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High temperature monitoring the height of condensed water in steam pipes

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Abstract

An in-service health monitoring system is needed for steam pipes to track through their wall the condensation of water. The system is required to measure the height of the condensed water inside the pipe while operating at temperatures that are as high as 250°C. The system needs to be able to make real time measurements while accounting for the effects of cavitation and wavy water surface. For this purpose, ultrasonic wave in pulse-echo configuration was used and reflected signals were acquired and auto-correlated to remove noise from the data and determine the water height. Transmitting and receiving the waves is done by piezoelectric transducers having Curie temperature that is significantly higher than 250°C. Measurements were made at temperatures as high as 250°C and have shown the feasibility of the test method. This manuscript reports the results of this feasibility study.

Keywords: High Temperatures (HT), HT piezoelectric transducers, Fluid Height Monitoring, health monitoring, monitoring steam condensation, Sensors

1.0 Introduction

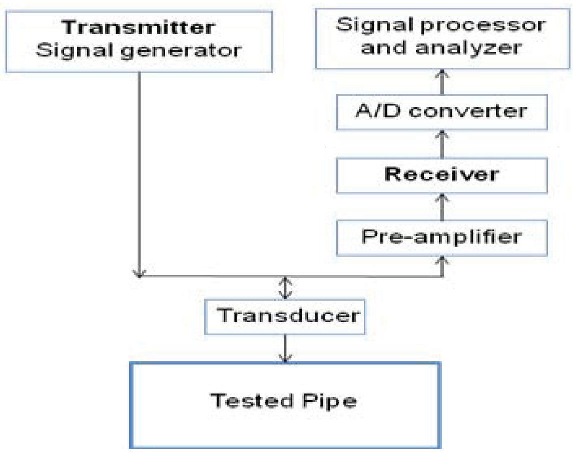
Steam pipe systems are used in various major cities including Manhattan and are operated as a district heating system carrying steam from central power stations under the streets to support heating, cooling, or supply power to high rise buildings and businesses. Health monitoring of such systems is critical to assure their safe operation. Excessive rise in the level of water condensation inside the steam pipes is a source of concern due to the possible excitation of water hammer effects that may lead to serious consequences including damaged vents, traps, regulators and piping. The water hammer effect is caused by accumulation of condensed water that is trapped in horizontal portions of the steam pipes. In this study, the authors sought to develop and demonstrate the feasibility of using an ultrasonic based technique of monitoring the condensate height that sustains the harsh environments of the steam pipe system (<250°C). Using pulse-echo and HT transducer, the feasibility was demonstrated with a good accuracy [Bar-Cohen et al., 2010a, 2010b, and 2010c].

Making nondestructive measurements of the water height level through a pipe wall may be feasible only by an ultrasonic method. For this purpose, there is a need to be able to measure with good accuracy a parameter that is related to the height of the water. Three techniques were considered: Pulse-Echo, Pitch-Catch and Acoustic Emission. The first two have the highest potential where the time-of-flight of the wave reflections from the top surface of the water is measured and the height is calculated using the wave velocity. For first order analysis, it is reasonable to assume that the speed of sound in water at elevated temperatures is close to the one at room temperature. In the case of Pulse-Echo, the transducer is connected to both the transmitter (function generator), which leads to generating elastic waves, and the receiver amplifies the reflected waves that are converted to electric signals. Alternatively, in the Pitch-Catch arrangement, the pair of transducers is physically separated. In this case, one transducer generates the waves and the reflected signals are received by the second transducer. Of the two methods, Pulse-Echo is more capable since there is no reliance on receiving the reflection at a specific angle. However, numerous reflections are received and they require an effective signal processing technique to identify the reflections from the top and bottom surfaces of the condensed water. Several issues needed to be accounted for, including strong reflections from the interface of the steel pipe, the effect of the pipe curvature, and the wave losses due to scattering from a non-flat surface of the pipe, there is an issue of interference of the multiple reflections within the pipe bottom wall; the pipe-transducer interface; turbulence in the condensed water; potential sediments in the bottom of the pipe inner surface along the path of the wave; and the multiple reflections inside the condensed water.

