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Online Monitoring of Pipe Wall Thinning by Electromagnetic Acoustic Resonance Method

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ABSTRACT

The electromagnetic acoustic resonance (EMAR) method provides accurate and stable evaluation in high temperature environment, and it is an effective tool for online monitoring. In this study, the EMAR method and the superposition of the n-th compression (SNC) for data processing are applied to online monitoring of pipe wall thinning, and the accuracy and reliability of the measurements are demonstrated through field tests using a large-scale corrosion test loop at high temperature. To measure the thickness of pipes with complicated wall thinning, the SNC extracts thickness information from the spectral responses of the EMAR. Results from monitoring test show that EMAR with SNC can evaluate pipe wall thinning with an accuracy of 10 μm at 165ºC. In addition, time evaluation of evaluated thickness decreases monotonically all over the test duration, which indicates high stability of this measurement technique.

KEYWORDS

online monitoring, NDT, EMAR, pipe wall thinning, thickness measurement, signal processing.

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1. Introduction

Pipes in nuclear and thermal power generation facilities are subjected to wall thinning, as they age, due to flow-accelerated corrosion and liquid droplet impingement erosion. The management of pipe wall thinning is therefore a challenge to be addressed. To further enhance safety in maintenance activities, plant operators are required to augment and strengthen their in-service inspections based on online monitoring in addition to other inspections that are heavily conducted during outages. Online monitoring of pipe wall thinning allows us to comprehend and closely evaluate changes in wall thinning with time during plant operation; this is expected to improve equipment reliability and safety.

There have been studies to apply electromagnetic acoustic transducers (EMATs) to the monitoring of pipe wall thinning [1, 2]. EMATs have the advantages of being capable of non-contact measurement and being unsusceptible to the state of test surfaces. They are used also for wall thickness measurement at high temperatures. However, they are lower in electroacoustic efficiency and signal-to-noise (SN) ratio compared with piezoelectric devices.

The electromagnetic acoustic resonance (EMAR) method using EMATs is based on the resonance of ultrasound that propagates in the plate thickness direction, and is capable of amplifying received signals to improve SN ratios[3]. However, there is ultrasound scattering and a decrease of resonance spectra amplitude in thinning areas, where wall thickness varies in a complicated manner. Moreover, multiple resonance frequencies are detected due to unevenness and slope on the bottom surface. This may make the evaluation of wall thickness difficult. The authors therefore proposed superposition of n-th compression (SNC) as an EMAR signal processing method, and evaluated the application of this method to curved surfaces [4].

Another advantage of EMAT monitoring is the easiness of installation. The permanent magnet of the EMAT probe allows installation and fixation on carbon steel pipes that may be subjected to flow-accelerated corrosion. Because of the non-contact nature of measurement, there is no need to

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peel off pipe-surface coating. Furthermore, EMATs that can withstand temperatures as high as 300 to 500°C have been developed [5, 6, 7], which can be installed beneath the heat insulator of piping.

In this study we apply EMAR to the online monitoring of pipe wall thinning under an actual machine's high temperature environment and discuss the possibility of quantitative evaluation of wall thinning. In order to reproduce wall thinning comparable to that of actual pipes by controlling the fluid conditions of pipes to accelerate wall thinning, large-scale equipment for testing pipe wall thinning is used to conduct the online monitoring of pipe wall thinning. We also improve the accuracy of SNC analysis by estimating the wall thickness to be measured and determining the orders of resonance.

2. Electromagnetic acoustic resonance (EMAR) method

2.1. Principles of EMAR

The typical EMAT consists of a coil and a permanent magnet. When radiofrequency burst current is applied to the coil placed on a nonmagnetic conductor specimen, eddy current is induced near the specimen surface. When a static magnetic field perpendicular to the specimen surface is further introduced by the permanent magnet, Ampere force parallel to the specimen surface is generated and a transverse wave having a frequency equal to that of the radiofrequency pulse applied to the coil propagates through the specimen. In the case of a ferromagnetic material specimen, magnetostriction changes cyclically due to the magnetostrictive effect caused by the magnetic field induced by the coil and the static magnetic field induced by the permanent magnet, and ultrasound waves are emitted as a result. Reception of ultrasound waves is conducted in a reverse way by detecting the voltage generated in the coil [8].

