



Original Article

High-temperature ultrasonic thickness monitoring for pipe thinning in a flow-accelerated corrosion proof test facility

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ABSTRACT

In order to monitor the pipe thinning caused by flow-accelerated corrosion (FAC) that occurs in coolant piping systems, a shear horizontal ultrasonic pitch-catch waveguide technique was developed for accurate pipe wall thickness monitoring. A clamping device for dry coupling contact between the end of the waveguide and pipe surface was designed and fabricated. A computer program for multi-channel on-line monitoring of the pipe thickness at high temperature was also developed. Both a four-channel buffer rod pulse-echo type and a shear horizontal ultrasonic waveguide type for high-temperature thickness monitoring system were successfully installed to the test section of the FAC proof test facility. The overall measurement error can be estimated as $\pm 10 \mu\text{m}$ during a cycle from room temperature to 200°C .

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1. Introduction

Local thinning in a carbon steel pipe caused by flow-accelerated corrosion (FAC) may occur inside the elbows and a crack or leakage may evolve, which is an important safety issue for ensuring the structural integrity of coolant systems [1–4].

Currently, the manual ultrasonic thickness gauge method is used to measure the FAC in the carbon steel piping in nuclear power plants. The ultrasonic method is a well-known and commonly used nondestructive testing technique to determine the thickness of the piping. However, a manual ultrasonic method reveals several disadvantages: inspections have to be performed during shutdowns with possible consequences of prolonging the down time and increasing the production losses, the insulation has to be removed and replaced for each manual measurement, and scaffolding has to be installed in inaccessible areas, resulting in considerable cost for intervention. In addition, the manual ultrasonic thickness measurement method is inefficient from the viewpoint of data reliability. The thickness data at each shutdown period can be scattered owing to the differences in ultrasonic examiners, ultrasonic devices, and data reading conditions, such as the temperature and ultrasonic coupling medium.

To characterize pipe wall thinning, cracking, and leakage from FAC, there is a need to monitor the pipe wall thickness at a high temperature with high accuracy. Conventional ultrasonic thickness measurement techniques cannot be applied to high temperatures of above 200°C , because conventional piezoelectric materials become depolarized at temperatures above the Curie temperature, and the difference in thermal expansion of the piezoelectric materials, coupling medium, and test pieces may cause a failure. Special piezoelectric transducers for specific use at high temperatures have been developed [5–10].

To solve the problems occurring in the propagation of ultrasound at high temperature, one of the possible methods is to put a buffer rod or waveguide (delay line) between the ultrasonic transducers and test pieces [11–15]. In the case of an ultrasonic waveguide technique, the dispersion characteristics of ultrasonic modes of the waveguide during the propagation of an ultrasonic wave should be considered [16]. The shear horizontal vibration mode was chosen because of no dispersion characteristics when the wave propagates in the plate.

An ultrasonic wall thickness monitoring technique using a shear horizontal waveguide has been developed. A dry clamping device with a solid coupling medium for the acoustic contact between the waveguide and pipe surface was designed and fabricated. The shear horizontal waveguides and clamping device result in an excellent S/N (signal to noise) ratio and high measurement accuracy with long

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exposure under elevated temperature conditions. In addition, a computer program for multi-channel on-line monitoring of the pipe thickness at high temperature was developed. The software is integrated to expand up to four channels to monitor several points of the pipe simultaneously, such as intrados and extrados points at the bent region of a pipe. The system has been successfully implemented to monitor the pipe thinning in an FAC proof test facility after a verification test for a long period of time.

2. Considerations for high-temperature ultrasonic thickness measurements

An ultrasonic thickness measurement is typically performed by measuring the transit time between consecutive echoes in a time domain. The thickness of the test piece can be determined using a known value of ultrasonic velocity combined with the transit time. Assuming that there is minimal ultrasonic dispersion, a sharper ultrasonic signal will increase the resolution of the measurement. In general, the most accurate way to perform a temporal measurement is to measure the peak to peak time or to perform pulse-echo overlaps [17]. Because the wall thinning in the carbon steel pipe is generally less than a few tens of μm per year, the measurement error should be kept at a minimum, possibly in the range of μm . Several sources of error in the measurement of the thickness reduction in a pipe can be pointed out: i) an error in the determination of the peak position of ultrasonic waveforms; ii) errors of ultrasonic velocity in the test pieces owing to a temperature variation or differences in temperature; iii) errors due to the measurement conditions between ultrasonic transducers and test pieces, such as ultrasonic coupling medium, contact pressure and other environmental factors; iv) errors due to the geometrical factors, such as surface roughness and curvature of the test piece; and v) errors due to the digital signal processing, such as the capability of an analog-to digital converter, or delay by the digital signal processing [18].

Conventional piezoelectric ultrasonic transducers cannot be used at high temperatures because the piezo-ceramics become depolarized at temperatures above the Curie temperature. In addition, as the temperature increases, the signal quality of the piezoelectric transducer can be degraded and an error in determining the peak position of the signals increases. To assure the acoustic contact between the ultrasonic transducer and test pieces at high temperature, a solid type ultrasonic coupling medium should be placed. Occasionally, acoustic contact between the ultrasonic transducer and the test pieces could fail due to the differences in thermal expansion coefficients when the pipe experiences thermal cycling during the plant operation.