An alternative method that was also considered is based on measuring emitted shock waves from cavitation that is potentially formed in the condensed water. This acoustic-emission method assumes that the greater the condensation height the more cavitation-implosions occur. The shock waves may be detectable if they are sufficiently strong in amplitude and possibly occur outside the spectrum of the noise that is expected from the street traffic and other mechanical activities that may generate underground sound. However, this approach is not a direct measurement and since it is based on estimate it is less accurate. This method was not pursued since the Pulse-Echo tests were shown to be capable of providing good accuracy.

2.0 Test system

A pulse-echo test system was assembled and the block diagram as well as photograph are shown in **Figure 1**. A steel pipe that is 91 cm (3 ft) long with two end walls was produced to simulate the steam pipe and was made of A53B steel alloy, having 40.6 cm (16 inch) diameter and 0.95 cm (3/8 inch) thick wall. Plumbing for water entry to fill the pipe and for draining were installed and the side walls were made of Plexiglas for viewing the inside of the pipe and physically measure the water height. Various transducers with different diameters and transmission frequencies were pressed against exterior bottom of the pipe with a couplant at the interface. The test transducers were driven by a transmitter/receiver (Panametrics) and were aligned via a miniature manipulator to maximize the received reflection amplitudes.



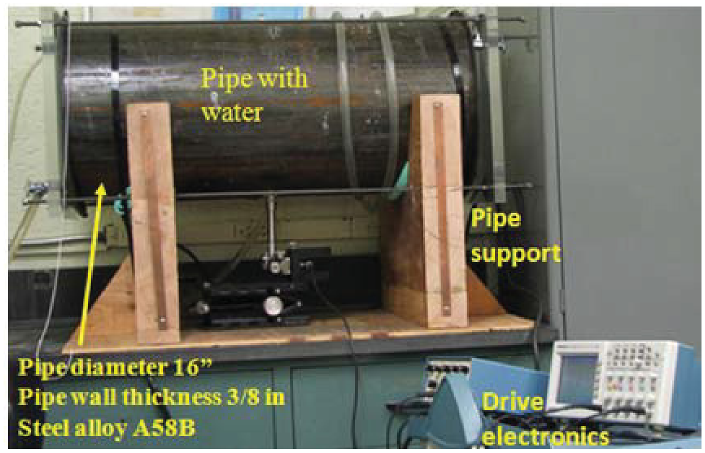


Figure 1: A schematic diagram of the test system and the steam pipe simulator as well as the ultrasonic test setup.

Generally, ultrasonic transducers are limited in their upper temperature operation range by the Curie temperature of the piezoelectric material that is used to generate the waves. In recent years, piezoelectric discs that can operate at temperatures that are as high as 850°C have been developed [Bar-Cohen, 2003; Sherrit et al, 2004; Bar-Cohen et al., 2011]. Also, for years it was known that the piezoelectric crystal LiNbO3 has a Curie temperature that exceeds 1000°C. While it offers High Temperature (HT) durability, its being a single crystal makes it fragile and it has lower efficiency than piezo-ceramic transducers. New materials, reported to have a high temperature capability [Bar-Cohen, 2003; Sherrit et al, 2004; Bar-Cohen et al., 2010d, Bar-Cohen et al., 2011], include the commercial piezo-ceramics PZ46 (by formerly Ferroperm and currently owned by Meggitt, Denmark) and piezo-ceramics based on Bismuth Titanate with various doping levels that were developed at Penn State University [Bar-Cohen et al., 2010d, Bar-Cohen et al., 2011]. The issues associated with the fabrication of HT ultrasonic transducers involve making a backing material that provides impedance matching, adhesion to the transducer and dampening of the multiple echoes that are generated and need to be eliminated in order to form the broadband signal required for high resolution. For this study, we had initially considered producing the transducers in-house, however after identifying a commercial source (Sigma Transducers) that produces custom made transducers specified to operate as high as 250°C we procured the required transducers.

