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Development of the Ultrasonic Method for Two-Phase Mixture Level Measurement

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ABSTRACT

An ultrasonic method is developed for the measurement of the two-phase mixture level in the reactor vessel or steam generator. The ultrasonic method is selected among the several non-nuclear two-phase mixture level measurement methods through two steps of selection procedure. A commercial ultrasonic level measurement method is modified for application into the high temperature, pressure, and other conditions. The calculation method of the ultrasonic velocity is modified to consider the medium as the homogeneous mixture of air and steam, and to be applied into the high temperature and pressure conditions. The cross-correlation technique is adopted as a detection method to reduce the effects of the attenuation and the diffused reflection caused by suface fluctuation. The waveguides are developed to reduce the loss of echo and to remove the effects of obstructs. The present experimental study shows that the developed ultrasonic method measures the two-phase mixture level more accurately than the conventional methods do.

1. INTRODUCTION

During the accident at the TMI-2 nuclear power plant, a condition of low water level and inadequate core cooling (ICC) in the reactor vessel existed but was not recognized for a long period of time, because the level instrumentation system of TMI-2 which was inferred from the pressurizer water level, did not measure the real level accurately. After the TMI-2 accident, several regulatory organizations emphasized the accurate measurement of liquid inventories such as the water level. The measurement of liquid level in the constant temperature and pressure conditions is a relatively simple process. However, the rapidly changing environmental conditions in the reactor applications preclude the use of these standard techniques. In addition, the water level at low temperature is differed from the two-phase mixture level at high temperature i.e. it is considered that the level can fluctuate and much froth can exist in this case. There is also a problem that most of the water level measurement techniques detect the collapsed level instead of the two-phase mixture level.

In order to develop the accurate measurement method for the two-phase mixture level, several methods are reviewed. The characteristics of previous methods are arranged and several methods were picked out through the selection procedure. In the present study, the ultrasonic method is selected and developed to apply into the nuclear reactor or steam generator. The selected method should be capable of providing an unambiguous indication of the inadequate core cooling, survive accident conditions, and work under any conditions. For satisfying these requirements, this method is being pursued. The commercial ultrasonic sensors usually measure the level considering only the temperature effect, so it can not measure the exact level at high temperature and pressure condition. Also it does not measure the level when it is applied the conditions of level fluctuating or the obstruct exisiting. The present study is carried out to improve the existing ultrasonic method focussing on these problems. The objectives of the present study are as follows: to obtain the accuracy of the measurement of the two-phase mixture level and to investigate the possibility of the application into the reactor vessel or steam generator through the development procedure and results.

2. SELECTION PROCEDURE

There have been many existing methods for the two-phase mixture level measurement including the single-phase water level measurement. In the present study, the methods were conveniently classified by non-nuclear and nuclear methods categories and were reviewed briefly focussing on the physical principles used to achieve the water level measuring purpose[1][2]. Although many measurement techniques appear good in principle, several important factors should be carefully considered before selecting one method to apply into the nuclear reactor or steam generator. Some of these factors are NRC licensing requirements, data quality, reliability, ability to survive during operation and abnormal conditions and impacts in existing reactors and plant operations when retrofitted. These considerations can be used as criteria to evaluate previous methods. The first selection procedure is carried out among the proposed or commercial non-nuclear methods. And then the firstly selected methods are investigated deeply, and tabulized by several standrards such as principles, measured parameter, accuracy, reliability, survivability, installation, retrofit, maintenance, cost and so on. According to the each standard, each method is graded for the second selection procedure[3][4]. The results of the second selection procedure are shown in Table 1. As shown in Table 1, the secondly selected methods are the heated thermocouple and the ultrasonic method, but the former has some disadvantages such as the possibility of the destruction of insulator at high temperature, complex signal processing by many signal from many thermocouples, and discontinuous signal from different points. Contrary to the heated thermocouple, the ultrasonic method is simple in principle and possible to acquire the continuous signals. Therefore, the ultrasonic method is selected finally and developed for the two-phase mixture level measurement method in the present study.