3. Development of a high-temperature ultrasonic monitoring system for determination of pipe thinning

3.1. Development of high-temperature ultrasonic thickness monitoring system with buffer rods

High-temperature ultrasonic thickness measurements can be accomplished through the insertion of a buffer rod between the ultrasonic transducer and the pipe, as shown in Fig. 1. The materials for the buffer rod should be acoustically stable and thermally shielded to prevent the temperature rise of the ultrasonic transducer during high-temperature operation. In addition, a general ultrasonic coupling medium, such as glycerin or machine oil, cannot be used for a high-temperature applications. A special solid coupling medium, such as a thin gold plate, is required to keep a good acoustic contact between the buffer rod and test pieces. The main problem of this technique is to maintain a good performance

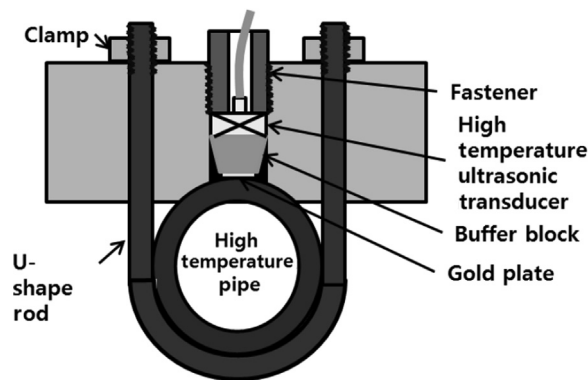


Fig. 1. Schematic drawing of an ultrasonic transducer assembly for high-temperature pipe thinning. The assembly consists of a high-temperature ultrasonic transducer, buffer rod, clamping device, and solid coupling medium for an acoustic contact.

for a long period of heat cycling operation. Occasionally, the ultrasonic energy transfer between the transducer and test piece fails due to a degraded or broken acoustic contact. Fig. 2 shows four-channel high-temperature ultrasonic transducers assembled to a test pipe for the thickness monitoring.

3.2. Development of high-temperature ultrasonic thickness monitoring system with waveguides

Another approach for an ultrasonic thickness measurement at high temperature is using an ultrasonic waveguide. To reduce the probability of acoustical breakage between the ultrasonic transducer and test pieces, an improved approach, an ultrasonic strip waveguide method, was attempted. A pair of shear horizontal transducers and strip waveguides were designed and fabricated. The shear horizontal vibration mode was chosen for proper ultrasonic energy transfer in the strip waveguides. Because the shear horizontal vibration modes in the plate show no dispersion characteristic, i.e., a constant wave velocity within a certain frequency range, the ultrasonic signal in the time domain is sharp and clear. This vibration mode gives an advantage in acquiring sensitive and accurate experimental data at high temperatures [19].

The shear wave transducers are attached to the edge of the waveguides. A 12.5-mm diameter ultrasonic shear transducer was coupled to the far end of the waveguide to excite and receive the shear horizontal mode. It was coupled by a shear coupling medium facing cross section of the strip. The polarization direction of the transducer should be aligned parallel to the width of the strip. A clamping device was designed and fabricated, which could attach two parallel strip waveguides with a separation of 1 mm to the plate, as shown in Fig. 3.

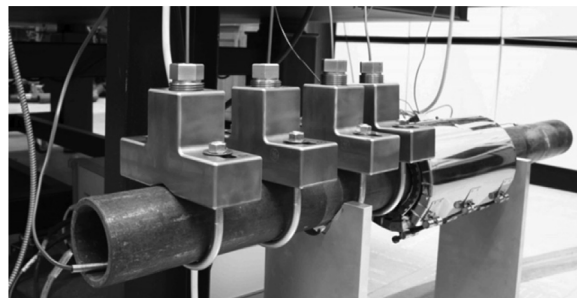


Fig. 2. High-temperature ultrasonic transducers were assembled on a pipe for thickness monitoring.

Compared to the pulse-echo techniques, the signal amplitude from the pitch-catch technique with a pair of strip waveguides is quite high and also results in a high S/N ratio. Because the receiving strip waveguide only receives signals that have been transmitted into the pipe specimen, it avoids pollution from unwanted reflection from the strip end. It should be noted that the signal clarity and transmission through the joint without considerable distortion is much more important than the transmitted amplitude [16].

To measure the flight time of the reflection, moving gates are set in the real-time acquisition system. The first gate is set to the signal from the end of the transmitting waveguide. The second gate is set to the first back wall echo signal, and the third gate set to the second back wall echo signal. The second and third gates are set as moving gates to follow the first gate setting. The peak position of the first and second back wall echoes are automatically determined as the flight time, and are denoted as t_1 and t_2 in Fig. 4.

Because the pitch-catch method shows no main bang signal and a very weak signal from the end of the transmitting waveguide, multiple reflection signals from the back wall of the pipe show a clear pattern and high S/N ratio. The signal from the end of the transmitting waveguide can be characterized for the condition of ultrasonic energy transfer from the waveguide to the pipe, in other words, the condition of acoustical contact between

the waveguide and pipe. The shear horizontal wave velocity of carbon steel is approximately 3,250 m/s, and the flight time to reflect from a 300 mm long strip waveguide is estimated as 180 microseconds. The flight time between the first back-wall and second back-wall of the 6 mm thick pipe is estimated as 3.7 microseconds.

The ultrasonic radiofrequency (rf) waveform in the time domain was acquired and processed for display on a PC screen. Because an ultrasonic rf waveform can deteriorate at high temperatures, the acquired ultrasonic signals were processed to obtain a higher S/N ratio. In addition, the system can check the signal quality and was designed to show an alarm marker when an unwanted signal is acquired and displayed on the screen. To obtain accurate thickness data, the flight time, t_1 and t_2 , was automatically determined and averaged several hundred times.