3.0 Signal processing and water height measurements

Various room temperature transducers with resonance frequencies in the range of 0.5 to 10.0 MHz with diameters of 0.25, 0.5 and 0.75 inch were used to determine the required operation parameters for the performing effective pulse-echo tests. The use of 5.0 MHz transducer was found to provide quite effective performance in terms of the sensitivity, resolution and accuracy of the measurements. Examples of the measured reflections pattern from the pipe with 2.5 cm (1.0 inch) and 12.7 cm (5.0 inch) water heights are shown in **Figure 2**. As can be seen, a significant number of reflections are received from pipe wall (the first set of reflections) and they are becoming further complicated by the multiple reflections within the water itself. This large number of reflections makes it difficult to base the determination of the height on simple time-of-flight data and therefore an auto-correction technique was used. For this purpose we used the autocorrelation function:

$$R_{xx}(\tau) = \frac{1}{T}\int_0^T x(t)x(t+\tau)dt$$

Where: τ is the time separation variable and T is the sampling period.

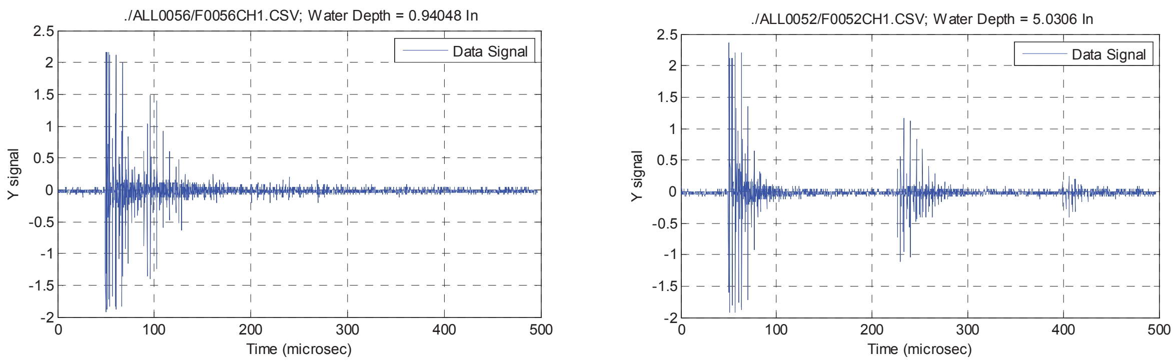


Figure 2: The reflections patterns received from the pipe with 1.0 and 5.0 inch water height.

An example of the auto-correlated function is shown in **Figure 3**. The time of flight was determined using a predetermined search window in the calculated auto-correlation function. The water height measurement was done both by physical observation from the side of the tank as well as the autocorrelation determination and the accuracy was found to be quite good, with a maximum difference of 6.0% (see **Table 2**). Some of the error is attributed to the inaccuracy of physical measurement of the water height based on measuring from the side wall of the tank. This may be the reason for the larger error for the lower water heights.

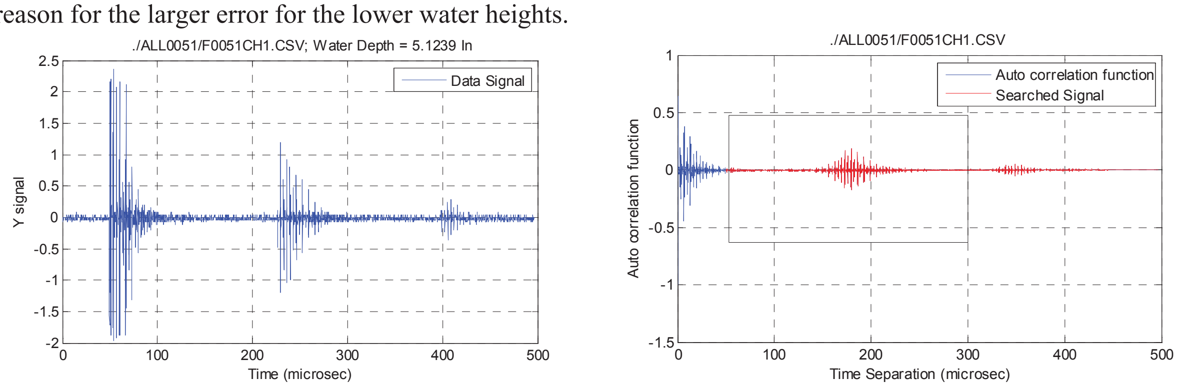


Figure 3: The time of flight (left) showing the first arrival time difference of 179.0 μsec and the calculated auto-correlation time difference of 179.6 μsec.