3. EXPERIMENTAL WORK AND RESULTS

3.1. Experimental Facility

The experimental facility consists of the ultrasonic sensor, the commercial signal processor, the oscilloscope, the tank, the electric heated, the three thermocouples, the pressure gauge, the pressure transmitter, the circuits for filtering, the air injection lines and so on. The schematic diagram of the experimental facility is shown in Figure 1. Before the signal processing, the level is measured by current output or displayed number. The signal processor, oscilloscope, and high pass filter are needed to observe the raw signal of ultrasonic wave.

3.2. Development Procedure

The principle of the conventional ultrasonic level sensor is as follows: As the velocity of an ultrasonic wave depends on the temperature, pressure and the state of medium, it can be calculated with the measured temperature and pressure[5]. The ultrasonic transducer emits the signal and receives the echo signal reflecting from the interface of liquid and gas, i.e. two-phase mixture level, and the processor measures the round trip time for the emitting signal to return to the sensor as an echo signal. With this measured time and the calculated velocity, the processor calculates the distance moved by ultrasonic waves. Figure 2 shows this principle of the ultrasonic level sensor. As stated above, Figure 3 shows these characteristics of emitting signals.

The pretests are performed to test the commercial ultrasonic level sensor and clearly identified the several problems such as the inaccuracy at the high temperature and pressure, the effects of obstructs and mist, and the loss of echo by surface fluctuation. In order to improve the commercial ultrasonic level sensor focussing on these problems, the following procedure is taken as shown in Figure 4: The measured level by the commercial ultrasonic level sensor is displayed in LCD in commercial processor or given in the form of current output(4-20 mA). For better signal processing, the raw emitting and echo signals are observed using the oscilloscope. In addition, the signals are processed using a high pass filter to remove the 60Hz AC in this process to observe both signals more clearly. And then, the accurate detection method of small echo signals is introduced. The correction formula considering the air/steam mixture at high temperature and high pressure are developed. Finally, the concept of waveguide is proposed to remove the obstruct effect and to reduce the attenuation of ultrasonic. The developed ultrasonic level measurement method from the procedure is tested through the experiment for various conditions.

3.3. Signal Processing

The purposes of the signal processing are as follows: First, the raw emitting signal and echo signal are capable to be observed to investigate the phenomena at various conditions. Second, the detection method is introduced to detect a small echo signal. The signal processing procedure is organized as shown in Figure 5. The raw signal of ultrasonic wave can be observed by setting the oscilloscope and high pass filter. From these raw signal, the round trip time of emitting signal can be measured. However, the fluctuation surface of water level cause the attenuation of the ultrasonic wave, i.e. the amplitude of the echo signal becomes so small as not to be distinguished from noises. Therefore, the cross-correlation technique is adopted as a detection method in present study to reduce the effects of loss of echo. In the present study, the cross-correlation technique is adopted to solve this problem to some degree.

The principle of the cross-correlation technique is as follows[6]: The cross-correlation function for two sets of data describes the general dependence of the values of one set of data on the other. Consider the pair of time history records x(t) and y(t) shown in Figure 6. The cross-correlation function, Rxy(τ), may be obtained by taking the average product for the two values x(t) and y(t+τ) over the observation time T. The resulting average product will approach an exact cross-correlation function as T approaches infinity:

$$R_{xy}(t) = \lim_{T \to \infty} \frac{1}{T} \int_0^T x(t)\, y(t+t)\, dt \cdot \qquad (1)$$

A typical plot of the cross-correlation versus time displacement, for a pair of time history records is shown in Figure 6. Note that the peaks indicate the existence of correlation between x(t) and y(t) for specfic time displacements, τ_1 and τ_2. Cross-correlation functions can be used to determine time delay such as the round trip flight time for an acoustic ranging system. The transmitted wave form is x(t) and the received signal plus noise is the function y(t). A cross-correlation measurement between x(t) and y(t+τ) yields the flight time information. As the function y(t) is displaced in time relative to the input, the cross-correlation function will peak at the time displacement equal to the time required for the acoustic pulse to travel to the target and return to the receiver. The results show that the round trip time measured by cross-correlation technique is very accurate in comparison with one by the oscilloscope as shown in Figure 7.