Because the sources of vibration and reception exist within the specimen surfaces, it is possible to conduct non-contact measurement. Therefore, a contact medium, which is required in ultrasonic thickness gauges using piezoelectric devices, is not required. In addition, EMATs are less susceptible to coating and rust on specimen surfaces.

An ultrasound burst wave that enters a specimen is reflected repeatedly on both ends of the specimen. When the wavelength is an integral multiple of the propagating distance in the specimen, the phase of the incident wave matches with that of the reflected wave and resonance occurs. The EMAR measurement method uses this phenomenon to improve the SN ratio of the received signals by amplifying echo waves whose amplitude has been attenuated by scattering.

The relationship between resonance frequency and specimen thickness is given by

$$f_n = n \times f_1 = n \times \frac{v}{2d} \tag{1}$$

where f_n is n^{th} resonance frequency, f_1 is fundamental resonance frequency, n is order of resonance, v is shear-wave velocity in the specimen, and d is specimen thickness.

2.2. Signal processing by the SNC method

Figure 1 shows a simulated wall-thinned specimen made of carbon steel SS400. The bottom surface of a plate 150 mm long, 50 mm wide, and 10 mm thick was processed two-dimensionally to form an R-shaped dent 2 mm deep and 70 mm wide as a simulated thinned wall. The sound velocity is 3240 m/s at room temperature. Figure 2 shows the result of EMAR measurement at a location 12.5 mm distant from the center of the dent. Because of the sloped nature of the dent bottom surface, signal intensity is lowered by ultrasound scattering, and resonance frequency peaks are unclear. Although the fundamental resonance frequency is 195 kHz in theory, there are several peaks around this value so it is difficult to determine the fundamental resonance frequency from peak distances.

The SNC method is an analytical method based on the cyclic appearance of resonance frequencies at integral multiples. This means that by reducing the frequency measurement results obtained by the EMAR method by a factor of n, the intensity of n^{th} order frequency f_n can be superimposed on the intensity of the fundamental resonance frequency f_1. Theoretically, for example, reducing the second resonance frequency f_2 by a factor of 2 results in coincidence with f_1, and reducing f_3 and f_4 by factors of 3 and 4, respectively, also results in coincidence with f_1.

As shown in Eq. (2), the fundamental resonance frequency f_1 is obtained from the maximum value of the average intensity of the spectrum obtained by superimposing the frequency results obtained by EMAR measurement and then reduced by a factor of n. Then, conversion from sound velocity to specimen thickness is conducted using Eq. (3). The maximum spectrum intensity so obtained is treated as the peak SNC value.

$$f_1 = \arg\max_f \left\{ \sum_n x\left(\frac{f}{n}\right) \Big/ m \right\} \tag{2}$$

$$d = \frac{v}{2 f_1} \tag{3}$$

Here, x (f) is SNC spectrum intensity, arg max (argument of the maximum) is the frequency at which the SNC spectrum intensity is maximum, and m is the number of superimposed resonance orders.

Resonance frequency, as well as the orders of resonance frequency contained within the test frequency range, depends on specimen thickness and sound velocity. For example, resonance frequency is 324 kHz when the pipe wall specimen thickness is 5.0 mm and sound velocity is 3240 m/s, and the orders of resonance frequency contained within the test frequency range of 1.5 to 3.5 MHz are integrals 5 through 10. By reducing the EMAR frequency measurement results by factors ranging from 5 to 10 and summing them up, the fundamental resonance frequency peak becomes clearly accented. The SNC spectrum intensity is the average value obtained for the added up resonance orders.

In the online monitoring test, sound velocity is determined using a calibration specimen whose material type is the same as that of the pipe under investigation. The estimated wall thickness used in the SNC analysis is the nominal thickness for the first round of test and the thickness measured at the (x-1)th round for the x^{th} round of test.

Figure 3 shows the result of SNC analysis applied to EMAR measurements on the simulated wall-thinned area shown in Fig. 2. The analysis assumed an estimated thickness of 8 mm and the range of orders n=8 to 17. The spectrum shows multiple fundamental resonance frequencies, indicating a variation in the bottom surface shape. The thickness value of 8.28 mm corresponding to the maximum-peak resonance frequency (195.7 kHz) is regarded as the wall thickness of the specimen.