Table 2: The difference between the measured and the autocorrelation calculations of water height.

Water height (cm (inch))	Calculated height (cm (inch))	Difference %
2.5 (1.0)	2.39 (0.94)	6.0
5.1 (2.0)	4.98 (1.96)	4.0
7.6 (3.0)	7.34 (2.89)	3.7
10.1 (4.0)	10.49 (4.13)	3.3
12.7 (5.0)	12.78 (5.03)	0.6

The process of acquiring the time-of-flight data and the autocorrelation processing were initially done separately by manually uploading the data onto the computer using the downloaded data from the digital scope. To automate the data acquisition and analysis that determines the water height directly by the computer using analog signals from the data acquisition system, a LabView computer program was written. The program samples the data acquisition card, saves the data to a file and, in parallel, processes the data in MatLab, using the autocorrelation code. Using the developed data acquisition and real-time signal processing system, a test was performed where the height of the water in the pipe was measured while draining at two different rates. The results are shown in **Figure 4** and the relatively high speed and accuracy obtained validated the feasibility of the developed method.

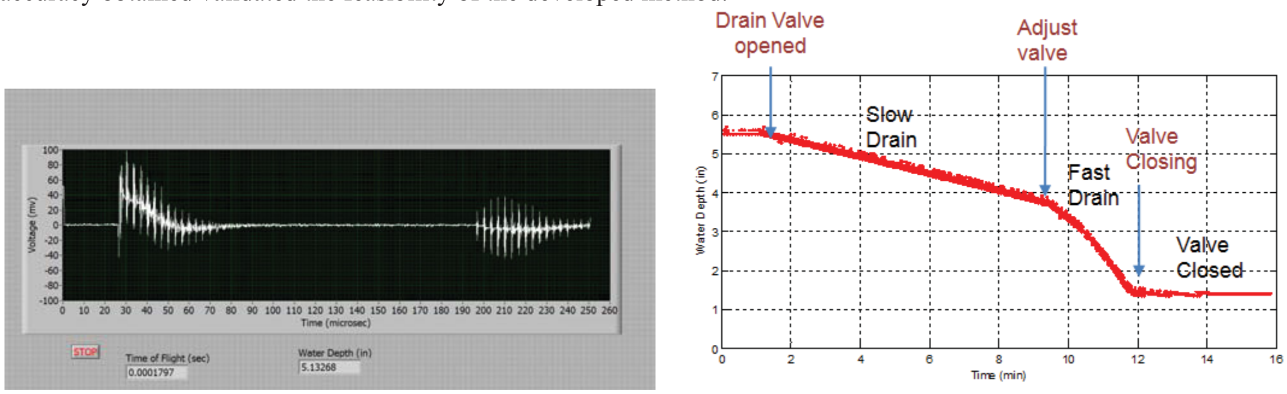


Figure 4: The time-of-flight record generated in real-time (left) and the determined water height for fast and slow draining rates (right).

3.1 Surface perturbation and bubbles interference

Using the developed self-measurement algorithm for determining the height in real-time, the capability to handle surface and bulk interferences was tested. For this purpose, surface perturbations were introduced by shaking the surface, rocking the container, and by introducing bubbles into the path of the acoustic wave. The test setup consisted of a pipe segment that was covered from its two sides by welded plates to form a container shape that allows direct access from the top surface. A schematic view of the cross-section of the test setup is shown in **Figure 5** (left) and **Figure 5**(right) shows a hose that introduced bubbles into the path of the wave inside the water.