3.4. Development of the Correction Formula

Since the measured level is determined by the velocity of ultrasonic, the accurately measured level is determined by the accurate velocity calculation. As mentioned above, the conventional method use the calculation method which consider only the temperature effect or only the air as a medium[7][8][9]. The former is following:

$$v = v_o \times (1 + 0.0018T), \qquad (2)$$

where v_o : ultrasonic velocity at room temperature (= 344.1 m/s at 20°C) .

And the latter is following:

$$v = \sqrt{\frac{g_{air} \cdot P}{r_{air}}} \ , \tag{3}$$

Where $g_{air} = {C_p}/{C_v}$, (4)

$$C_{v,air} = C_{v,air}(T,P) \ . \tag{5}$$

The above formulas are incorrect at high temperature and pressure as shown in Figure 8. Therefore, the new correction formula is developed considering the mixture medium model in the present study. The medium changes as the water in a tank is boiled, so, the change of air/steam fraction should be considered. This correction uses the air mass fraction calculated by saturation pressure to consider the mixture medium and postulates that the mixutre of steam and air is mixed homogeneously. The developed TP mixture correction formula is

$$v = \sqrt{\frac{g_{mixture} \cdot P}{r_{mixture}}} \ , \tag{6}$$

where $g_{mixture} = W_{air} \cdot g_{air} + (1 - W_{air}) \cdot g_{steam}$, (7)

$$r_{mixture} = W_{air} \cdot r_{air} + (1 - W_{air}) \cdot r_{steam} \ , \tag{8}$$

$$W_{air} = \frac{P_{air}}{P_{air} + \frac{M_{air}}{M_{steam}} P_{sat}} \ , \tag{9}$$

$$P_{measured} = P_{sat} + P_{air} \ . \tag{10}$$

The results that the measured level is corrected by each correction formula are shown in this section. The experiment is performed as the following three cases: (1) at the high temperature and pressure, (2) at the high temperature and constant pressure, and (3) at high pressure and constant temperature. The results are shown in Figure 8 for the high temperature and high pressure case. This results shows that the formular which considers the mixture of air/steam, is the most proper one which is possible to apply into the ultrasonic level sensor at high temperature and high presseure conditions.

3.5. Surface Fluctuation Effects

This experiment is carried out in order to investigate the degree of surface fluctuation effects. When the water level is fluctuating, the attenuation of echo signals is increasing because of the diffused reflection. As the diffused reflection increases further, the echo signal becomes much smaller and, as a result, can be lost. This phenomenon is called the loss of echo. To remove or reduce these effects, the cross-correlation technique is applied and the waveguide is designed. In this section, it is tested how much the adopted detection method, cross-correlation technique, can detect the echo signals without waveguides[10].

Before the tests of surface fluctuation effects, the flow regime in the present operating range is determined. In this experiment, the maximum air flow rate injected into the tank is about 500lpm which can produce the churn flow. In these cases, the actual level is fluctuating by 5 to 10 cm above the collapsed level.

In order to reduce the effect of loss of echo, the cross-correlatioin technique is adopted in the present study. In this section, the cross-correlation technique is tested when the water level fluctuates. For this experiment, the air mass flow injected into the tank is controlled through changing the degree of surface fluctuation. Figure 9 shows the results of this experiment. The measured level processed by the cross-correlation technique well traces the averaged actual level. Though the echo can not be distinguished with the naked eye, the level can be measured using this cross-correlation technique.

If loss of echo happens frequently, the measurement of water level is impossible. Therefore, the method to remove or reduce the loss of echo is needed. In the present study, the waveguide is designed and tested here.

