

Application of the Through-Transmitted Ultrasound Signal to the Identification of Two-Phase Flow Patterns in Vertical Tubes

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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 determine the vertical two phase flow pattern. The ultrasonic measurement system developed in the present study not only provides the measurement functions required for the identification of vertical two phase flow pattern but also makes the 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. In addition to the identification of flow patterns, the qualitative information for each flow pattern can be obtained, which includes void fraction in bubbly flow, length of slug bubble and liquid tail characteristics in slug flow, and stable or transient condition of the flow patterns, etc.

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 visual and photographic observation, pressure drop measurement technique (Tutu, 1982), radiation (X-ray or gamma-ray) measurement technique (Jones and Zuber, 1975), electric conductivity measurement technique (Haberstrah and Griffith, 1965), and electric impedance or conductance measurement techniques (Song and Chung, 1994; Song et al., 1995, 1998), and ultrasonic measurement technique for horizontal flow (Chang and Morala, 1990). Ultrasonic technique 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.

In the present study, ultrasonic through transmission technique is developed as a method for the identification of flow pattern and its transition criteria in vertical two-phase flow. Measurement principle, experimental apparatus, and results are described.

2. Measurement Principle

2.1 Characteristics of Ultrasonic Wave

When ultrasonic longitudinal wave is normally incident on 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. The reflection and transmission ratios of energy and sound pressure are determined by the acoustic impedances of two media. The reflection ratio (R) and transmission ratio (T) of sound pressure are as follows when the ultrasonic wave is incident normally on the interface of two media:

$$R = \frac{P_r}{P_i} = \frac{r_2 c_2 - r_1 c_1}{r_1 c_1 + r_2 c_2} = \frac{Z_2 - Z_1}{Z_1 + Z_2} \quad (1)$$

$$T = \frac{P_t}{P_i} = \frac{2r_2 c_2}{r_1 c_1 + r_2 c_2} = \frac{2Z_2}{Z_1 + Z_2} \quad (2)$$

where P_i , P_r , P_t denote sound pressures of incident wave, reflected wave, and transmitted wave, respectively. \tilde{n} is the density of each media and c is the sound speed in each media, and $\tilde{n}c$ is called "acoustic impedance" of

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, reflection ratio of sound pressure becomes close to 1 and almost 100% reflection of incident ultrasonic wave occurs when the acoustic impedances of two media are significantly different such as those of air and water. Such an almost 100% reflection of incident ultrasonic wave at the gas and liquid interface is the phenomena that make the identification of two phase flow pattern with ultrasonic measurement technique possible.

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

Two-phase flow pattern identification method using ultrasonic through transmission technique is first suggested through the present study as far as the authors know. The technique is expected to be useful particularly for the identification of vertical two-phase flow pattern.

Ultrasonic pulse-echo technique uses the time of flight characteristics of received echo signals for the flow pattern identification, on the other hand, ultrasonic through transmission technique uses transmission ratio and magnitude of transmitted wave for the flow pattern identification.

For single-phase flow, all the pulsed or incident ultrasonic waves are transmitted and arrive on the receiving transducer because there is no gas-liquid interface.

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

In case of slug/churn flow, it consists of slug/churn bubble larger than ultrasonic beam diameter and liquid tail/bulk. When slug/churn bubble passes ultrasonic beam path, pulsed or incident ultrasonic waves totally reflect back at the bubble interface. As a result, there is no transmitted ultrasonic signal which arrives on the receiving transducer. On the other hand, when the liquid tail/bulk, which accompanies small bubbles, passes ultrasonic beam path, part of pulsed or incident ultrasonic waves arrive on the receiving transducer. Due to the inherent periodicity of slug/churn flow, received ultrasonic signal shows periodic characteristics.

In case of annular flow, gas core larger than ultrasonic beam diameter is established in the center of flow channel. Therefore, all the pulsed or incident ultrasonic waves reflect back at the gas core-liquid film interface, and no ultrasonic signal arrive on the receiving transducer.