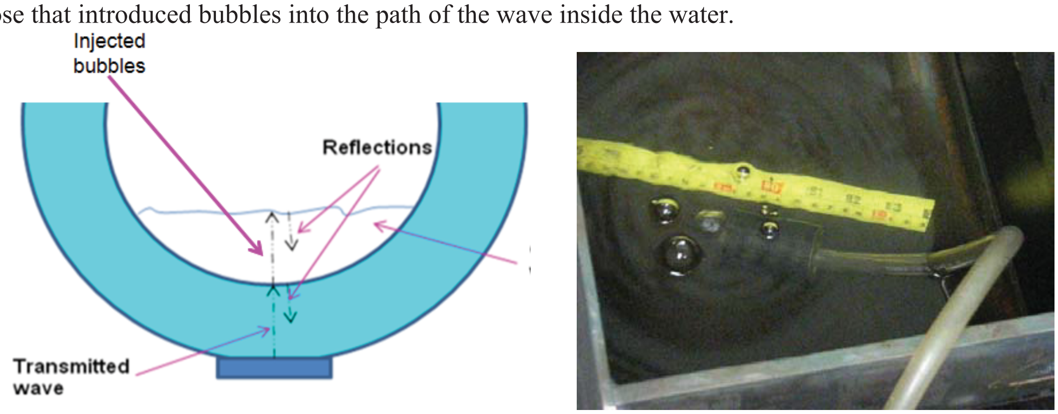


Figure 5: The cross-section illustration of the test setup (left) and the bubbles that were introduced into the water via the shown hose (right).

Each test consisted of one minute of water at "rest", one minute of perturbation (bubbling or shaking) and one minute of water at "rest" again. The data was acquired while calculating a moving average while excluding the outlier data. The bubbles were generation at the rate of ~3 bubbles per second and the surface wobbling was done at a rate of 2-3 Hz. The bubbles introduction consisted placing an air tube 1.3 cm (0.5 inch) from the bottom of the pipe surface and the example of generating bubbles 2.5 cm (1 inch) away from the wave path is shown in **Figure 6**. A noisy data was acquired in the window of time that the perturbation was introduced but the running average provided a reasonable accuracy of the water height measurement. Similar results were observed when introducing bubbles at various locations along the wave path as well as the direct shaking of the water surface by placing a small bowl into the water surface and raising and lowering it manually away from the water path.

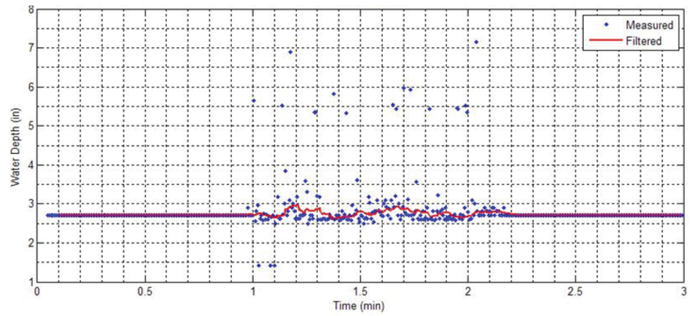


Figure 6: The water height data obtained during surface rest and perturbation from bubbles that were generated 0.5” from the bottom of the pipe at 1” away from the ultrasonic wave path.

4.0 High temperature tests

In order to simulate the condition of 250°C, a high temperature chamber was used consisting of oven Model 6680 (made by Blue M). The HT testbed consisted of the container shape pipe section that was mentioned earlier. This container was filled with safflower oil, which is able to sustain high temperatures, as a substitute for condensed water. Using this test setup, tests could be performed at high temperatures while avoiding the need to deal with the hazards of high pressure that would be generated if water in a closed chamber is used. HT transducers (made by Sigma Transducers, Richmond, WA) with a resonance frequency of 1.0, 2.25 and 5 MHz and with 12.7 cm (0.5 inch) diameter HT transducers were tested. Tests were performed using a 5MHz transducer but the attenuation inside the safflower oil was found to be too high to allow for good height measurement accuracy. Since the selected oil is only a temporary solution for the need to simulate condensed water a lower frequency transducer was used for this stage of feasibility study and will be replaced with 5MHz when it will be applied to the actual pipe test. Using a 2.25 MHz transducer an adequate resolution and sensitivity was observed providing a reasonable compromise.

