0m and inner diameters of 7.5mm and 20.0mm, respectively. The material of the channel with 7.5mm inner diameter is stainless steel, and a transparent acryl union block is inserted at the elevation of 600mm from the bottom. Visual observation of the flow pattern and ultrasonic measurement are made at this transparent acryl union block. The channel with an inner diameter of 20.0mm is made of transparent acryl, and the ultrasonic measurement is made at the elevation of 600mm from the bottom. Air-water mixers are connected to the bottom of the channels, and two ball floating type flow meters having different measuring ranges are installed at the upstream of the mixer for air and water, respectively.

In the present study only the channel with an inner diameter of 20mm has been used, and both the channels with two different inner diameters were used in the previous study of Chu and Song. In addition, in the previous study the ultrasonic pulsing and receiving transducers were directly attached to the acryl pipe walls, which resulted in much higher transmission ratio than the stainless steel pipe condition as mentioned earlier. Therefore, in the present study, some modification has been made to the channel with a 20mm inner diameter to simulate the actual ultrasonic propagation characteristic through a high temperature and pressure stainless steel pipe, as shown in Fig. 4.

The maximum allowable temperature for ultrasonic transducers is about 200℃. For application to a higher temperature surface, it is the general approach to install the cooling rod to the high temperature surface, and then attach the ultrasonic transducer to the opposite end of the cooling rod where the temperature decreases below the maximum allowable temperature. As a practical simulation approach, two 70mm long stainless steel buffer cooling rods are installed at both sides of the acryl pipe.

With this approach, the material effect of the pipe wall and the buffer cooling rod on the ultrasonic propagation can be practically simulated. The material effect means the acoustic impedance difference between the wall and water, and the resultant transmission ratio. But the temperature effect, i.e. the change of attenuation coefficient of the wall and water, on the ultrasonic propagation can not be considered. However, the material effect has a much more dominant effect on the ultrasonic propagation over the temperature effect.

The ultrasonic transducer is model A133S of Panametrics, Inc., and it has the frequency of 2.25MHz and element diameter of 6.0mm. Ultrasonic pulser/receiver is model 5077PR of Panametrics, Inc., it has the maximum pulse amplitude of 400V, bandwidth of 35MHz, and voltage gain of 0~59dB.

A data acquisition system consists of (1) a high speed A/D board which converts a 2.25MHz analog signal of the transmitted ultrasonic wave to an 8 bit digital signal, (2) interface program which controls the A/D board, processes the digital signal into the data appropriate for flow pattern identification, and displays the processed signals on the PC monitor as a form of alphanumeric values and graphics, and (3) a PC which saves the processed data on the hard disk. High speed A/D board is the model NI5112 of National InstrumentsTM. It has a real time sampling rate upto 100MS/s, and on-board memory of 32MByte, thus it is possible to process the measured data and save the data on a hard disk in real time. As a result, it has an advantage of flexibility in measurement and process of data. A graphic user interface programmed by LabVIEWTM provides various input windows for the control of the A/D board, and various graphic windows displaying the measured and processed ultrasonic signals. The data acquisition system of the present study provides various functions for the real time identification of vertical two-phase flow patterns.

4. Experimental Results

Characteristics of the transmitted ultrasonic signals have been measured for various air/water vertical two-phase flow patterns, using the present ultrasonic measurement system. Two-phase flow patterns can be identified from the transmitted ultrasonic signals based on the reflection characteristics at the gas-liquid interface.

Figures 5~7 show the pulsed or incident ultrasonic waves, and transmitted or received ultrasonic waves at the opposite side, for a single phase liquid flow, annular flow, and bubbly flow, respectively. In the case of a single-phase liquid flow, fairly high voltage (or sound pressure) of the transmitted ultrasonic wave is measured because the reflection of the incident ultrasonic wave at the gas interface does not occur. In the case of an annular flow, however, there is no measurement of the transmitted ultrasonic signal due to the total reflection of the incident ultrasonic wave at the central gas core interface. On the other hand, Fig. 6 shows the partially reflected ultrasonic wave at the small bubble interface. The measured voltage (or sound pressure) is lower than the voltage for a single-phase liquid flow.