3. Experiments

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

Test section has two vertical channels with 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 transparent acryl union block is installed at 600mm from the bottom. Visual observation of flow pattern and ultrasonic measurement are made at this transparent acryl union block. The channel with inner diameter of 20.0mm is made of transparent acryl, and ultrasonic measurement is made at 600mm from the bottom.

Air-water mixers are connected to the bottom of the channels, and two flow meters having different measuring ranges are installed upstream of the mixer for air and water respectively.

The ultrasonic transducer is model V201 of Panametrics, Inc., and it has the frequency of 5.0MHz and element diameter of 6.0mm. Ultrasonic pulser/receiver is model UPR-035 of C&M Tech., Inc., it has the max. pulse amplitude of 245V, bandwidth of 35MHz, and voltage gain of 7~79dB.

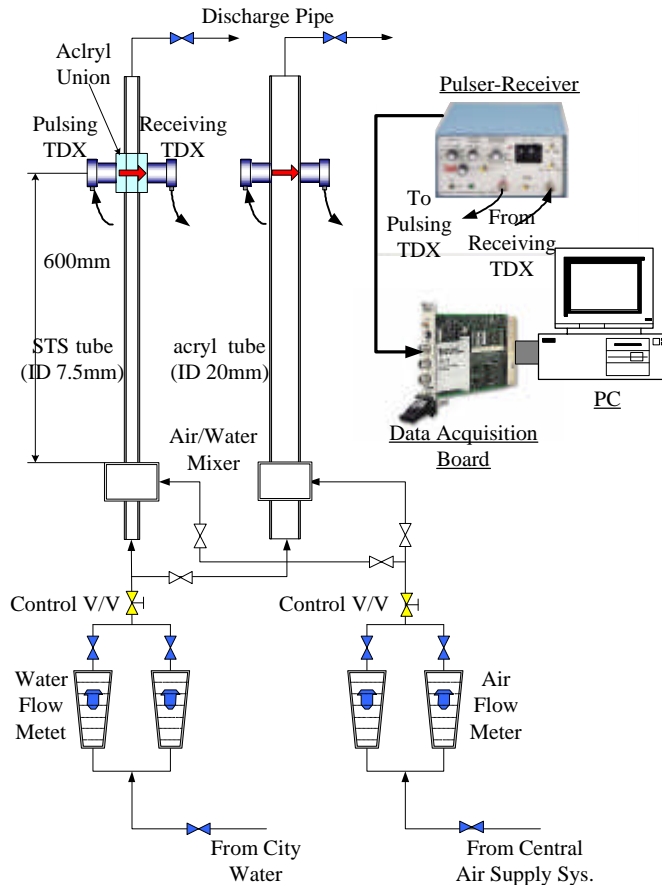


Fig. 1 Schematic of Test Apparatus

Data acquisition system consists of (1) high speed A/D board which converts 5MHz analog signal of transmitted ultrasonic wave to 8 bit digital signal, (2) interface program which controls A/D board, processes the digital signal into the data for the flow pattern identification, and displays the processed signals on the PC monitor as a form of alphanumeric value and graphics, and (3) PC which saves the processed data on the hard disk.

High speed A/D board is model NI5112 of National InstrumentsTM. It has 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 hard disk in real time. As a result, it has an advantage of flexibility in measurement and process of data.

Graphic user interface programmed by LabVIEWTM provides various input windows for the control of 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 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 2~4 shows the pulsed or incident ultrasonic waves and transmitted or received ultrasonic waves at opposite side, for single phase liquid flow, annular flow, and bubbly flow, respectively. In case of single-phase liquid flow, fairly high voltage (or sound pressure) of transmitted ultrasonic wave is measured because the reflection of incident ultrasonic wave at the gas interface does not occur. In case of annular flow, however, there is no measurement of transmitted ultrasonic signal due to the total reflection of incident ultrasonic wave at the central gas core interface. On the other hand, Fig. 4 shows the partially reflected ultrasonic wave at the small bubble interface. The measured voltage (or sound pressure) is lower than the voltage for single-phase liquid flow.