Because the ultrasonic velocity is a function of temperature, variation in the ultrasonic wave velocity at high temperature can be a major source of errors. High-temperature thickness monitoring devices require a prior calibration to reflect the relationship between the ultrasonic velocity and temperature. The shear wave velocity data at each temperature are determined from the flight time data at each temperature with an assumption of the known thickness. Fig. 5 shows the relationship between the shear horizontal wave velocity in the carbon steel pipe and temperature [20]. Based on the flight time data and calibration relationship

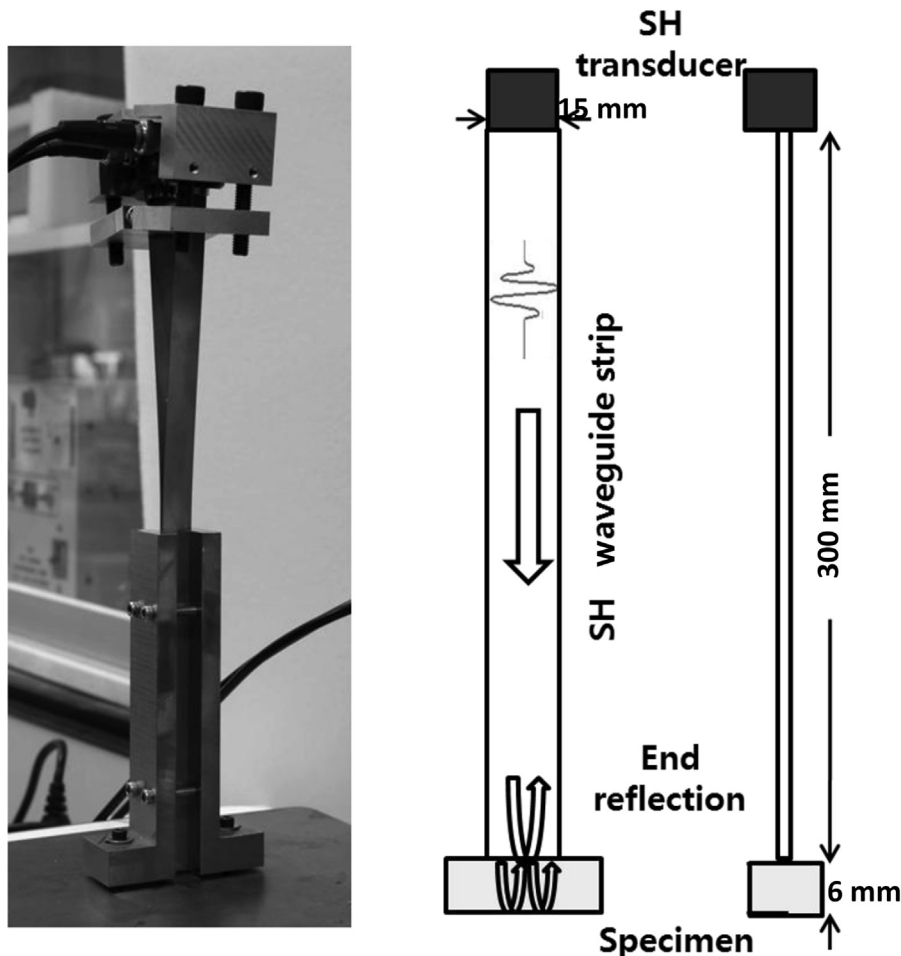


Fig. 3. Design of a pair of waveguides for high-temperature thickness monitoring (right) and an assembly of pitch-catch type ultrasonic transducers with a pair of strip waveguides (left). SH (shear horizontal).

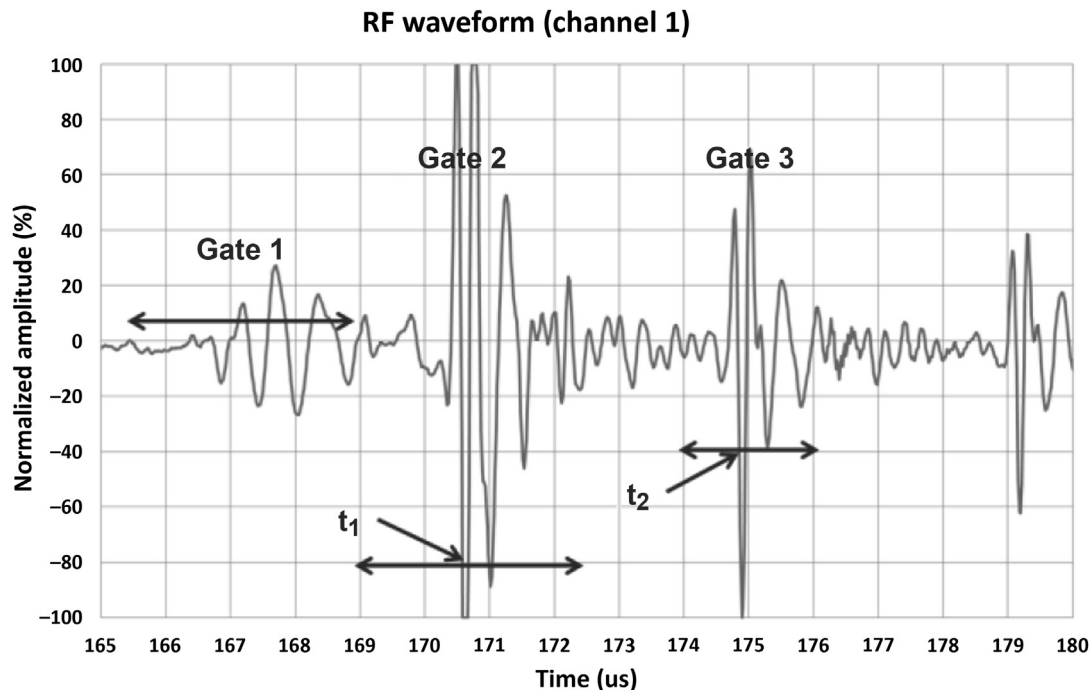


Fig. 4. Typical ultrasonic back wall echo signals with moving gates. The signal acquired using pitch-catch type ultrasonic transducers with a pair of strip waveguides. Signals with low amplitude at the end-reflection in Gate 1 and high amplitude from the back-wall in Gate 2 and Gate 3 are shown. RF (radio frequency).