3.6. Design and Application of Waveguide

Finally, the waveguide concept is introduced. The waveguide is designed to reduce the attenuation and the echo loss of ultarsonic wave, and to remove the effects of obstruct. The waveguide is designed so that the hole size should be small so as to prevent the attenuation of ultrasonic and large so as to equalize the two-phase mixture level in the waveguide with the real two-phase mixture level outer waveguide. The waveguides are designed and manufactured with these requirements. The installation and design of waveguide are shown in Figure 10. From the experimental results using each type, the most optimal hole size of waveguide is 20mm which is the minimum hole size to obtain the actual two-phase mixture level and the attenuation of ultrasonic is considerably decreased at this size. Figure 11 shows the degree of attenuation and fluctuation of actual level and the measured level by the ultrasonic sensor. The maximum level and the minimum level in Figure 11 represent the highest level and the lowest level respectively. Als o it shows the level measured by the ultrasonic sensor is fluctuating as the actual level is fluctuating.

4. CONCLUSIONS

The ultrasonic method is developed to measure the two-phase mixture level in the reactor vessel or steam generator and tested experimentally. From experimental results, the following conclusions are obtained: (1)The developed ultrasonic level method in the present study accurately measures the two-phase mixture level at high temperature and pressure with the correction formula considering the homogeneous mixture of the air and steam. (2)When the attenuation of echo signals by surface fluctuation exists, the echo signal can be detected with the adopted cross-correlation method. This method can detect the small echo signal caused by the attenuation. (3)The waveguide concept is developed to reduce the attenuation of ultrasonic waves and to remove the effects of obstructs. And then the most optimal hole size is proposed according to the degree of attenuation and the accurate representation of the actual two-phase mixuture level. Consequently, it can be concluded that the developed ultrasonic level sensor correctly measure the two-phase mixture level.

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Table 1. Result of second selection procedure

Device	**Conductivity prove**	**Microwave**	**Heated TC**	**Ultrasonic**	**Differential Pressure**
Measured Parameter	Local electrical conductivity	Reflected microwave	Temperature	Reflected ultrasonic wave	Pressure difference
Interpretation	A Actual level	A Actual level	A Actual level	A Actual level	C Collapsed level
Accuracy	B Erroratic data	C Unproved	A Simple design	B Various signal processing	A Simple
Proven Tech.	B	C	B	B	A
Reliability	A	A	A	A	A
Survivability	B Unqualified	A	A	A	B
Installation & Retrofit	C Multiple penetration	C Optical penetration	A	B Waveguide	C Multiple penetration
Maintenance	A	B	A	A	A
Cost	A	B	A	A	B
Overall Grade	B+	B0	A-	A-	B+