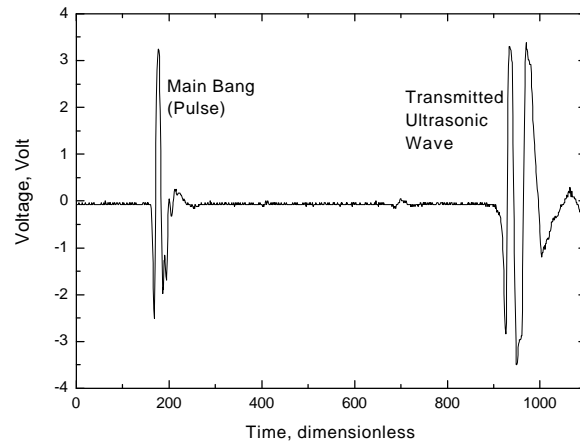


Fig. 2 Pulsed and Transmitted Ultrasonic Waves for Single-Phase Liquid Flow

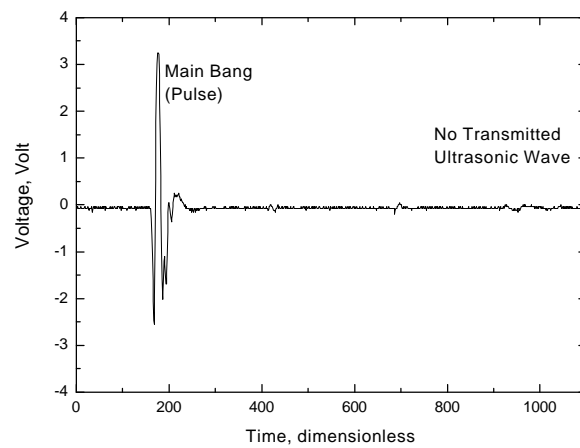


Fig. 3 Pulsed and Transmitted Ultrasonic Waves for Annular Flow

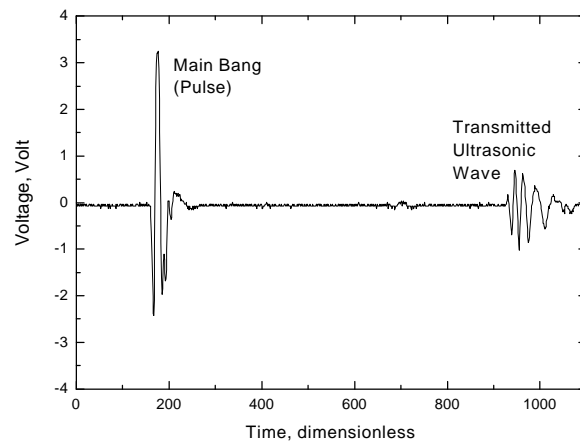


Fig. 4 Pulsed and Transmitted Ultrasonic Waves for Bubbly Flow

4.1 Single-Phase Liquid Flow

For single phase liquid flow, as mentioned above, every pulsed or incident ultrasonic wave arrives on the receiving transducer with maximum constant voltage because there is no reflection at the gas-liquid interface. Figure 5 shows the peak voltage values of transmitted ultrasonic waves for 500 consecutive incidents ultrasonic waves. That is, horizontal axis denotes the order of the incident ultrasonic waves and vertical axis denotes the measured peak voltage of transmitted ultrasonic waves.