2.3. Outline of measurement

The EMAR measurement equipment consists of a high power pulsar receiver (RITEC RPR-4000), a preamplifier (RITEC PASJ-0.1-20) to amplify the received signals, a wide range decade filter (NF FV-628B) to filter the received signals, an oscilloscope (TEKTRONIX DPO4104) to observe waveform and collect data, and a personal computer to store and analyze waveform data.

Because the pipe temperature is 165°C as a test condition, the EMAT probe must be heat resistant. Therefore, a heat resistant polyimide coated wire is used for the coil, and a pair of high Curie temperature samarium-cobalt magnets, each having dimensions of 10 mm in width, 20 mm in length, and 20 mm in height (i.e., exciting direction), are used for the permanent magnet. Transmitting and receiving coils are configured separately. The transmitting coil diameter is designed to be 10 mm to lessen the area of incidence and suppress the effect of ultrasound scattering due to the variation in the bottom surface shape. The receiving coil diameter is designed to be 20 mm to lessen the attenuation of the received signals. The coil wire diameter is 0.12 mm, and the transmitting and receiving coils have 40 and 80 turns of wire, respectively. The separate configuration of transmitting and receiving coils allows the preamplifier to be placed closer to the probe location, leading to an improved SN ratio. With a test frequency range between 1.5 and 3.5 MHz and a sweep spacing of 10 kHz, the received signals are subjected to superheterodyne processing, and synchronous detection is conducted at 1 kHz frequency intervals to obtain EMAR measurement data.

The EMAT probe was installed on the pipe without peeling off surface coating. A preliminary test was conducted to confirm the relationship between lift-off distance and SNC signal. The specimen used is a calibration specimen (STPT370) 5 mm thick. A plastic sheet 0.2 mm thick was sandwiched between the EMAT and the specimen, and measurement was conducted while varying the lift-off distance. Figure 4 shows the peak SNC value of the received signals obtained for different lift-off distances from the specimen under the above-noted measurement conditions. The peak value decreased as the lift-off distance was increased; it was reduced by half at a lift-off distance of 1 mm. Because the coating thickness is somewhere less than 200 μm, peak attenuation due to the coating is estimated to be less than 10%. It was demonstrated that measurement could be done successfully without removing the coating. The variation of lift-off distance had no effect on the resonance frequency, which remained at 323.4 kHz.

3. Monitoring test with pipe wall thinning test equipment

3.1 Test description

The pipe wall thinning test equipment allows testing of pipe wall thinning under a single-phase or two-phase flow environment by simulating the water flow conditions of a nuclear power plant [9]. Figure 5 outlines the setup of a test pipe installed on the pipe wall thinning test equipment. The test pipe is made of carbon steel STPT370 of 50A Sch80 with an inner diameter of 49.5 mm, outer diameter of 60.5 mm, nominal wall thickness of 5.5 mm, and length of 1350 mm. Upstream of the test pipe, there is a pipe elbow and a throttling orifice. Fluid flows upward through this section as shown in the figure, and there is a U-bend downstream of this section. These features cause fluid turbulence in the test pipe, accelerating wall thinning.

Two simulated wall thinning tests were conducted. One is to generate a two-phase flow in the test pipe to accelerate wall thinning, and the other is to generate a single-phase flow with different amounts of dissolved oxygen. The fluid temperature in the pipe was 165°C which is within the temperature range where pipes are susceptible to flow-accelerated corrosion. The pipe of the test section was wrapped in insulating material and enclosed in a metal protector, and the pipe and the fluid in the pipe had the same temperature.

EMATs were installed directly on the pipe surface without peeling off the surface coating. Each EMAT was held by the magnetic force of its permanent magnet and was secured in place with wire so that it would not get misaligned by any accidental contact caused by such as installing and removing insulator material.

The length of the distributing cable connecting between the EMAT probe installed on the test pipe and the measurement equipment installed in the control room was about 32 m. The SN ratio was found to decrease as received signals were transmitted through the cable, because of signal attenuation and added noise. To solve this problem, the preamplifier was placed close to the measurement area to amplify only the received signals, and a distribution cable with a smaller coefficient of attenuation was adopted. As a result, the SN ratio was improved.

3.2 Results of wall thinning monitoring test under two-phase flow environment

The first test is a simulated wall thinning test conducted at a pipe temperature of 165°C under the deaerated two-phase flow environment. The test period was about two months, during which the system was shut down twice for periodic inspection. The probe was placed at about 650 mm from the orifice end, and a biaxial cable was used for the distribution cable.