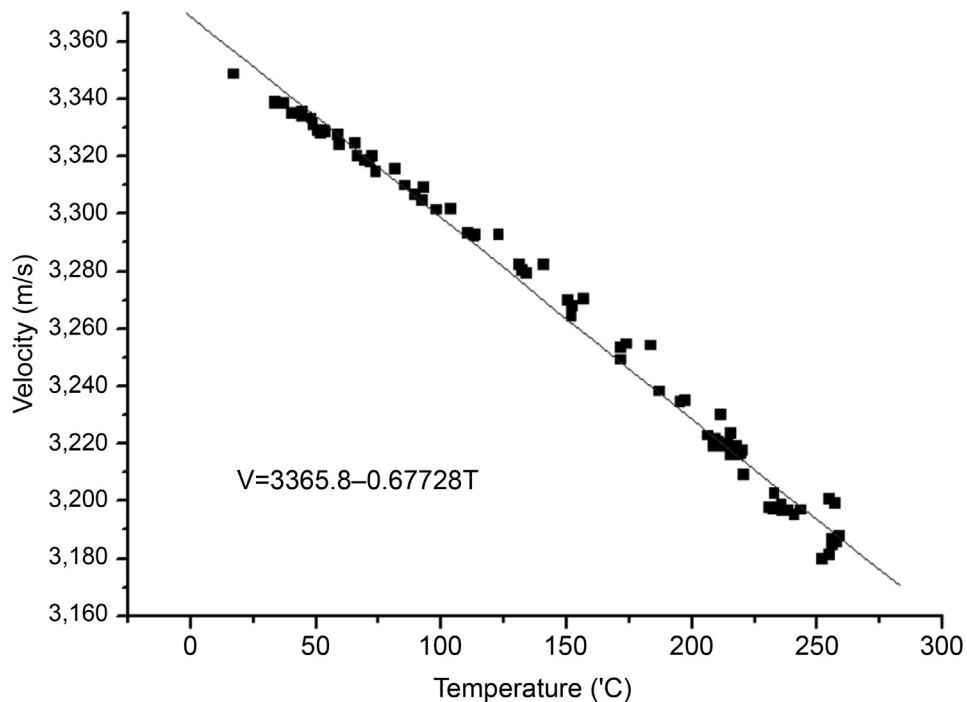


Fig. 5. Calibration of shear wave velocity with temperature of carbon steel SA 106.

between the shear wave velocity and temperature, the wall thickness is determined at the designated temperature and displayed periodically.

A single-channel ultrasonic thickness monitoring system developed for the laboratory test was expanded into a multi-channel ultrasonic thickness monitoring system for implementation to the FAC proof test facility. Fig. 6 shows the concept of

improvement from a single-channel to a multichannel ultrasonic thickness monitoring system.

A four-channel ultrasonic multiplexer (Model OPMUX 12.0, OPTTEL Sp., Poland) and an A/D (analog-to-digital) converter with an industrial PC were used. Two shear wave transducers with a frequency of 5 MHz were used for the pitch-catch technique; one for the ultrasonic transmission, and the other for ultrasonic reception.

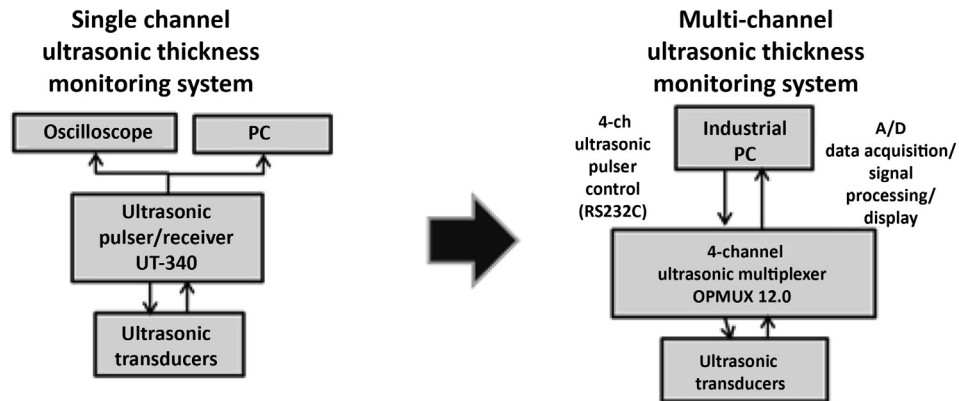


Fig. 6. Block diagram showing improvement from single-channel to multi-channel ultrasonic thickness monitoring system. A/D (analog-to-digital); PC (personnel computer).