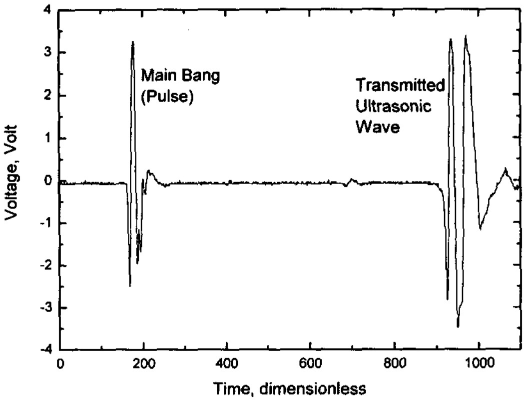

Fig. 5. Pulsed and Transmitted Ultrasonic Waves for Single-Phase Liquid Flow

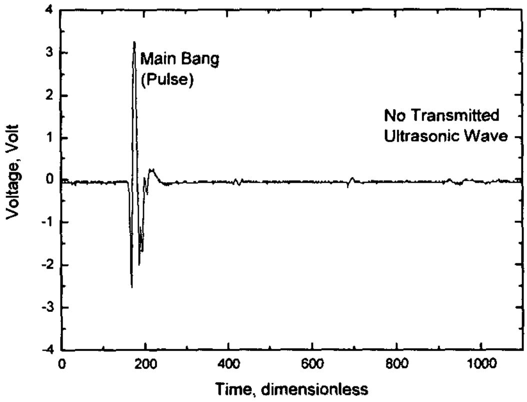

Fig. 6. Pulsed and Transmitted Ultrasonic Waves for Annular Flow

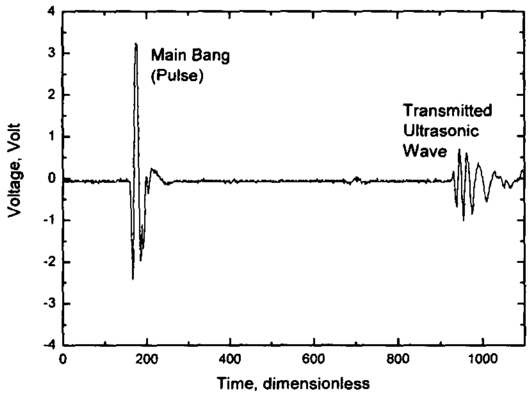

Fig. 7. Pulsed and Transmitted Ultrasonic Waves for Bubbly Flow

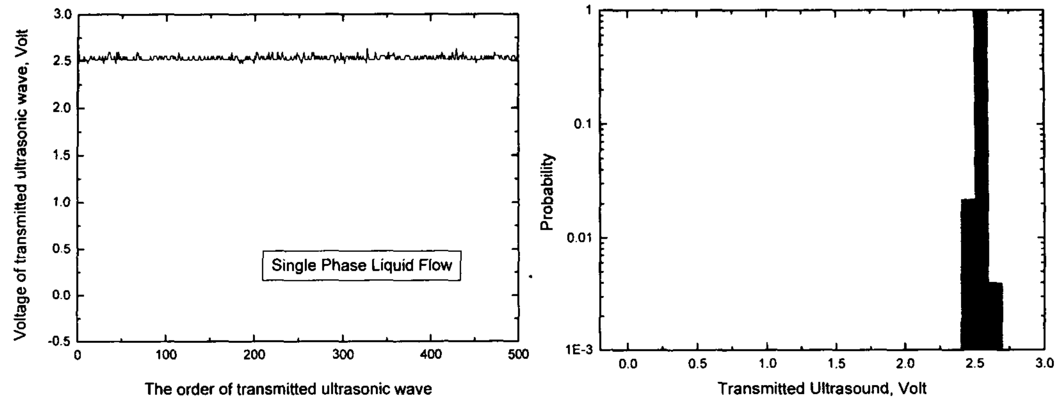

Fig. 8. Transmitted Ultrasonic Signals for Single-Phase Liquid Flow : Time Sequential Plot (left) and Probability Density Distribution (right)

4.1. Single-Phase Liquid Flow

For a single phase liquid flow, as mentioned above, every pulsed or incident ultrasonic wave arrives at the receiving transducer with a maximum constant voltage because there is no reflection at the gas-liquid interface. Figure 8 (left) shows the peak voltage values of the transmitted ultrasonic waves for 500 consecutive incidents of ultrasonic waves. That is, the horizontal axis denotes the order of the incident ultrasonic waves, and the vertical axis denotes the measured peak voltage of the transmitted ultrasonic waves. Figure 8 (right) shows the probability density distribution of the time sequential plot of the peak voltage of the transmitted ultrasonic waves.