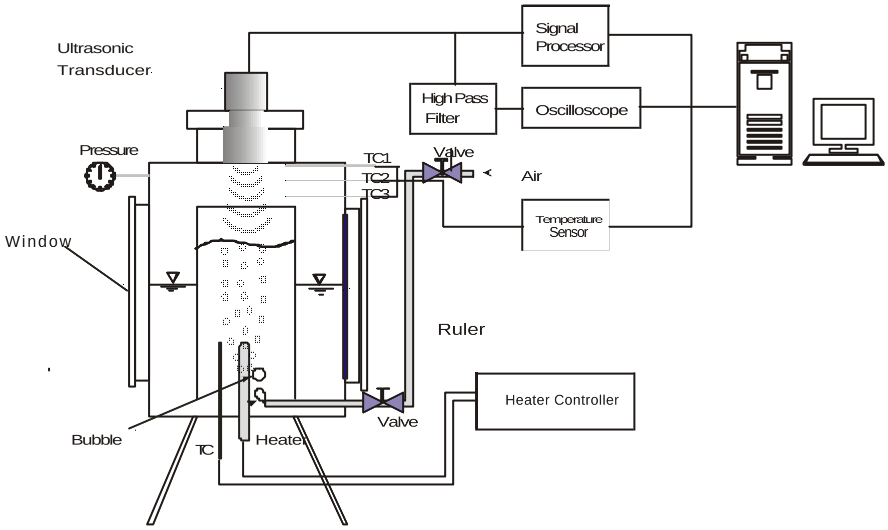

Figure 1. Experimental facility

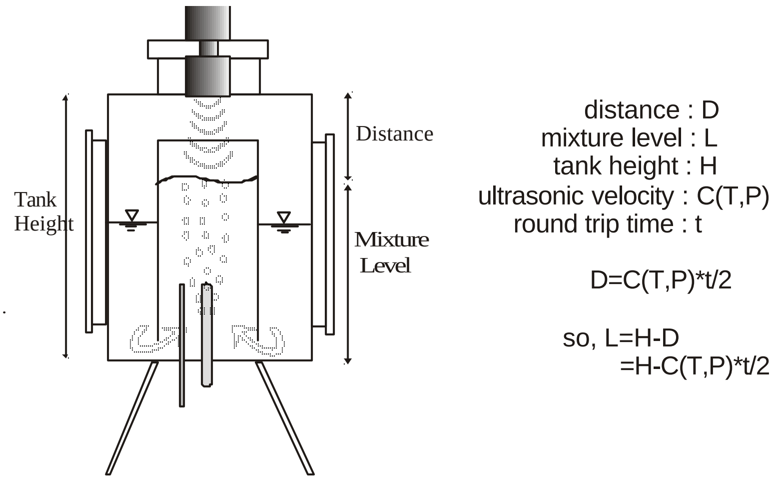

Figure 2. Principle of the ultrasonic level sensor

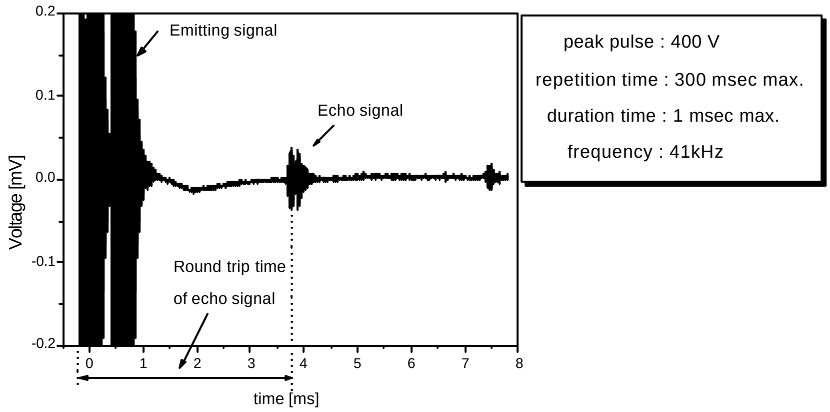

Figure 3. The characteristic of transducer