Using a calibration specimen 5 mm thick, the fundamental resonance frequency was measured by EMAR at room temperature to determine the sound velocity as 3240 m/s. Figure 6 compares SNC signals obtained during the rise of pipe temperature: at room temperature before the start-up of equipment and at 165°C. It is shown that at the higher temperature, SNC peaks tend to be lower in both intensity and resonance frequency. This can be explained by the peak attenuation at the elevated temperature, associated with the decreased flux density of the magnet as well as the decreased sound velocity associated with the decreased elastic modulus. Figure 7 shows the change of sound velocity with the rise of pipe temperature during the equipment startup. The initial wall thickness was calculated from the sound velocity obtained by using the calibration specimen; sound velocity during the temperature rise was determined by assuming that the wall thickness stayed the same. The sound velocity decreased nearly linearly as the pipe temperature rose. The sound velocity of 3180 m/s at the operating temperature was used for evaluating wall thickness.

The orders of resonance frequency in the SNC analysis of the monitoring test were determined as follows. The nominal wall thickness of 5.5 mm was adopted in the initial round of measurement. Because sound velocity at 165°C during operation is 3180 m/s, the orders of resonance frequency included in the test frequency range of 1.5 to 3.5 MHz are n=6 to 12. In the x^{th} round of measurement from the start of the test, the order of resonance frequency is determined on the basis of the $(x\text{-}1)^{th}$ round of thickness measurement, and the wall thickness is calculated from the resonance frequency obtained by the SNC method.

Figure 8 shows the change of pipe wall thickness with time evaluated by EMAR under a high temperature environment during the operation of the pipe wall thinning test equipment. The thickness measured by EMAR in the first round was 5.42 mm and that measured in the last round was 5.24 mm, resulting in a thickness reduction of 0.18 mm. After the completion of the test, the test pipe was cut out and its cross section was observed under a microscope for measurement. The wall thickness at the location where the EMATs were installed was 5.18 mm, which means a difference of 0.06 mm from the final thickness measurement by EMAR. Whereas the area of 10 mm in diameter, corresponding to the size of the EMAT probe, was measured by EMAR to evaluate wall thickness, the center of the probe was measured under the microscope; this probably caused the difference in thickness evaluation. The difference, however, is within the allowable range, as compared with the error of ± 0.1 mm in the ultrasound thickness gauge.

Figure 8 shows the reduction of wall thickness with time. During the measurement period of 58 days, the thickness was reduced at a rate of 3.0 μm per day.

Figure 9 shows the initial spectrum obtained by SNC analysis and that obtained 30 days later. Compared with the former SNC spectrum, the latter shows a shift of resonance frequency to the higher side, a reduction in amplitude, and an increase in the number of peaks. This indicates the occurrence of unevenness and slope on the inner surfaces of the pipe. It is considered that the change in the bottom surface shape caused ultrasound scattering, which resulted in decreased amplitude and multiple peaks.

3.3 Results of wall thinning monitoring test under single-phase flow environment

The second test was conducted at a pipe temperature of 165°C under the single-phase flow environment with the addition of a small amount of dissolved oxygen. The 24-day duration from the startup of equipment was defined as the first test period. Then, operation for adjusting water quality was performed for 6 days, and the 25th to 55th days of equipment operation was defined as the second test period. The mount of dissolved oxygen was changed between the two test periods. It is considered, in principle, that wall thinning did not occur during the water quality adjustment operation, during which the test pipe was bypassed.

Three EMAT probes, circumferentially aligned, were installed at about 160 mm from the orifice end, and measurement was conducted without peeling off the coating on the installed area. A 3D-2V coaxial cable with a low attenuation rate was used for the distribution cable.

Using three EMAT probes on a calibration specimen 5 mm thick, fundamental resonance frequency was measured by EMAR at room temperature. The resulting sound velocity was 3240 m/s in each case. Because thickness was evaluated from resonance frequency in the EMAR method, it is considered that there were no differences in thickness measurement among the three probes.