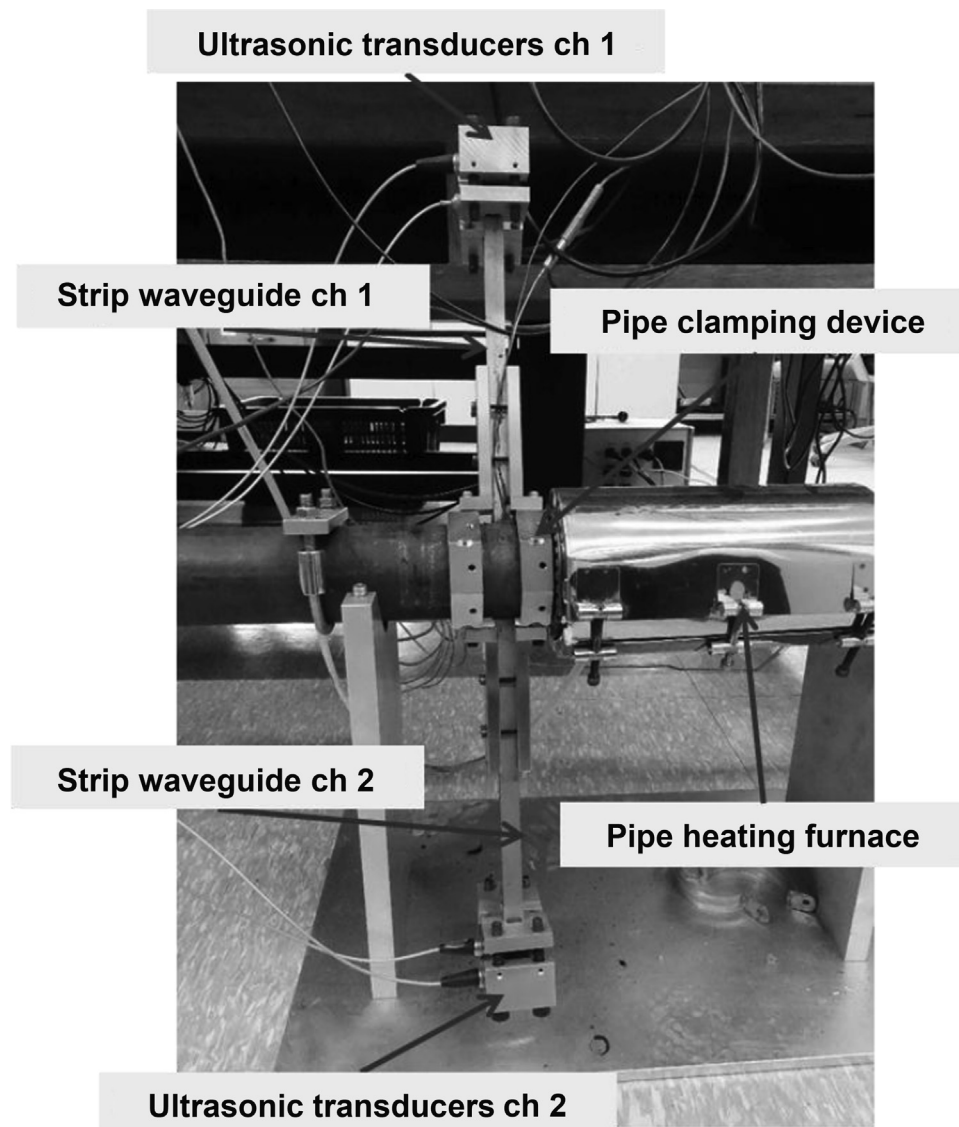


Fig. 7. A setup for a long-term high-temperature experiment during the development stage. Two channel pitch-catch waveguides, a pipe clamping device, and a test pipe with a portable furnace are shown. Ch. (channel).

The pitch-catch strip waveguide method shows many advantages to a conventional pulse-echo method, such as no main bang signal, and a weak signal from the end of the transmitting waveguide.

A computer program and hardware setup for a multi-channel ultrasonic thickness monitoring system was developed with an integration of the waveguides and shear horizontal transducers. All information on the high-temperature ultrasonic thickness monitoring system can be displayed on a PC monitor. The display contains information on the ultrasonic signal acquired in real time, including the gate setting and various parameters. It also shows the thickness readout with the designated time intervals, ultrasonic flight time, and real-time temperature reading at the point of measurement.

For the laboratory test of the long-term high-temperature experiment, a furnace with circular heating elements was installed in the pipe, and the temperatures of several points on the pipe were measured using thermocouples, as shown in Fig. 7.

4. Implementation to FAC proof test facility

Both a four-channel buffer rod type high-temperature ultrasonic thickness monitoring system and a multi-channel ultrasonic waveguide high-temperature thickness monitoring system are installed in the test section of the FAC proof facility, as shown in Fig. 8.

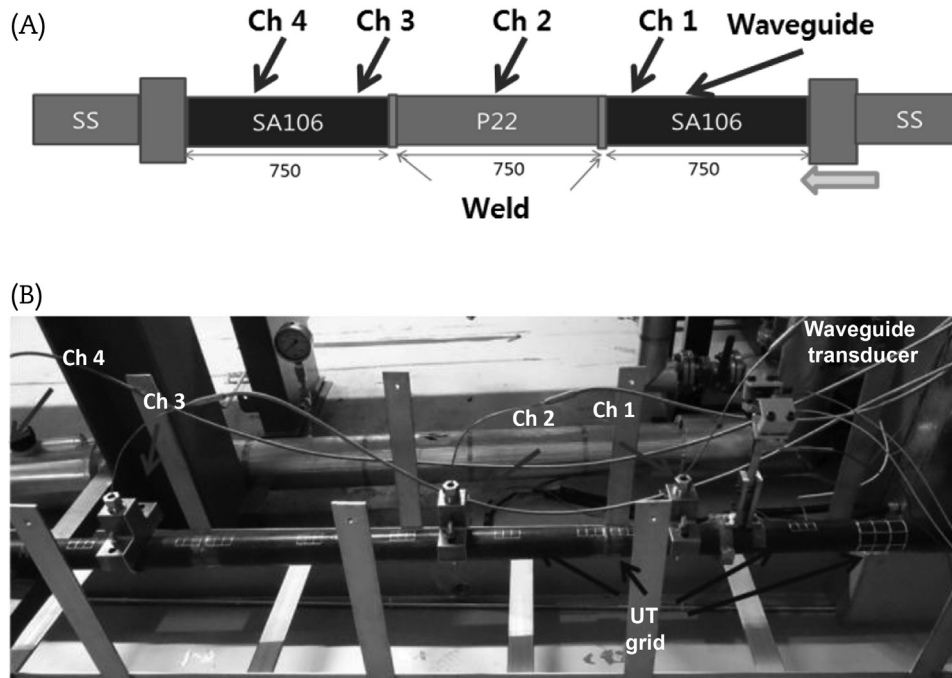


Fig. 8. A schematic drawing of the configuration (A) and photo (B) showing the four-channel buffer rod type ultrasonic transducers and a shear horizontal waveguide type transducer installed on the test section pipe in the flow-accelerated corrosion (FAC) proof test facility. Ch. (channel); SS (stainless steel); UT (ultrasonic testing).