The setup with the HT transducer was subjected to 250°C for 2.5 hours, kept at 250°C for 2 hours, and then cooled to room temperature in about 2.5 hours. Since oil has low heat conduction there was a need to assure that the temperature inside matches the chamber as closely as possible. For this purpose, a thermocouple was inserted into the oil and tracked the temperature as it has risen. The height of the safflower was measured while tracking the temperature of the chamber and the oil and the results are shown in **Figure 7**. During the increase and decrease of the temperature, the setup was checked every 50°C. The section missing data points near the middle of the height readings was due to a temporary loss of couplant, which was caused by its depletion due to the heat and pressure to keep in place by the mounting fixture. The problem was fixed by opening the chamber and replenishing the interface with additional couplant. As can be seen from the graph in **Figure 7**, once the couplant addition was made the readings were resumed with no problems. As far as the reading of the oil temperature, the thermocouple was removed at approximately 175°C because our portable thermocouple is limited to this range (this is the reason for the N/A under the 200°C reading). Given the observed correctness of measured temperatures and the fact that we kept the test at 250°C for 2.5 hours, it is believed that the temperature of 250°C was reached. With the current setup the amplitude at 250°C was visible but the current data acquisition was not able to perform the measurement and it will be improved in a follow on study.

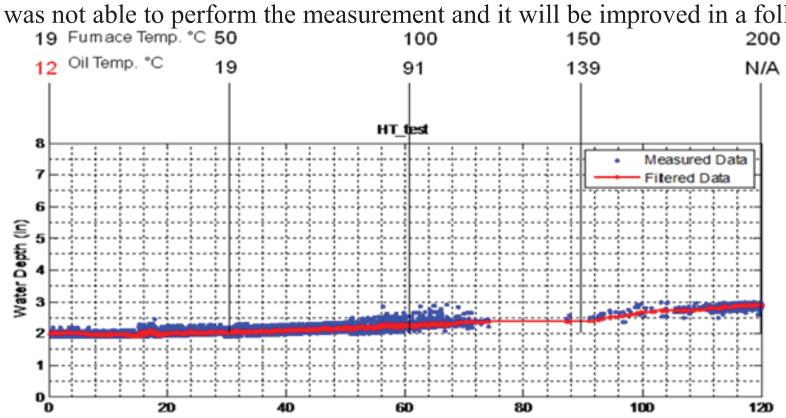


Figure 7: The measured height as a function of time and the temperature in the oven and the safflower oil. The blue dots are the readings and the red line is the running-average of the determined data.

5.0 Conclusions

The feasibility of a health monitoring system was demonstrated to measure the condensed water height in a steam pipe and established the capability to operate as a means of prevent potential failures in steam pipes. The elements that are at low technology readiness level (TRL) and the required efforts to establish the critical capabilities were investigated. Testbeds for performing measurements at room temperature and inside a chamber at 250^{o}C were developed and used to perform the required tests. It was demonstrated that Pulse-Echo ultrasonic testing at room temperature provides an average difference (measured – calculated) of 3.3% in determining the water height thru the pipe wall. The height was measured in the range of 2.5 to 12.7 cm (1.0 to 5.0 inches). The developed test method consists of acquiring the reflections and performing autocorrelation analysis to determine the time-of-flight of the signal from the bottom inner side of the pipe to the top surface of the water. Initially, the data acquisition was done on a digital scope and manually transferring the data to a computer for processing. Once the concept was proven, the process was enhanced for real-time operation to allow testing the effect of water surface disturbances and presence of bubbles, simulating the expected conditions inside the pipe in field conditions. These tests were quite successful where in spite of the surface perturbations good accuracy was obtained. Additionally, the height was tracked as the water was drained and the measurements were found quite accurate. For testing the operation at 250^{o}C, flat Pulse-Echo transducers that are 12.7 cm (0. Inch) diameter and 1.0, 2.25 and 5 MHZ resonance frequencies were used. Safflower oil provided a replacement for the condensed water in order to avoid safety issues related to steam and high pressure. Even though the use of 5.0 MHz was found quite effective in providing a reasonable sensitivity and resolution, due to the high attenuation in the oil the high temperature tests were made via a 2.25 MHz transducer. Tests at as high as 250^{o}C were made and while the amplitude dropped sufficient reflections amplitude was received from the top surface of the oil and the transducer did not sustain any damage even though the process took at least 7.5 hours with 2.5 hours at 250^{o}C. In a follow-on study, it is planned to enhance the amplitude of the measured signals and the data acquisition process in order to be able to acquire reflections that would provide automated monitoring capability at 250^{o}C.

6.0 acknowledgement

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