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Development of pipe temperature prediction correlations using ultrasound

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1. Introduction

Gas **V**oid **M**onitoring and **C**ontrolling **S**ystem (called GVMCS) has been suggested to monitor and control gas accumulation inside a pipe. This system can measure liquid level inside a pipe in order to convert gas void fraction without any pipe modification using ultrasonic wave. Therefore, one of the essential GVMCS components can be an ultrasound transducer. The transducer is to create an ultrasonic acoustic wave and to receive the reflected wave from the liquid surface.

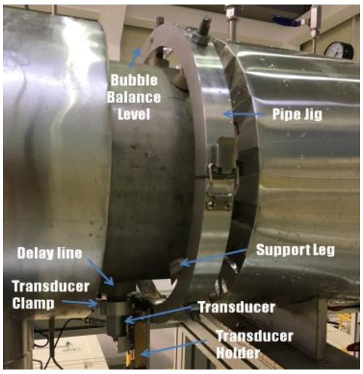

Fig. 1 GVMCS installation on a pipe

The simple principle of GVMCS is that ultrasonic transducer is located beneath of a pipe and acoustic wave is created by the transducer and it passes through a wall of a pipe and liquid and reflected by the liquid surface due to acoustic impedance difference and the reflected wave can be detected by the transducer. The reason why the transducer is located beneath of the pipe is because acoustic wave cannot be passed through an interface between liquid and gas due to the huge difference of acoustic impedance. Therefore, GVMCS can measure the liquid level inside a pipe through pipe wall and liquid. However, there is a restriction to use the transducer in terms of temperature.

Ultrasonic transducer is generally combined with a piezoelectric disc, a backing element and a quarter-wave matching layer which should be acoustically coupled and bonded together. However, those components are mechanically failed or degraded due to the thermal expansion/contraction when the transducer exposes in high temperature circumstance [1].

So, a temperature buffer called “delay-line” is suggested for GVMCS located between the pipe surface and the transducer in order to secure the integrity of the transducer in terms of high temperature.

The speed of sound can be defined as a function of temperature and other properties of material such as specific heat ratio, molecular weight of the medium and gas constant [2]. The transient time of the ultrasound echoes is affected by temperature-dependent changes in the velocity of the ultrasound propagation. So, temperature of a medium is fundamental information in order to achieve accurate measurement using ultrasound. If there is a temperature measurement device for a medium, there will no need to predict the temperature. However, some location of possible GVMCS installation can have no chance to get the temperature of the medium. In theory, the measurement of the transit time of an acoustic signal can predict the temperature of the medium which acoustic wave propagates through. This method was first suggested by Mayer in 1873 [3].

From these reviews the pipe temperature prediction using the delay-line for GVMCS has been suggested. However, the role of delay-line is a temperature buffer which means the delay-line itself cannot be isothermal condition. This means that there should be temperature gradient from the pipe wall and the transducer. In this regard, the temperature gradient prediction method has been provided by Y. Jia [4]. However, this method cannot be applied to GVMCS due to short transient time.

As a result, the pipe temperature prediction for GVMCS will be established by the correlation between the time of flight and the pipe temperature obtained by the delay-line experiments.

2. Delay-Line Test

2.1 Delay-Line Test Facility

In this section the delay-line test facility will be introduced. This experimental facility consists of four major components such as a delay-line chamber with a heating plate, the pulser & receiver, an oscilloscope and the data acquisition system (DAS) presented as Fig. 2. The delay-line chamber is a test section that includes the heating plate, the ultrasonic transducer with the delay-line and a sample which can represent thickness and radius of a pipe. The heating plate was installed as upside-down with the pipe wall sample to simulate GVMCS installation. The delay-line and the ultrasonic transducer for the test are installed as same as GVMCS.

For the tests, ultrasound can be produced by the pulser and receiver with pulse-echo mode connected to the transducer. The echo signal from the transducer is presented and manually saved by the oscilloscope via the pulser and receiver. There are three thermocouples to measure the temperature. One is located at the interface between the pipe wall sample and the delay-line and the other is for the interface between the delay-line and the transducer. Another is installed at the chamber for measuring atmospheric temperature inside the chamber. Those temperature data are automatically saved by DAS with 1 second interval.

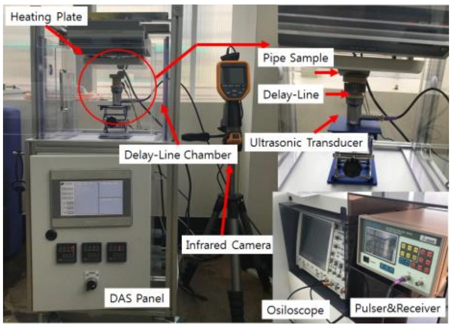

Fig. 2 Installation of the delay-line experimental facility

2.2 Delay-Line and Ultrasound Transducer

The delay-line for the tests is same one for the GVMCS. The length of the delay-line is 40mm with 29mm diameter. The material of the delay-line is (Poly Ether Ether Keton (called PEEK) which is one of engineering plastic having high thermal resistivity. The transducer is a commercial one which has center frequency of 2MHz with operation range 0 ~ 50°C.