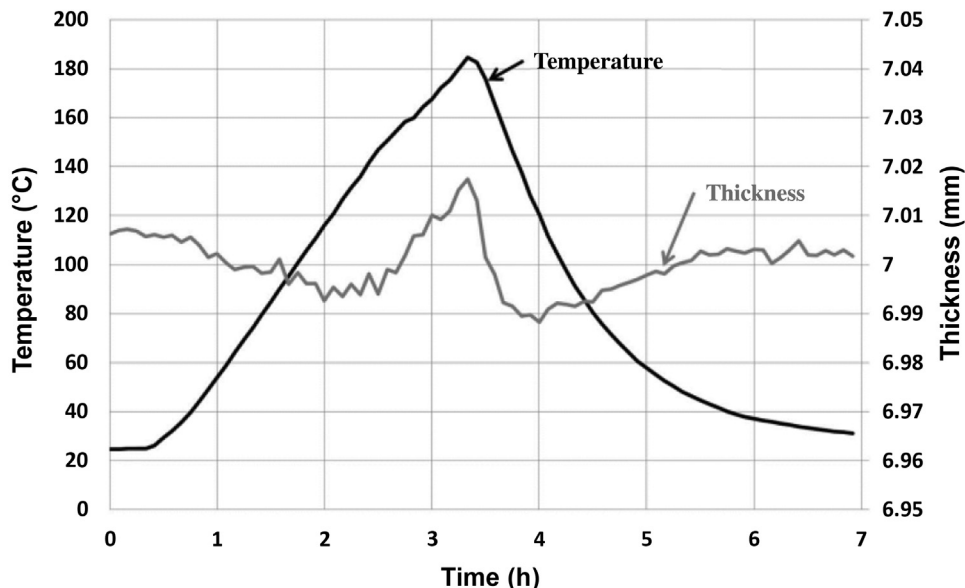


Fig. 9. Measurement error with temperature variation. The overall measurement error can be estimated as $\pm 10 \mu\text{m}$ during a cycle from room temperature to approximately 200°C .

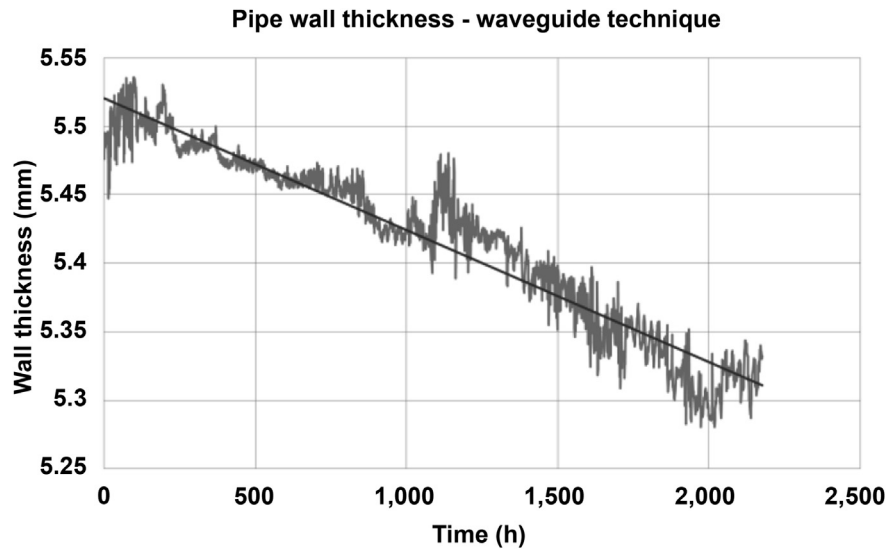


Fig. 10. Pipe wall thickness monitoring data acquired from the long-term operation of the FAC proof test facility: pipe wall thickness reduction determined by a shear horizontal ultrasonic waveguide pitch-catch technique.

The straight type test section consists of three parts; two carbon steel pipes (SA106 Gr. B) and a low alloy steel pipe (P22) in the middle, where the dimensions of each pipe are an outer diameter of 60.4 mm, nominal wall thickness of 5.54 mm, and length of 750 mm. Three parts of the test section are welded and grounded. Four-channel buffer rod high-temperature transducer assemblies were installed on the outer surface of the carbon steel pipes (SA106 Gr. B) and stainless steel pipe (P22), as shown in Fig. 8. In addition, a multi-channel ultrasonic waveguide type transducer assembly was installed to the outer surface of the first carbon steel pipe.

One of the key issues for a successful implementation of the FAC proof test facility is to ensure the stable performance of the ultrasonic transducers at high temperature for a long period of time. In particular, one of the most important factors is the mechanical and acoustical integrity between the strip waveguides, a solid coupling medium (i.e., gold plate with thickness of 100–200 μm), and the clamping devices. The multi-channel

ultrasonic transducer assembly was installed on a test pipe and the ultrasonic signals were acquired for a long period of time at high temperature.

Three gates were set to cover the ultrasonic signals, and the flight time was determined at the position of the maximum amplitudes when exceeding the threshold values. A computer program was developed to determine the flight time at the point of t_1 in gate 2 and t_2 in gate 3, and the difference between the flight times were converted into the distance, in other words, the thickness of the pipe. The temperature dependences of the shear wave velocity were calibrated as shown in Fig. 5. Measurement errors were minimized by a moving gate control with a temperature variation, normalization of the signal amplitude, automatic determination of the ultrasonic flight time, and temperature compensation. The overall measurement error can be estimated as $\pm 10 \mu\text{m}$ during a cycle from room temperature to approximately 200°C , as shown in Fig. 9.