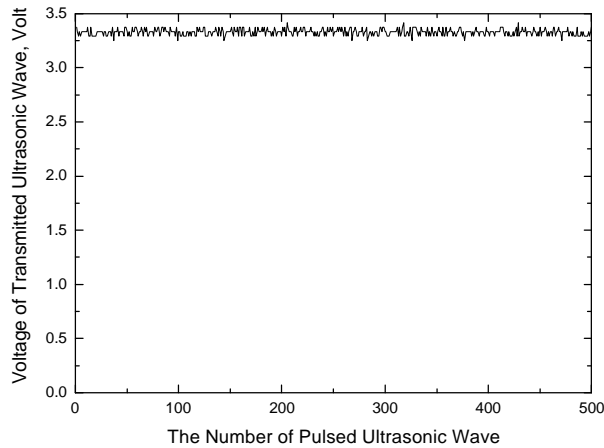


Fig. 5 Transmitted Ultrasonic Signals for Single-Phase Liquid Flow

4.2 Bubbly Flow

For bubbly flow, characteristics of transmitted ultrasonic wave is determined by the bubble size and the bubble number density (i.e., interaction possibility between ultrasonic wave and bubbles). Figures 6~9 show the peak voltage values of transmitted ultrasonic waves for 500 consecutive incident ultrasonic waves for the test section of I.D. 7.5mm. Similar characteristics of transmitted ultrasonic waves have been obtained for the test section of I.D. 20.0mm.

Figure 6 shows the characteristics of peak values of transmitted ultrasonic waves when water and air flow rates are low. Some small bubbles at the inlet grow up to single bubbles with diameter of 2~4mm at the ultrasonic measurement elevation. When the bubbles pass through the ultrasonic beam path, partial reflection and transmission of incident ultrasonic waves occur. In other case that bubble does not exist at the ultrasonic beam path, all the incident ultrasonic waves arrive on the receiving transducer with maximum voltage. As can be seen in Fig. 6, interaction possibility between ultrasonic wave and bubble is very low due to the low bubble number density.

Figure 7 is the case that water and air flow rates are slightly increased from the condition of Fig. 6. The bubble number density is increased but the single bubbles with diameter of 2~4mm flow independently without coalescence. It can be seen that the partial reflection probability is increased than Fig. 6.

Figure 8 shows the characteristics of peak values of transmitted ultrasonic waves when water and air flow rates are further increased from the condition of Fig. 7. A lot of bubbles are continuously flowing upward in group, not single independent bubbles. Because of very narrow gap between bubbles, partial reflection probability dominates 100% transmission probability. In some regions of very high bubble density or void fraction, total reflection can be observed.

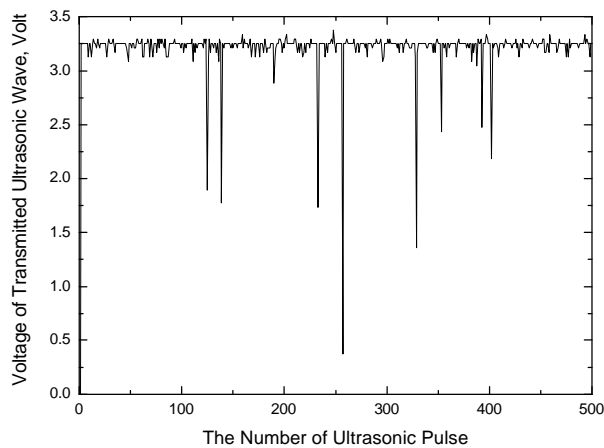


Fig. 6 Transmitted Ultrasonic Signals for Bubbly Flow with Very Low Void Fraction