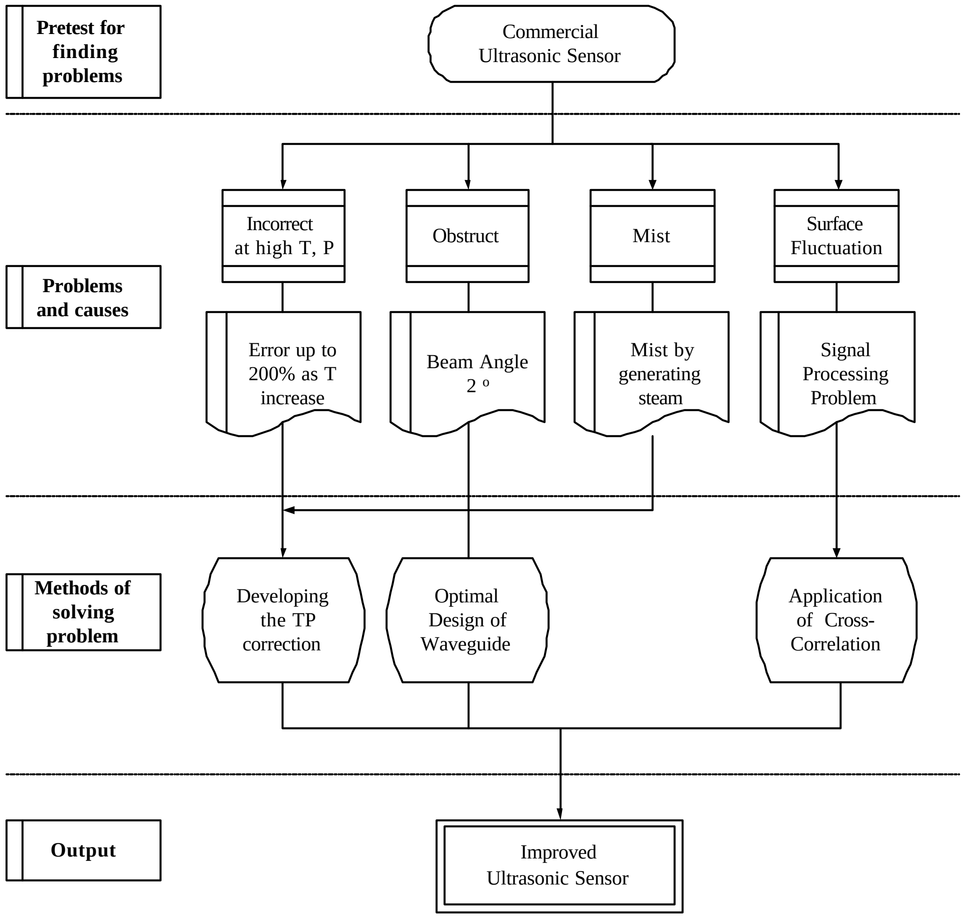

Figure 4. Experimental procedure for improving the ultrasonic sensor

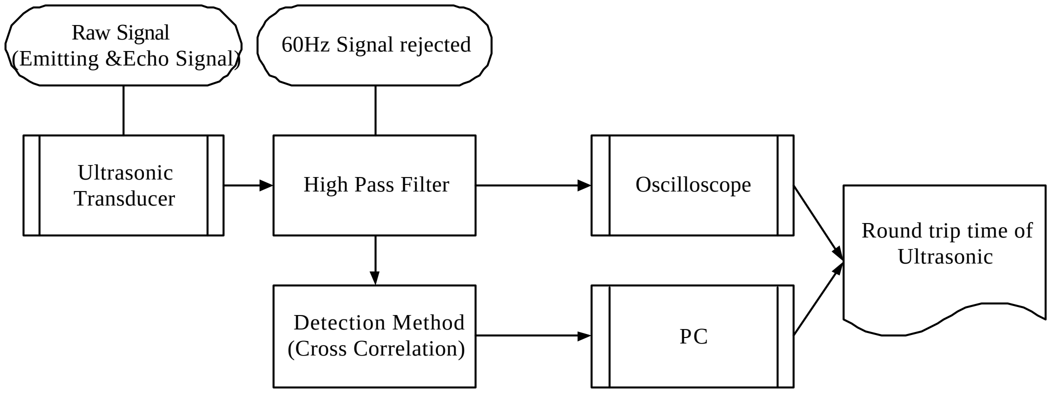

Figure 5. Signal processing procedure

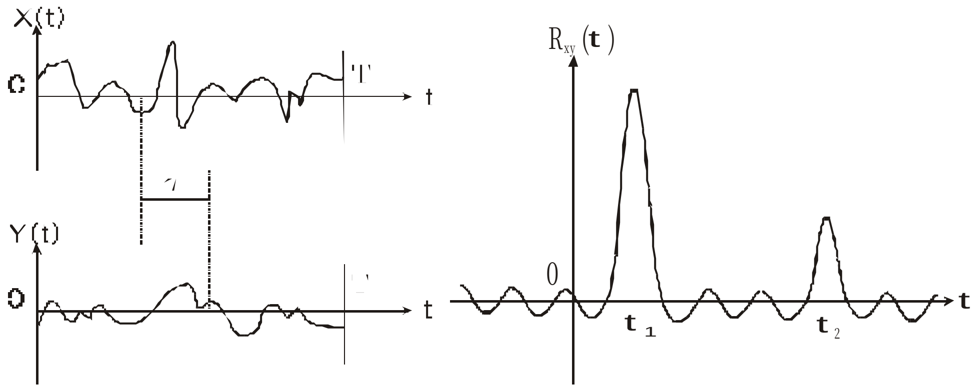

Figure 6. Two signals with time history and cross-correlaion function