2.3 Test matrix

The temperature range for the tests is 20 ~ 150°C which is the target range for the GVMCS. There are four tests are conducted followed by the test matrix given in Table I. There is no change about the facility set-up for all tests without the chamber temperature and the procedure.

Table I: Test Matrix

Test No.	Pipe surface temp.	Chamber temp.	Temp. from
Case 1	20 ~ 150°C	20°C	20°C
Case 2	20 ~ 150°C	15°C	20°C
Case 3	20 ~ 150°C	20°C	20°C
Case 4	20 ~ 150°C	40°C	150°C

Case 1 is the reference test. Case 1 and 2 can be compared in order to verify the effect of atmospheric temperature. Case 3 is a repeat test for Case 1. Comparison between Case 1 and 4 can present the effect of the pipe surface temperature increases or decreases. The acoustic signal variations are expected in terms of the pipe surface temperature from the tests. In addition, the correlations between the time of flight and the pipe temperature of each case are provided and the correlations are analyzed by comparison among the test results in order to achieve the representative correlation.

3. Test Results

3.1 Speed of sound variation 20 ℃ and 150 ℃

The acoustic signal in terms of the pipe temperature is presented in Fig. 3 from the reference test.

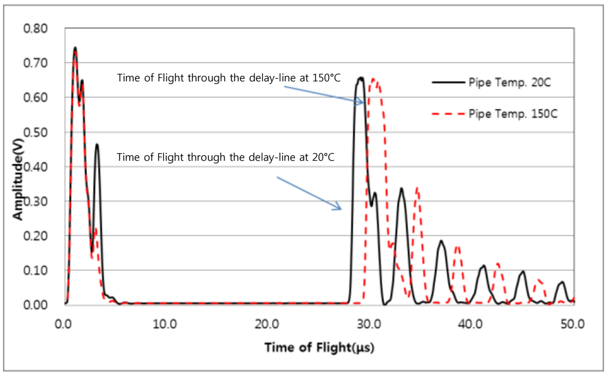

Fig. 3 Acoustic signals in terms of the pipe temperature

The continuous and dotted line presents the acoustic signal when the pipe temperature is 20°C and 150°C with the achieved speed of sound 2524m/s and 2409m/s respectively. The speed of sound in PEEK which is obtained by the experiments by Carlson [5] is about 2586m/s at 20°C with 5MHz center frequency. This is very similar results with the delay-line experiments. The difference may come from the system difference such as center frequency of the used transducer, temperature gradient effect and the resolution difference of the system.

3.2 Time of flight variation in terms of temperature

The results of time of flight through the delay-line in terms of the pipe temperature for the tests are presented in Fig. 4 ~ 7. Blue, red and green dot represent the temperature of the pipe, the transducer and the chamber respectively. The correlation of each case is presented as a continuous line on the each figure with the equation.

The difference between the case 1(Fig. 4) and the case 2(Fig. 5) can be found by the each correlation. The case 1 is the second order equation and the case 2 is represented as a linear function. This can be caused by the temperature difference between at the chamber and the interface. The pipe temperature was similar with the chamber temperature from the case 1. However, the case 2 had 5°C difference. This seems like when the pipe wall was heated initially the boundary temperature may affect the delay-line slightly. This effect may exist until the pipe temperature about 30°C. After the temperature range, the tendency of the result looks like a linear function.

The tendency of the results from the comparison between the case 1 and 2 was similar with each other.

The difference between the case 1 and 4 was the initial temperature of the tests and the procedure to control the temperature. The case 1 was started from the atmospheric temperature to increase until 150 °C and the case 2 was vice versa. The shape of the correlation for the case 1 was negative second order type and the positive second order shape was achieved from the case 2. This difference may be caused by the energy absorption and dissipation process due to the atomic movement. In order to verify and clear to understand about this difference, more studies will be conducted in near future.