Figure 10 shows the result of wall thickness evaluation by online monitoring. There are differences in initially measured thickness among the three probes. On the other hand, the same type of pipe with a nominal thickness of 5.5 mm was measured by using a micrometer, and the results ranged between 5.1 and 5.6 mm. The measured values are within the specified thickness allowance in manufacturing of ± 10%, or ± 0.55 mm. Because there were no differences among the sound velocities measured with the three probes, the differences in wall thickness initially measured probably reflect different thicknesses that occurred during pipe manufacturing.

In all three probes, there is a correlation between wall thinning and elapsed time. During the 23 days of the first test period after the startup of equipment, changes in thickness of 0.10 mm in probe No. 1, 0.09 mm in probe No. 2, and 0.11 mm in probe No. 3 were observed.

Table 1 shows the amounts of wall thinning per day during the two test periods with different water quality. The reduced thickness per day is 4.8 μm for probe No. 1, 5.1 μm for No. 2, and 4.3 μm for No. 3 in the first test period; and 5.2 μm for probe No.1, 5.5 μm for No. 2, and 4.4 μm for No. 3 in the second test period. In every probe, the amount of thinning during the second test period was greater than that of the first test period. The EMAR measurement results show a difference in the rate of wall thinning between the two test periods, for which the amount of dissolved oxygen was different.

4. Conclusions

In this study we applied EMAR to the online monitoring of pipe wall thinning under an actual high temperature environment and discussed the possibility of quantitative evaluation of wall thinning. Using equipment for testing pipe wall thinning that can reproduce wall thinning comparable to that of actual pipes by accelerating wall thinning, we conducted online monitoring of wall thinning at a pipe temperature of 165°C under two-phase and single-phase flow environments.

1) In the two online monitoring tests using pipe wall thinning test equipment, we evaluated the progression of wall thinning with time at a high temperature of 165°C and found a difference in thinning rate between different fluid flow conditions.
2) In the first test, the difference between the EMAR measurement and the microscopic measurement at the end of the test was 0.06 mm.
3) Comparison of waveforms obtained by SNC analysis after the wall thinning process in the first test showed attenuated SNC peak intensities and multiple peaks, indicating a change in the bottom surface shape.
4) Installation of probes was facile because measurement could be made without peeling off the pipe coating and the probes could easily be held on the measurement location with the help of the probe magnets.

Without requiring special skills for probe installation, we could estimate the presence or absence of bottom surface shape variation from the attenuation of SNC peak intensities and the number of peaks around the SNC peaks at high temperatures through thickness evaluation equivalent to that of ultrasonic testing, and could evaluate the progression of wall thinning with time.

The following advantages are expected from monitoring-based inspections using EMAR and SNC analyses.

(1) Because it is possible to evaluate changes in wall thinning on the order of 0.01 mm, the rate of wall thinning can be evaluated accurately. Further improvements in equipment reliability and safety are expected.
(2) It is also considered possible to apply this approach to the verification of pipe wall thinning evaluation methods, the verification of adequateness of representative locations for wall thinning measurement, and the clarification of wall thinning mechanisms.
(3) By monitoring the details of wall thinning due to changes in the flow conditions in piping in response to increased reactor output, we can expect to raise reactor output while ensuring the safety of pipe systems.

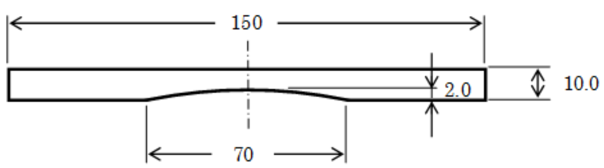

Fig.1 Cross section of the specimen with a simulated wall thinning.

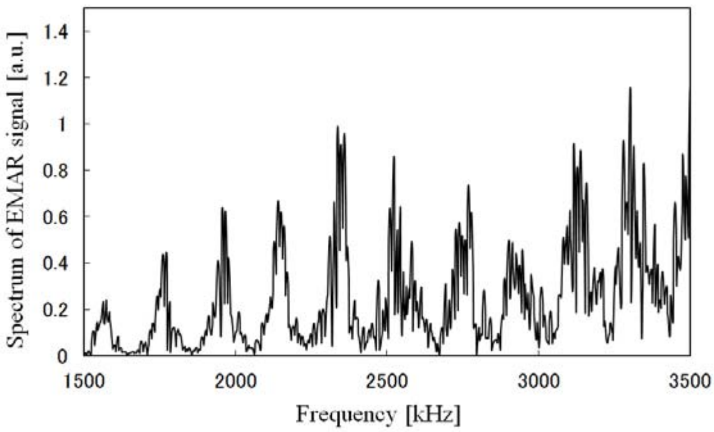

Fig.2 EMAR signal of wall thinning position.