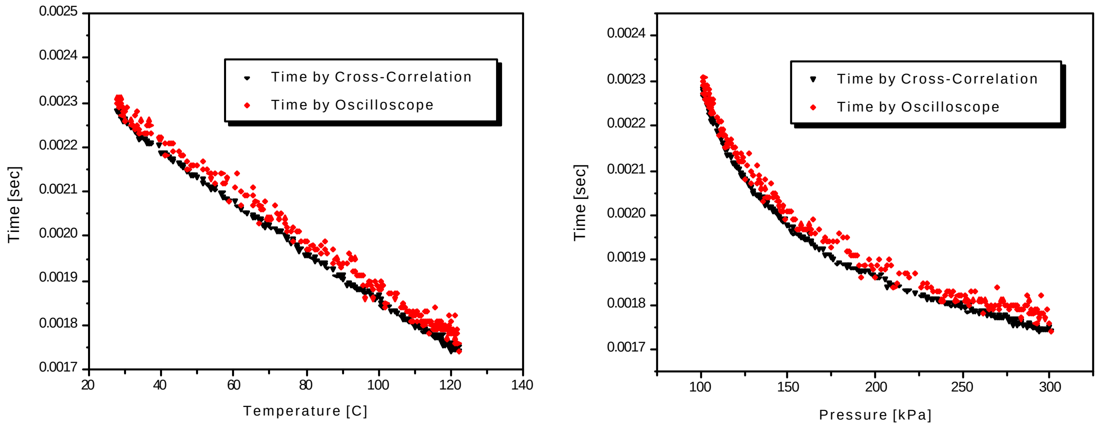

Figure 7. Comparing round trip times estimated by the cross-correlation technique and oscilloscope

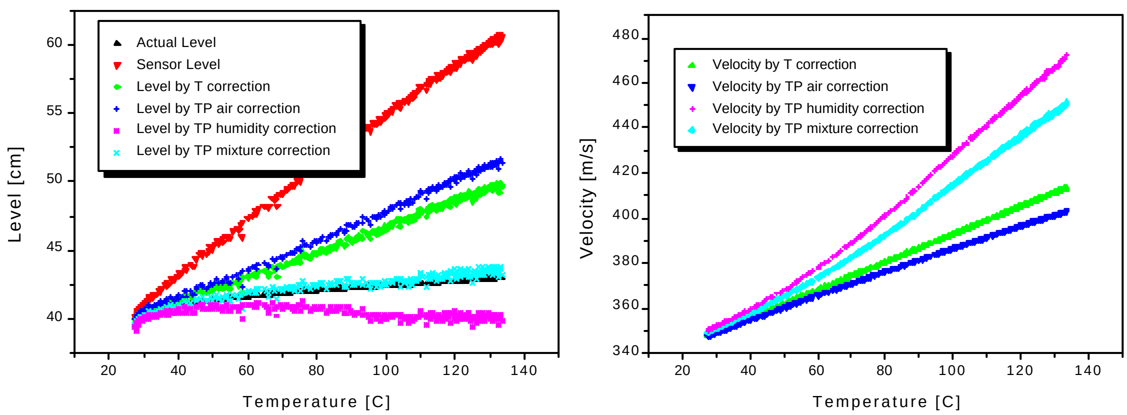

Figure 8. Measured level and Calculated velocity at high temperature and pressure