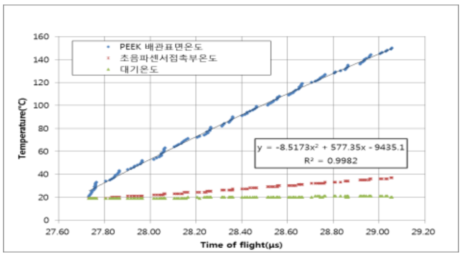

Fig. 4 Time of flight variation in terms of the pipe temperature for the case 1

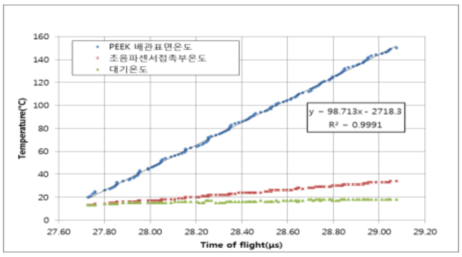

Fig. 5 Time of flight variation in terms of the pipe temperature for the case 2

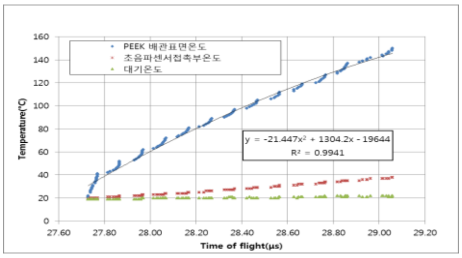

Fig. 6 Time of flight variation in terms of the pipe temperature for the case 3

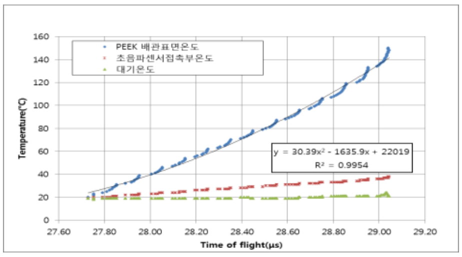

Fig. 7 Time of flight variation in terms of the pipe temperature for the case 4

3.3 The representative correlation for the GVMCS

In the previous section, four different correlations are provided. In order to decide the representative correlation, all data should be applied to those correlations and compared the results with each other for analyzing the error. The obtained correlations from the tests are given in Table II, where T_{tof} is the acoustic signal time of flight by the pulse echo mode.

Table II: The correlations from the each case

Test. No.	Correlation
Case 1	$-8.5173T_{tof}^2+577.35\ T_{tof} - 9435.1$
Case 2	$98.713T_{tof} - 2718.3$
Case 3	$-21.447\ T_{tof}^2+1304.2T_{tof}-19644$
Case 4	$30.39T_{tof}^2-1635.9T_{tof}^2+22019$

Those correlations are analyzed by applying the obtained data from each case for the each correlation and the best fitted correlation is selected as the representative correlation among one of those correlations. The analyzed errors are shown in Table III ~ Table VI from the use of the correlation obtained by the case 1 ~ 4, respectively. The correlation from the case 1 can describe the best fitted results which has minimum average error compared to other cases.

Table III: Analyzed Result for the case 1 correlation

Data Used.	Error Range(°C)	Averaged Error(°C)
Case 1	0.01 ~ 5.69	2.45
Case 2	0.06 ~ 9.66	5.55
Case 3	0.05 ~ 12.51	5.30
Case 4	0.64 ~ 22.16	14.86

Table IV: Analyzed Result for the case 2 correlation

Data Used.	Error Range(°C)	Averaged Error(°C)
Case 1	0.01 ~ 10.98	5.64
Case 2	0.01 ~ 3.03	0.92
Case 3	0.17 ~ 19.61	10.63
Case 4	0.04 ~ 17.50	10.15

Table V: Analyzed Result for the case 3 correlation

Data Used.	Error Range(°C)	Averaged Error(°C)
Case 1	0.07 ~ 10.04	4.40
Case 2	0.19 ~ 15.64	9.43
Case 3	0.01 ~ 9.50	2.55
Case 4	0.17 ~ 26.11	17.28

Table VI: Analyzed Result for the case 4 correlation

Data Used.	Error Range(°C)	Averaged Error(°C)
Case 1	0.30 ~ 22.73	14.68
Case 2	0.33 ~ 16.56	10.26
Case 3	0.05 ~ 12.51	5.30
Case 4	0.03 ~ 8.93	2.02

3. Conclusions

Gas **V**oid **M**onitoring and **C**ontrolling **S**ystem (GVMCS) has been suggested to measure the gas void inside a pipe using ultrasound on high temperature condition. The speed of sound can be described as a function of temperature. Also, the ultrasound transducer has usage restriction on the high temperature condition such as mechanical fault and degradation. Thus the delay-line has been suggested for protecting the transducer from high temperature as a temperature buffer. Also, the speed of sound varies depended on temperature. In order to achieve the accurate measurement using ultrasound, the pipe temperature prediction should be necessary for the GVMCS. The idea to predict the pipe temperature using GVMCS can be obtained by studying the relationship between the time of flight on the delay-line and pipe the temperature. Therefore, the delay-line test facility is introduced and four tests were conducted including the reference case. As a result, the best fitted correlation was suggested and this will be applied to the GVMCS operation program to verify the precision of the measurement. More research will be conducted to increase the measurement accuracy of the GVMCS.

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