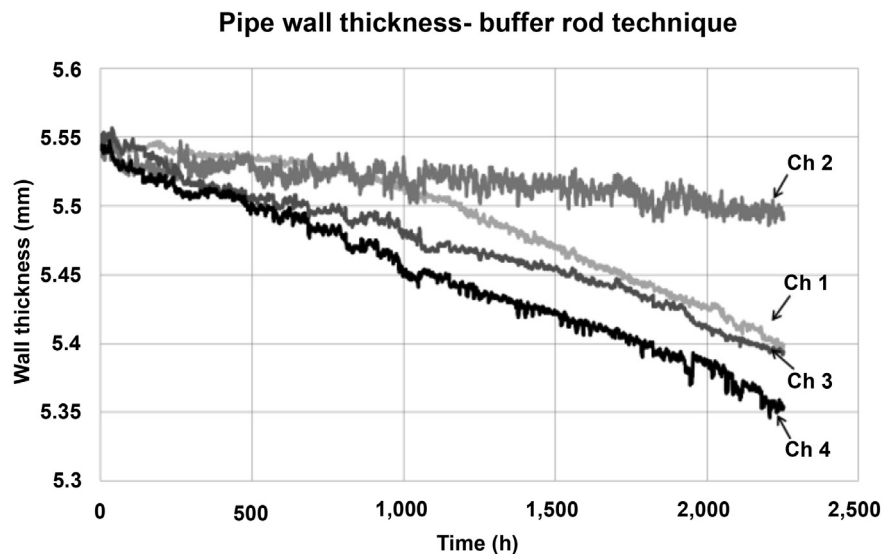


Fig. 11. Pipe wall thickness monitoring data acquired from the long-term operation of the flow-accelerated corrosion (FAC) proof test facility: pipe wall thickness reduction determined using a buffer rod pulse-echo technique.

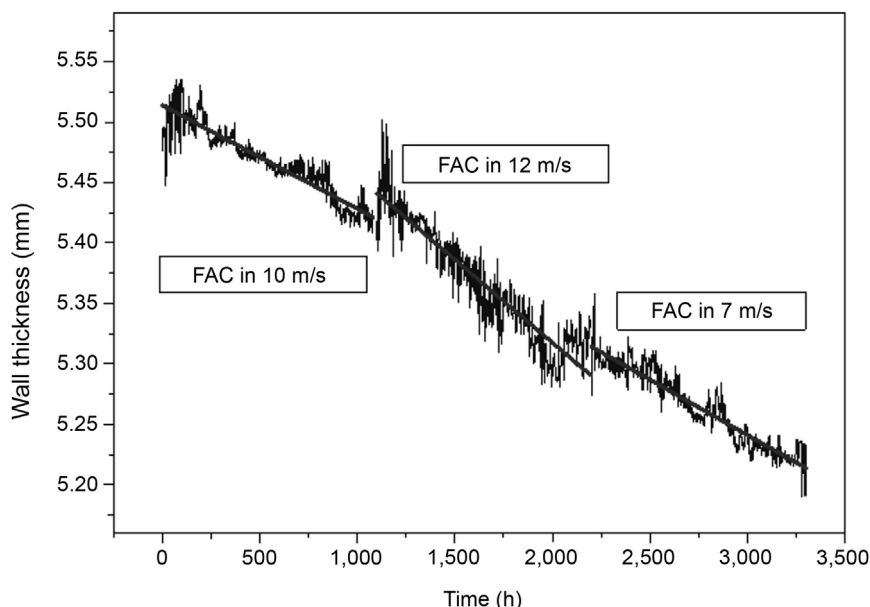


Fig. 12. Pipe wall thickness monitoring of carbon steel piping in the flow-accelerated corrosion (FAC) proof test facility: different wall-thinning ratios observed depending on the flow velocities.

Fig. 10 shows pipe wall-thinning data acquired from an operation of approximately 2,300 h. The temperature of the coolant flowing in the pipe was maintained at 150°C, but measured at the pipe surface as $\approx 130^\circ\text{C}$. The wall thickness reduction of $\approx 200\ \mu\text{m}$ was determined by using the waveguide pitch-catch technique.

The four-channel buffer rod pulse-echo technique was also implemented in the FAC proof test facility. Fig. 11 shows typical data acquired from an operation of approximately 2,300 h. It shows a reduction of the pipe wall thickness: Channel 1 at the position of carbon steel pipe A (SA106 Gr. B), Channel 2 at the position of low alloy steel (P22), and Channel 3 and Channel 4 at the position of carbon steel pipe B (SA 106 Gr. B), as shown in Fig. 8. The amount of wall thickness reduction can be estimated as approximately 150–200 μm at different positions of the carbon steel pipe and approximately 30 μm at the low alloy steel pipe. The amount of wall thickness reduction determined by the waveguide pitch-catch technique and buffer rod pulse-echo technique are consistent with some variations depending on the locations. The amount of pipe wall thinning in the low alloy steel is less than that of carbon steel. This fact is quite reasonable, and is attributed to the difference in Cr content in alloy, i.e., 0.04 wt% in carbon steel and 0.2 wt% in low alloy steel.

Fig. 12 shows a variation of the pipe wall-thinning rate, or slope of the wall thickness reduction, depending on the flow velocity. It shows three stages with different flow velocities: 10 m/s, 12 m/s, and 7 m/s for approximately 1,000 h each. As the flow velocity increases from 7 m/s to 12 m/s, the wall-thinning rate increases. This observation is also consistent with the fact that the wall-thinning rate is proportional to the flow velocity.