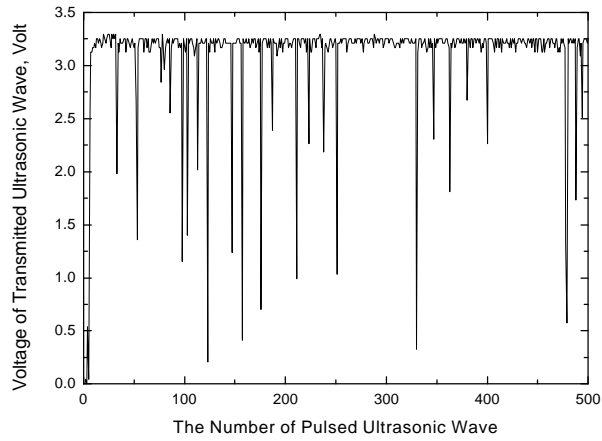


Fig. 7 Transmitted Ultrasonic Signals for Bubbly Flow with Low Void Fraction

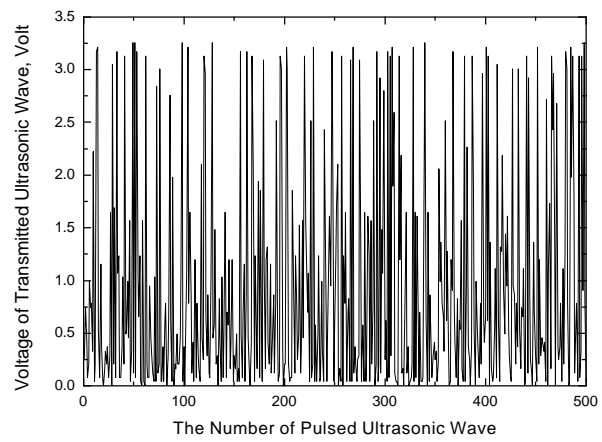


Fig. 8 Transmitted Ultrasonic Signals for Bubbly Flow with High Void Fraction

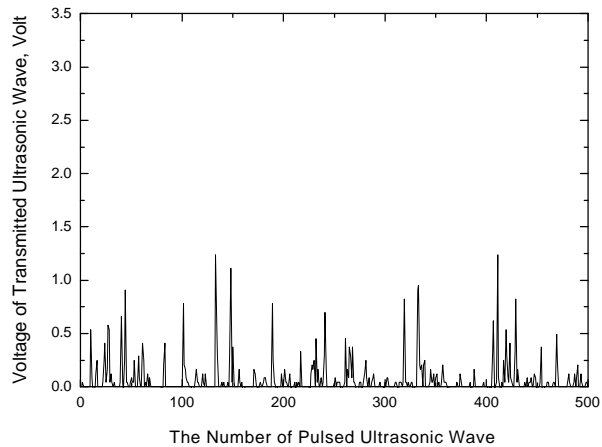


Fig. 9 Transmitted Ultrasonic Signals for Bubbly Flow with Very High Void Fraction (Transition Condition from Bubbly to Annular Flow)

Figure 9 shows the characteristics of peak values of transmitted ultrasonic waves just before the transition to annular flow. The water flow rate is further increased from the condition of Fig. 8. The diameter of bubble is smallest, but the bubble density is highest. Therefore, transmission probability is lowest.

4.3 Slug Flow

As illustrated in Fig. 10, two types of slug flow patterns are observed in the present study. In the channel with inner diameter of 7.5mm, it is observed that several short slug bubbles with length less than 10mm flow in series,

not growing into single long slug bubble. The gap between consecutive bubbles is very narrow. In the channel with inner diameter of 20.0mm, on the other hand, single slug bubble with length of about 30.0mm and following liquid tail with small bubbles are observed. Each slug bubble is separated from each other with a certain distance. The difference between two slug flow patterns is probably due to the surface tension effect.

Figures 11 and 12 show the characteristics of peak values of transmitted ultrasonic waves for each flow condition. When slug bubble passes through the ultrasonic beam path, total reflection of incident ultrasonic wave occurs and as a result any transmitted signal is not measured. When liquid tail passes through the ultrasonic beam path, on the other hand, partial reflection occurs because the gap between consecutive bubbles is smaller than ultrasonic beam diameter (Fig. 11) or many small bubbles are in the liquid tail (Fig. 12). In addition, 100% transmission of incident ultrasonic wave with maximum voltage occurs when the liquid column passes through the ultrasonic beam path.