4.2. Bubbly Flow

For a bubbly flow, the characteristics of a transmitted ultrasonic wave is determined by the bubble size and the bubble number density (i.e., interaction possibility between ultrasonic wave and bubbles). Figures 9~11 show (1) the peak voltage values of the transmitted ultrasonic waves for 500 consecutive incident ultrasonic waves and (2) the

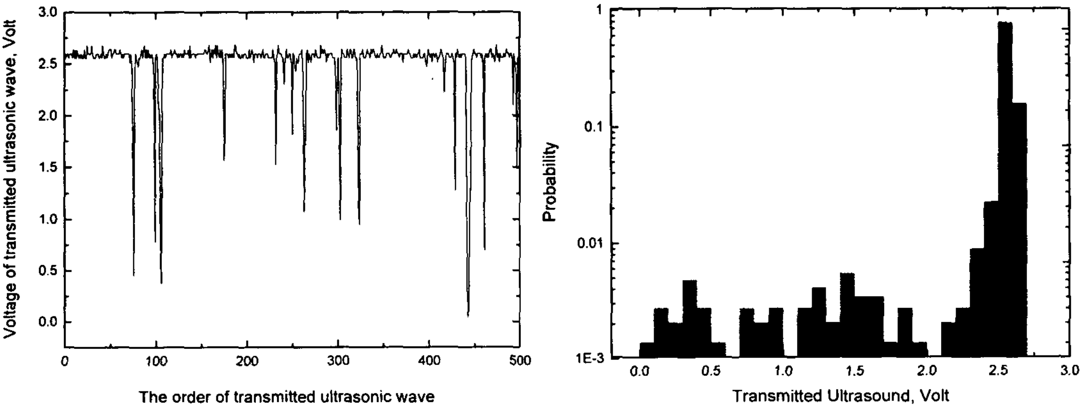

Fig. 9. Transmitted Ultrasonic Signals for Bubbly Flow with Low Void Fraction : Time Sequential Plot (left) and Probability Density Distribution (right)

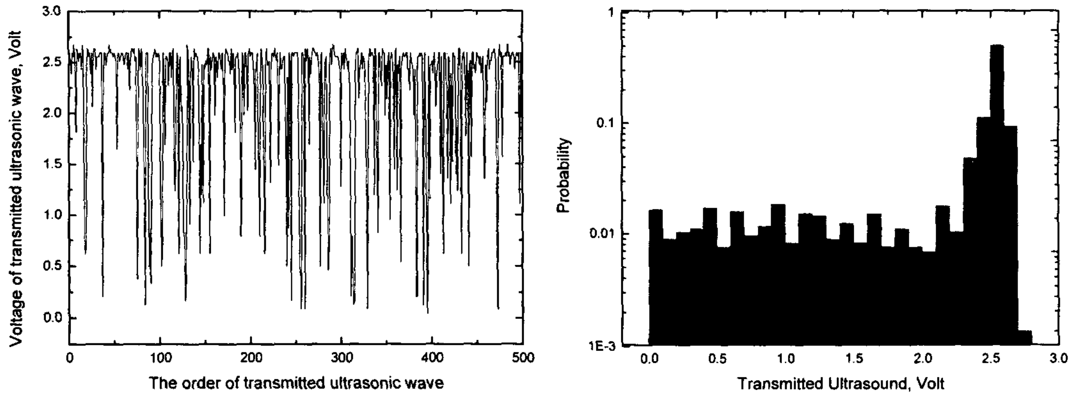

Fig. 10. Transmitted Ultrasonic Signals for Bubbly Flow with High Void Fraction : Time Sequential Plot (left) and Probability Density Distribution (right)