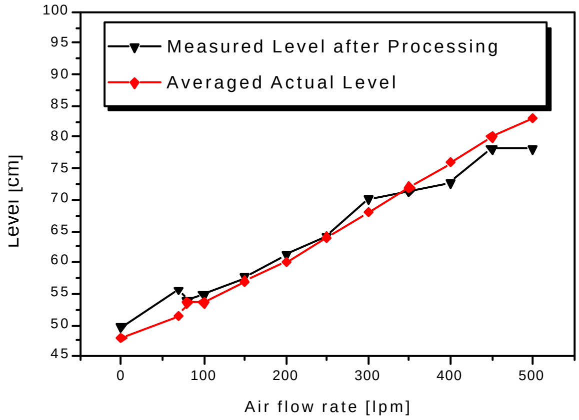

Figure 9. Measured level with surface fluctuation

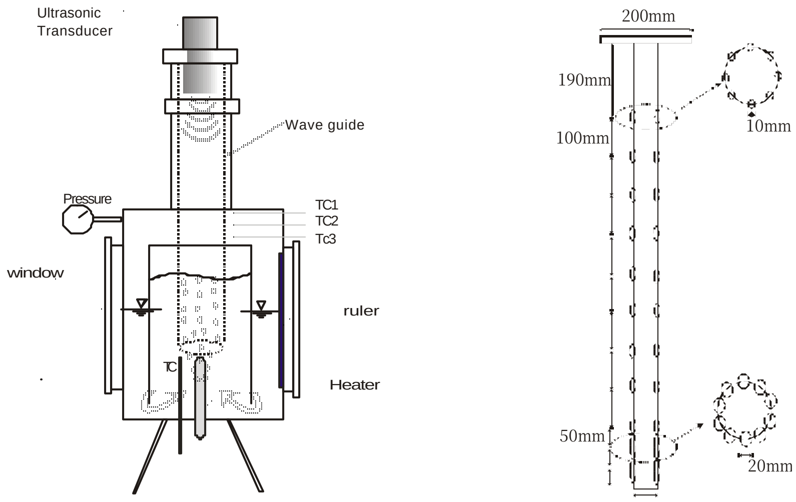

Figure 10. Experimental facility for waveguide and waveguide

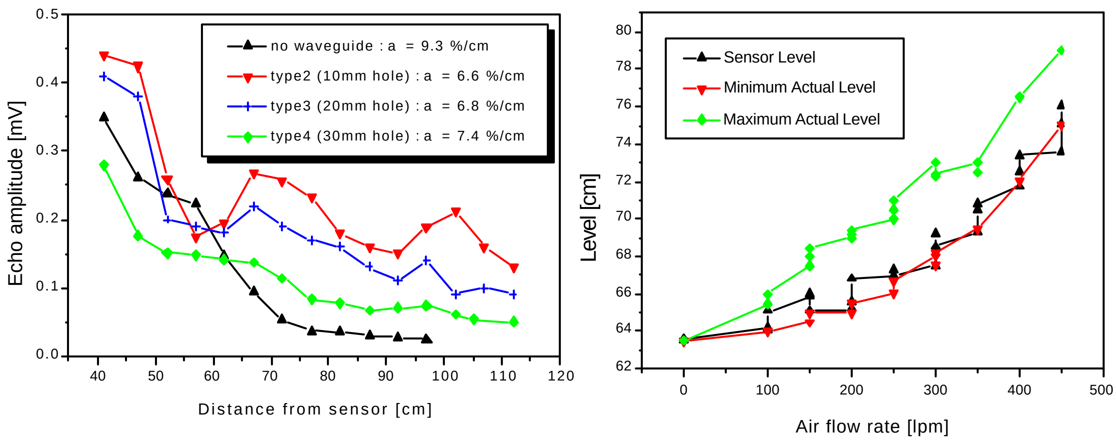

Figure 11. Degree of ultrasonic attenuation and experiment results of surface fluctuaion with waveguides