All the features of these two slug flow patterns are easily found out from the measurement of transmitted ultrasonic signals as Figs. 11 and 12.

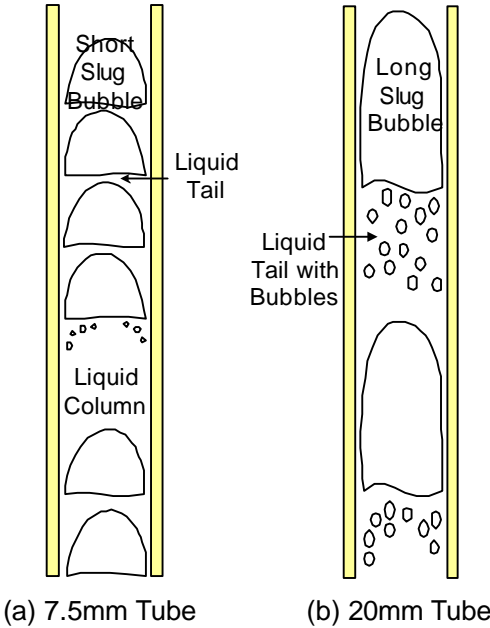


Fig. 10 Visually Observed Slug Flow Patterns

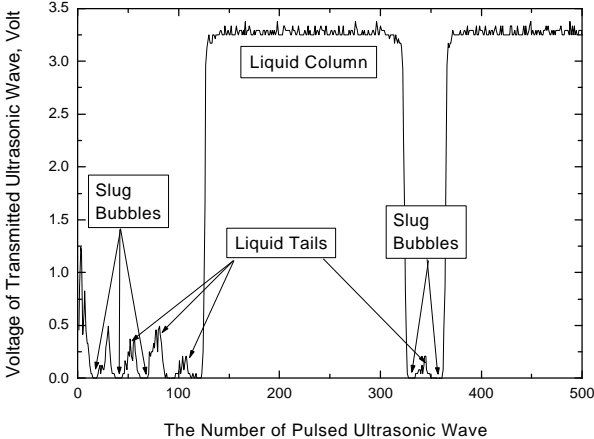


Fig. 11 Transmitted Ultrasonic Signals for Slug Flow with Short Slug Bubble

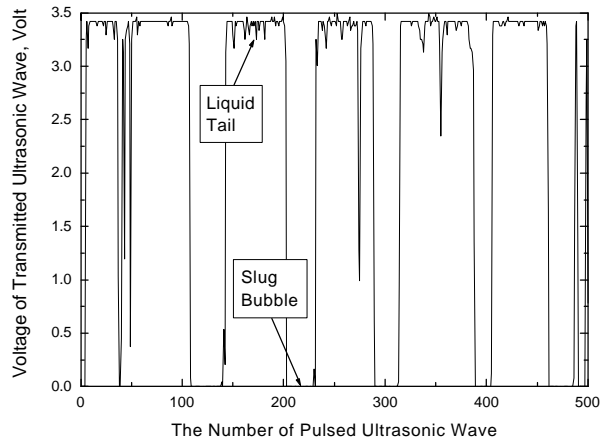


Fig. 12 Transmitted Ultrasonic Signals for Slug Flow with Long Slug Bubble

4.4 Churn Flow

Figure 13 shows the characteristics of peak values of transmitted ultrasonic waves for churn flow in the channel with inner diameter of 20.0mm. Overall pattern of transmitted ultrasonic signals of Fig. 13 is similar to that of Fig. 12. However, churn flow has the following characteristics different from normal slug flow: churn bubble has much deformed and irregular shape, and liquid slug between churn bubbles shows chaotic motion of repetitive collapse and recovery due to excessive gas flow. Such a chaotic motion and existence of churn bubble as well as periodic characteristics are well illustrated in the measurement result of Fig. 13.