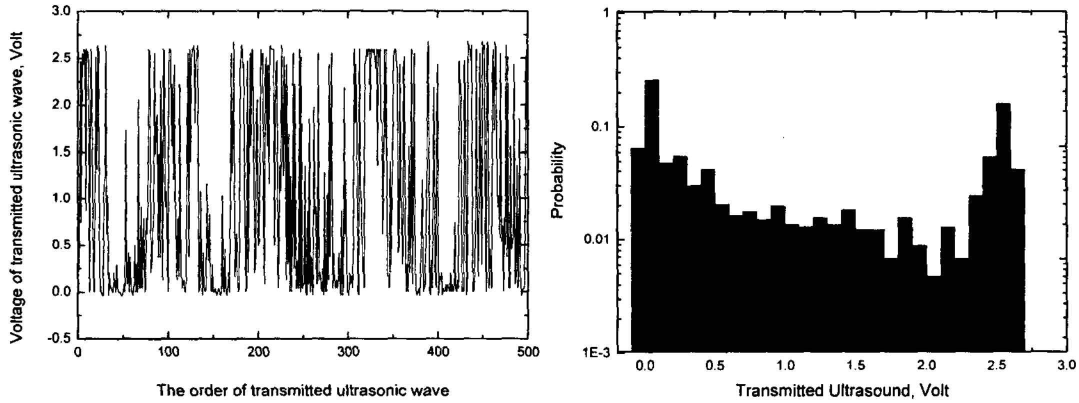

Fig. 11. Transmitted Ultrasonic Signals for Bubbly Flow with Very High Void Fraction (Close to the Transition Condition from Bubbly to Annular or Dispersed Bubbly Flow) : Time Sequential Plot (left) and Probability Density Distribution (right)

probability density distributions, for the test section that has an inner diameter of 20mm and 70mm long stainless steel buffer cooling rods.

Figure 9 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for the bubbly flow when the water and air flow rates are low. Some small bubbles at the inlet grow up to single bubbles with a diameter of 2~4mm at the ultrasonic measurement elevation. When the bubbles pass through the ultrasonic beam path, partial reflection and transmission of the incident ultrasonic waves occur. In the other case that the bubble does not exist at the ultrasonic beam path, all the incident ultrasonic waves arrive at the receiving transducer with a maximum voltage. As can be seen in Fig. 9, interaction possibility between the ultrasonic wave and bubble is low due to the low bubble number density and/or void fraction.

Figure 10 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for a bubbly flow when the water and air flow rates are further increased from the condition of Fig. 9, which means higher bubble number density and/or void fraction. A lot of bubbles are continuously flowing upward in a group, not single independent bubbles. Because of the very narrow gap between the bubbles, partial reflection probability dominates over the full transmission probability. In some regions of a very high bubble density or void fraction, a total reflection can be observed.

Figure 11 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for a bubbly flow that is close to the transition condition to the dispersed bubbly flow. The water flow rate is further increased from the condition of Fig. 10. The bubble number density is highest, thus the transmission probability is lowest. The total reflection probability is comparable to the full transmission probability.

4.3. Slug Flow

Figure 12 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for a slug flow condition. When a slug bubble passes through the ultrasonic beam path, a total reflection of the incident ultrasonic wave occurs and as a result any transmitted signal is not measured. When the liquid tail passes through the ultrasonic beam path, on the other hand, a partial reflection occurs, because some small bubbles are in the liquid tail. In addition, the time sequential plot of Fig. 12 shows the inherent periodic characteristic of the slug flow.

4.4. Churn Flow

Figure 13 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for a churn flow. Overall pattern of the transmitted ultrasonic signals of Fig. 13 is similar to that of Fig. 12. However, a churn flow has the following characteristics different from a normal slug flow: a churn bubble has much more deformed and irregular shape, and the liquid slug between the churn bubbles shows chaotic motion of a repetitive collapse and recovery due to an excessive gas flow. Such a chaotic motion and existence of a churn bubble as well as the periodic characteristics are well illustrated in the time sequential plot of Fig. 13.