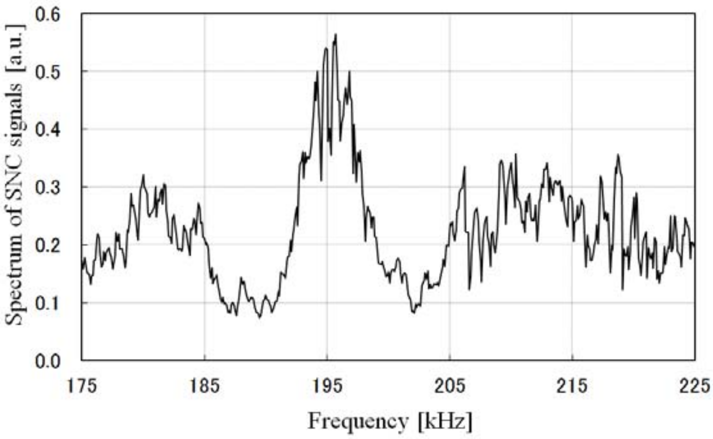

Fig.3 Signal of superposition of n-th compression (SNC).

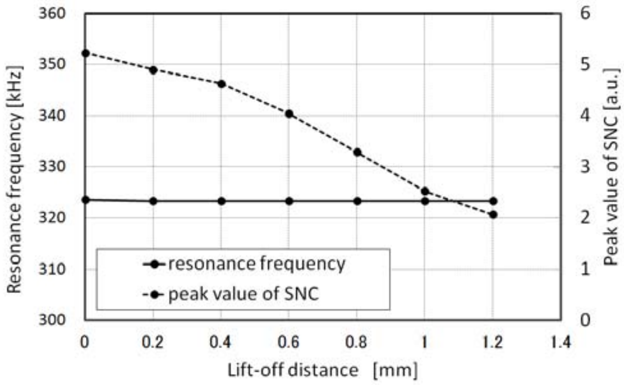

Fig.4 Relationship between SNC peak, resonance frequency and lift-off distance.

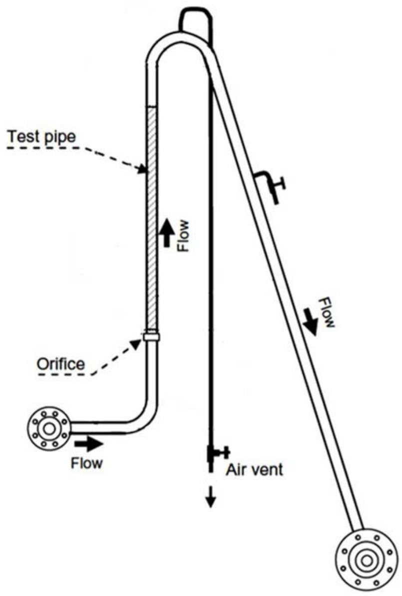

Fig.5 Layout drawing of test pipe.

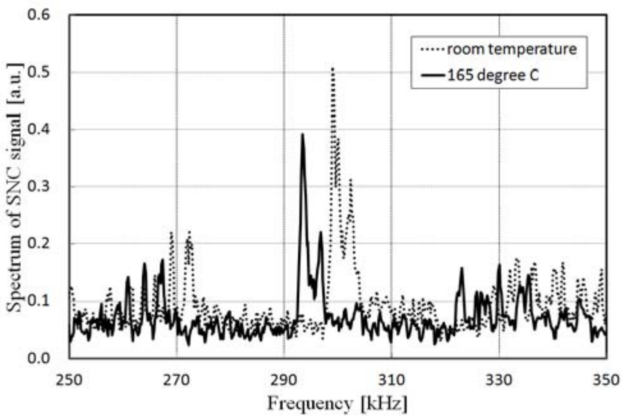

Fig.6 Comparison between signals at high and room temperature.