It should be noted that the on-line high-temperature pipe wall thinning monitoring system was successfully implemented in the FAC proof test facility. The system verified a stable operation at a temperature cycling up to 200°C for several months. It also shows a superior performance compared with other similar systems, which kept the measurement error at less than $\pm 10\ \mu\text{m}$. The system can be applied to the monitoring of pipe thinning or wall thickness measurement in any industrial applications, as well as in nuclear power plants.

5. Conclusions

A shear horizontal ultrasonic pitch-catch waveguide technique was developed for accurate pipe wall thickness monitoring in the FAC proof test facility. A clamping device for dry coupling contact between the end of the waveguide and pipe surface was also designed and fabricated. A computer program for multichannel online monitoring of the pipe thickness at high temperature was developed.

Measurement errors were minimized using a moving gate control with temperature variation, normalization of the signal amplitude, automatic determination of the ultrasonic flight time, and temperature compensation capabilities. The overall measurement error can be estimated as $\pm 10\ \mu\text{m}$ during a cycle from room temperature to approximately 200°C.

Both a four-channel buffer rod type high-temperature ultrasonic thickness monitoring system and a multi-channel ultrasonic waveguide high-temperature thickness monitoring system were successfully installed in the test section of the FAC proof test facility. The system verified stable operation at a temperature cycling of up to 200°C for several months and shows a superior performance over other similar systems. The system can be applied to high-temperature thickness monitoring in any industrial applications, as well as in nuclear power plants.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

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References

- [1] D. Kim, Y. Cho, J. Lee, Assessment of wall-thinning in carbon steel pipe by using laser-generated guided wave, *Nucl. Eng. Tech.* 42 (2010) 546–551.

- [2] H.S. Chung, A review of CANDU feeder wall thinning, *Nucl. Eng. Tech.* 42 (2010) 568–575.
- [3] Y.H. Choi, S.C. Kang, Evaluation of piping integrity in thinned main feedwater pipes, *J. Kor. Nucl. Soc.* 32 (2000) 67–76.
- [4] F. Inada, Japanese pipe wall thinning management based on JSME rules and recent R&D studies to enhance the rules, in: IAEA Technical Meeting/Workshop on E/C Including FAC and EAC Issues in NPP, April 2009.
- [5] A. Macnab, K.J. Kirk, A. Cochran, Ultrasonic transducers for high temperature application, *IEE. Proc. Sci. Meas. Tech.* 145 (1998) 229–236.
- [6] A. Megrich, L. Lebrun, M. Troccaz, Materials of $\text{Bi}_4\text{Ti}_3\text{O}_{12}$ type for high temperature acoustic piezo-sensors, *Sens. Actuators A* 78 (1999) 88–91.
- [7] K.T. Wu, M. Kobayashi, C.K. Jen, Integrated high-temperature piezoelectric plate acoustic wave transducers using mode conversion, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 56 (2009) 1218–1224.
- [8] R. Kazys, A. Voleisis, R. Sliteris, B. Voleisiene, L. Mazeika, P.H. Kupschus, H.A. Abderrahim, Development of ultrasonic sensors for operation in a heavy liquid metal, *IEEE Sens. J.* 6 (2006) 1134–1143.
- [9] A. Baba, C.T. Searfoss, B.R. Tittermann, High temperature ultrasonic transducer up to 1000°C using lithium niobate single crystal, *Appl. Phys. Lett.* 97 (2010) 232901.
- [10] R. Kazys, V. Voleisis, B. Voleisiene, High temperature ultrasonic transducers: review, *Ultrasound* 63 (2008) 7–17.
- [11] W.J. Zhou, M.N. Ichchou, J.M. Mencik, Analysis of wave propagation in cylindrical pipes with local inhomogeneities, *J. Sound Vib* 319 (2009) 335–354.
- [12] N. Nurmalia, H. Nakamura, M. Ogi, K. Hirao, Nakahata, Mode conversion behavior of SH guided wave in a tapered plate, *NDT E Int.* 45 (2012) 156–161.
- [13] F. Honarvar, F. Salehi, V. Safavi, A. Mokhtari, A.N. Sinclair, Ultrasonic monitoring of erosion/corrosion thinning rates in industrial piping systems, *Ultrasonics* 53 (2013) 1251–1258.
- [14] R. Carandente, A. Lovstad, P. Cawley, The influence of sharp edges in corrosion profiles on the reflection of guided waves, *NDT E Int.* 52 (2012) 57–68.
- [15] L.A. Francis, J.M. Friedt, P. Bertrand, Influence of electromagnetic interferences on the mass sensitivity of Love mode surface acoustic wave sensors, *Sens. Actuators A* 123–124 (2005) 360–369.
- [16] Y.M. Cheong, H.P. Kim, D.H. Lee, A shear horizontal waveguide technique for monitoring of high temperature pipe thinning, in: Trans. Korean Nuclear Society Spring Meeting, May 2014.
- [17] S. Dixon, C. Edwards, S.B. Palmer, High accuracy non-contact ultrasonic thickness gauging of aluminum sheet using electromagnetic acoustic transducers, *Ultrasonics* 39 (2001) 445–453.
- [18] Y.M. Cheong, H.N. Kim, H.P. Kim, An ultrasonic waveguide technique for on-line monitoring of the high temperature pipe thinning, in: Trans. Korean Society for Non-destructive Testing Spring Conf., May 2013.
- [19] F.B. Celga, P. Cawley, J. Allin, J. Davies, High-temperature (>500°C) wall thickness monitoring using dry-coupled ultrasonic waveguide transducers, *IEEE Trans. Ultrason. Ferroelectric. Freq. Control* 58 (2011) 156–167.
- [20] Y.M. Cheong, J.H. Kim, J.H. Hong, H.K. Jeong, Measurement of dynamic elastic constants of rpv steel weld due to localized microstructural variation, *J. Korean Soc. Non-Destructive Test.* 20 (2001) 559–564.