When the gas flow is further increase from the

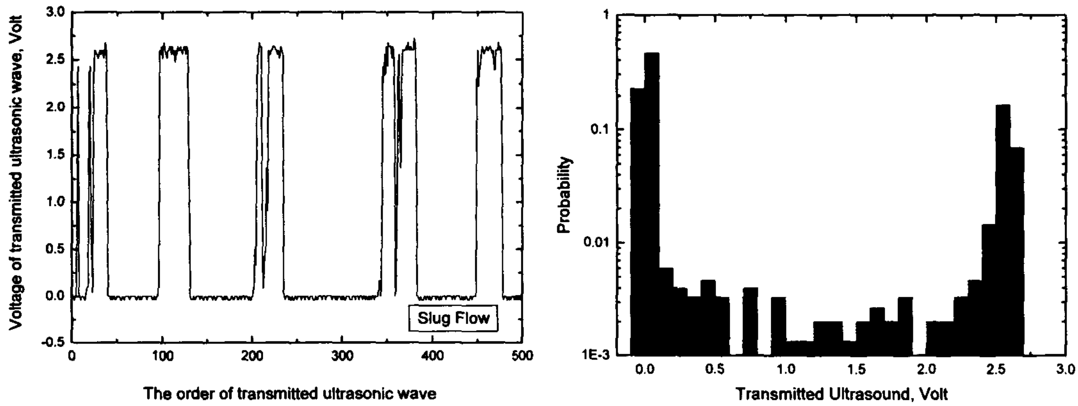

Fig. 12. Transmitted Ultrasonic Signals for Slug Flow : Time Sequential Plot (left) and Probability Density Distribution (right)

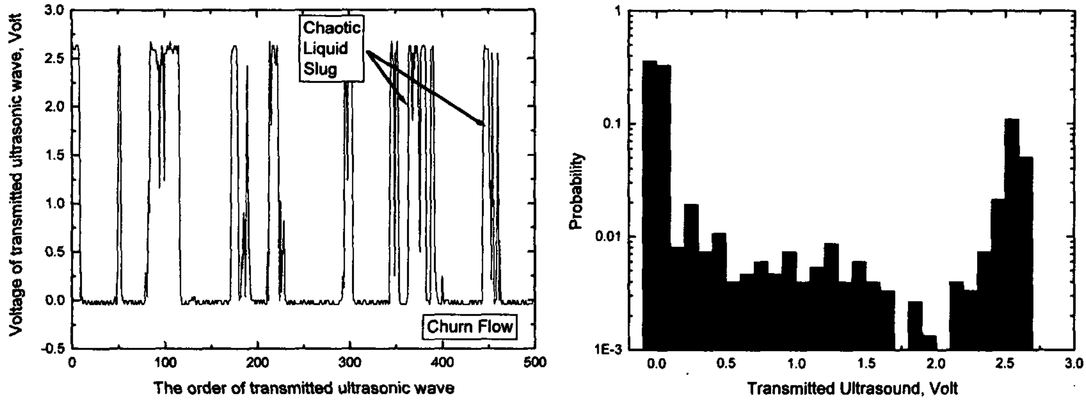

Fig. 13. Transmitted Ultrasonic Signals for Churn Flow : Time Sequential Plot (left) and Probability Density Distribution (right)

condition of Fig. 13, transition to an annular flow occurs. Figure 14 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for a churn-to-annular flow. Establishment and temporary collapse of an annular flow repeats itself at this flow condition. At the time of collapse, a liquid slug having similar characteristics of a churn flow is formed. However, frequency and duration time of the liquid slug is smaller than those of a normal churn flow. The measured results of Figs. 13 and 14 show these different features very well.

4.5. Annular Flow

Figure 15 shows the time sequential plot and the probability density distribution of the peak values of the transmitted ultrasonic waves for an annular flow. All the pulsed or incident ultrasonic waves are totally reflected at the central gas core interface. As a result, no transmitted ultrasonic signal is measured at the receiving transducer.