When the gas flow is further increase from the condition of Fig. 13, transition to annular flow occurs. Figure 14 shows the characteristics of peak values of transmitted ultrasonic waves just before the transition to annular flow. Establishment and temporary collapse of annular flow repeats at this flow condition. At the time of collapse, liquid slug having similar characteristics of churn flow is formed. However, frequency and duration time of the liquid slug is smaller than those of 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 characteristics of peak values of transmitted ultrasonic waves for 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.

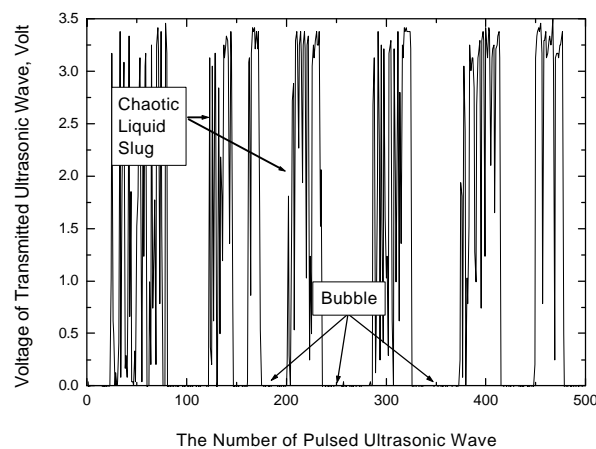


Fig. 13 Transmitted Ultrasonic Signals for Churn Flow

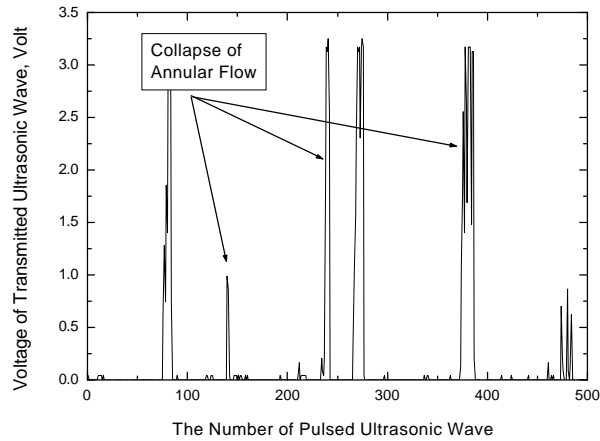


Fig. 14 Transmitted Ultrasonic Signals for the Transition Condition from Churn to Annular Flow

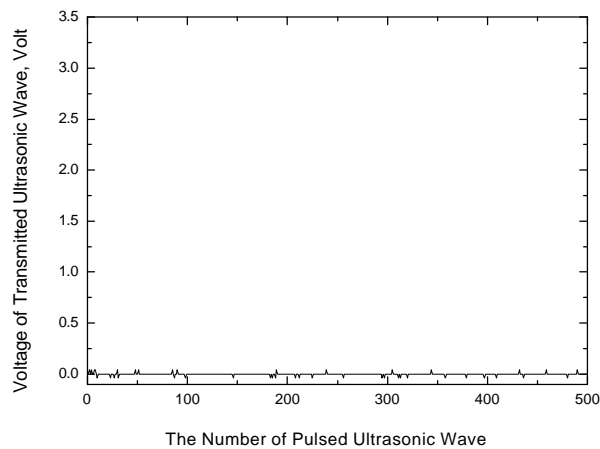


Fig. 15 Transmitted Ultrasonic Signals for Annular Flow

5. Conclusions

In the present study, a new measurement technique has been developed, which uses ultrasonic transmission signals in order to identify the vertical two phase flow pattern.

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

It is very straight-forward to identify the various vertical two phase flow patterns such as bubbly, slug, churn, annular flow etc. from the measurement results of the developed ultrasonic system. In addition to the identification of flow patterns, qualitative information for each flow pattern can be obtained, which include void fraction in bubbly flow, length of slug bubble and liquid tail characteristics in slug flow, and stable or transient condition of each flow pattern, etc.

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

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