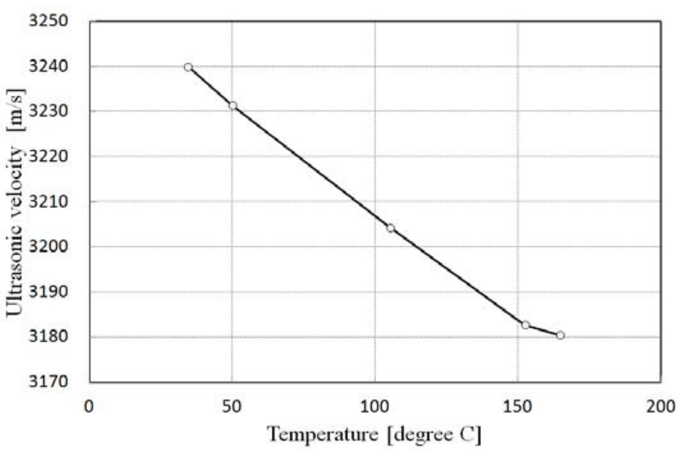

Fig.7 Temperature dependence of acoustic velocity.

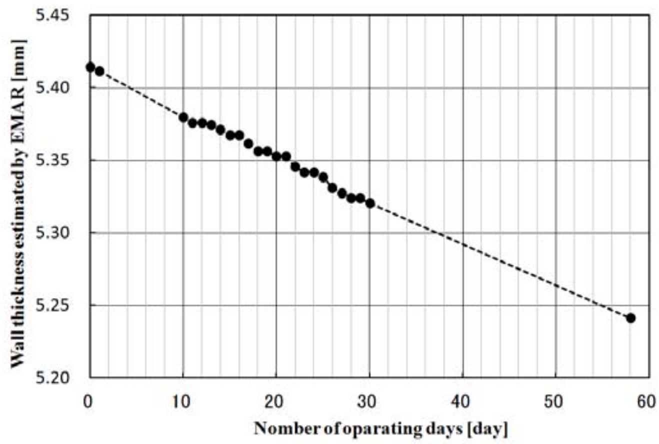

Fig.8 Measurement result with two-phase flow.

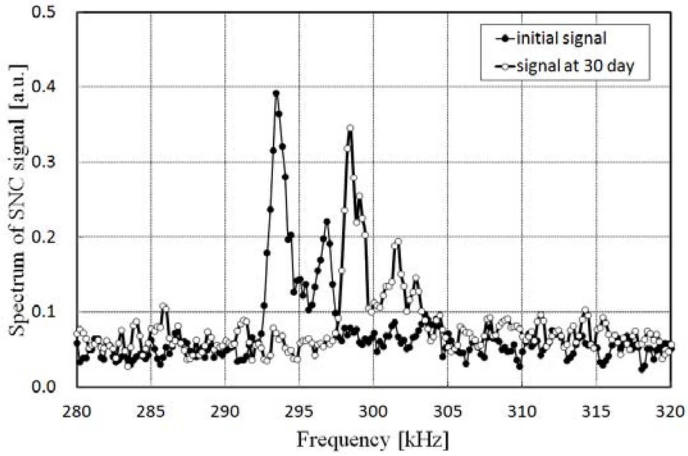

Fig.9 Comparison between initial signal and the signal at 30 days.

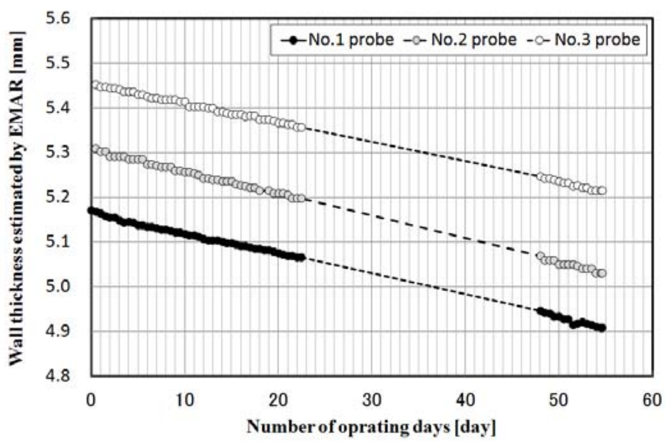

Fig.10 Measurement result with single-phase flow.

Table 1 Amount of thinning [μm/day].

Period	No.1probe	No.2 probe	No.3 probe
I	4.8	5.1	4.3
II	5.2	5.5	4.4

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