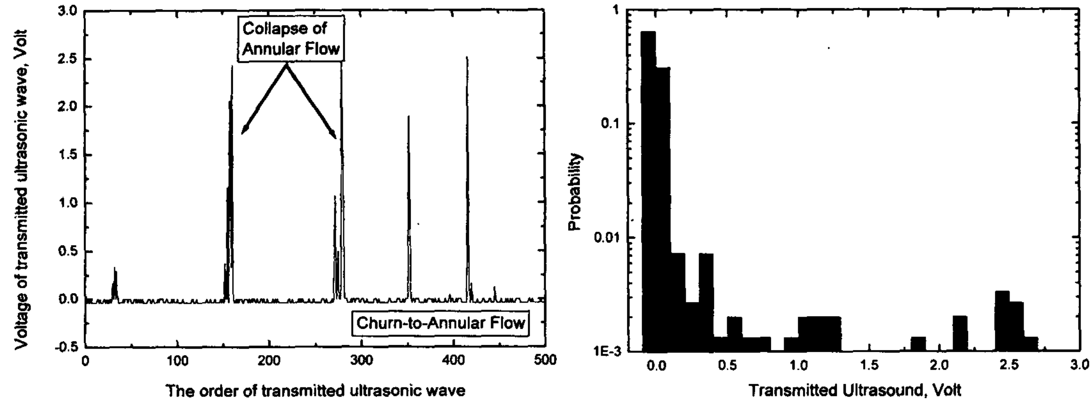

Fig. 14. Transmitted Ultrasonic Signals for the Transition Condition from Churn to Annular Flow : Time Sequential Plot (left) and Probability Density Distribution (right)

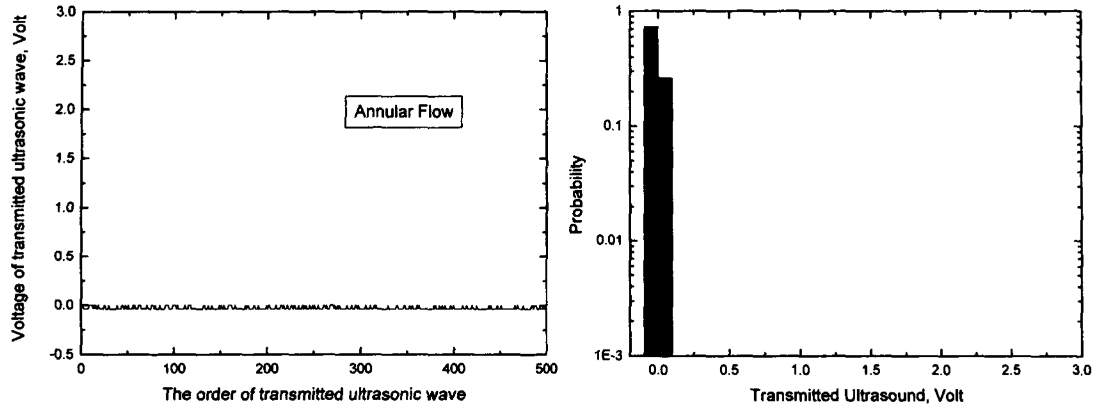

Fig. 15. Transmitted Ultrasonic Signals for Annular Flow : Time Sequential Plot (left) and Probability Density Distribution (right)

5. Conclusions

In the present study, a new measurement technique was developed, which uses ultrasonic transmission signals in order to identify the vertical two phase flow pattern. A series of experiments have been performed in a transparent channel with a stainless steel buffer cooling rod to simulate the ultrasonic propagation characteristics through the high temperature and pressure channel.

The ultrasonic measurement system developed in the present study not only provides the information required for the identification of a vertical two phase flow pattern but also makes real time identification possible.

It is very straight-forward to interpret the transmitted ultrasonic signals into the identification of various vertical two phase flow patterns such as bubbly, slug, churn, churn-to-annular flow, and annular flow. However, the time sequential plot would be more effective for the interpretation of the transmitted ultrasonic signal and give more information about the two phase flow condition.

The present method would be very effective for flow pattern identification in various high temperature and high pressure thermal hydraulic test facilities owing to the features of easy installation and treatment, non-intrusion, and straight-forward analysis, etc.

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