Toshifumi YUJI[1], Hiroyuki KINOSHITA[1], Toshio BOUNO[2], Nuttee THUNGSUK[3], Sunun TATI[4], Thaweesak TANARAM[4], Narong MUNGKUNG[5]

University of Miyazaki (1), National Institute of Technology, Sasebo College (2), Dhonburi Rajabhat University Samut-Prakan (3) Pibulsongkram Rajabhat University (4), King Mongkut's University of Technology Thonburi (5)

doi:10.15199/48.2020.09.28

Estimate of Scale Thickness for Iron Pipes in Geothermal Power Generation Using Acoustic Emission Sensor

***Abstract**. Currently, geothermal power generation is attracting attention in Japan as the next renewable energy source. However, tapping of this energy requires substantial equipment and entails enormous maintenance costs for this equipment. In particular, in the steel pipes connected to steam wells in geothermal power generation stations, when water vapor is collected from steam wells, the hot spring component known as yunohana (mineral encrustations left by hot springs) precipitates and forms into scale and adheres to the steel pipes. This causes clogging and deterioration of pipes by metal corrosion due to the sulfur content, which requires periodic maintenance and other measures to be taken for most equipment. Consequently, a remaining life assessment technique for maximizing the life of steel pipes connected to geothermal power generation steam wells is required as a continual improvement measure for enabling stable usage of equipment over a long period of time. As a non-destructive test, we used ultrasonic sensors to measure the ultrasonic waves generated from changes in the water flow due to changes in the thickness of the scale adhering to the inside of the pipes and the ultrasonic waves propagated from the change locations of the metal surface, and this enabled us to confirm the buildup of scale using an acoustic emission (AE) sensor for successfully assessing the remaining life.*

Streszczenie.** W artykule omówiono wykorzystanie wód geotermalnych jako odnawialnego źródła energii. Głównym problemem the metody jest zużywanie się stalowych rur doprowadzających pare I gorącą wodę. W artykule opisano wykorzystanie czujników ultradźwiękowych do analizy emisji akustycznej I w ten sposób do badania stanu rurociągu. **Metoda określania grubości rury stosowanej w geotermalnych źródłach energii bazująca pomiarze emisji akustycznej

Keywords: Acoustic emission sensor, Geothermal generation, Maharanobis distance, Scale, Fast fourier transform method.
Słowa kluczowe: geotermalne źródła energii elektrycznej, czujniki ultradźwiękowe, emisja akustyczna

Introduction

As a result of the Fukushima nuclear plant reactor number 1 accident caused by the Tohoku Region Pacific Ocean Earthquake in Japan in March 2011 [1], a shift from the Japanese government's energy policy of dependence on nuclear power to renewable energy, such as solar and wind power, and achieving decarbonization of main power sources have been cited as targets for basic energy policies [2]. Currently, the renewable energy source in Japan that is attracting the most attention is geothermal power generation [3-6]. Japan, one of the world's leading volcanic countries, has some of the largest geothermal resources in the world, but the use of geothermal resources for power generation in Japan remains at a low level of only about 2.0 % [7]. One of the main reasons for slow adoption of geothermal power generation in Japan is that the power distribution networks are owned exclusively by power companies for each region, and so it is difficult for new companies to enter into the market from other fields. Also, in those regions suitable for building of geothermal power stations, most are located on lands of national parks, semi-national parks, and similar areas, and so building of geothermal power stations faces hurdles under the Natural Parks Law. The need for coordination of hot spring sources with hot spring regions has also been raised as an issue. Some important key points are that, compared to nuclear power generation and thermo-electric power generation, geothermal power generation is implemented on a smaller scale, uses relatively larger land sites for their power generation facilities, and incurs substantial maintenance fees due to the metal corrosion of equipment from sulfur and other content [8-10]. In the energy supply sources for geothermal power generation, when water vapor is collected from steam wells in the water vapor of magma chambers, the hot spring component known as yunohana (mineral encrustations left by hot springs) precipitates and forms into scale (sulfur components dissolved in the water that adhere to the inside of the pipes) and adheres to the steel pipes. This causes clogging and deterioration of pipes by metal corrosion due to the sulfur content, which requires periodic maintenance and other measures for most equipment.

Previously, the authors proposed maximizing the life of steel pipes connected to geothermal power generation steam wells as a continual improvement measure for enabling stable usage of equipment in geothermal power generation stations over a long period of time. Currently, the typical method for assessing the remaining life of steel pipes connected to geothermal power generation steam wells is a non-destructive test using X-rays by manual operation. Together with the complete replacement required periodically, this entails tremendous costs. To achieve this required maintenance and low-cost, non-destructive testing, we started to develop a remaining life and deterioration assessment technique for the steel pipes connected to geothermal power generation steam wells that is a simple, non-destructive test technique using vibration sensors. These vibration sensors successfully enabled us to capture changes in the vibrations of the water flow in steel pipes based on changes in the thickness of the scale adhering to the inside of the steel pipes [11].

In this paper, instead of impact sensors, we used ultrasonic sensors capable of capturing ultrasonic waves that are thought to be generated from the deteriorated metal locations of the steel pipes. Then, we measured the ultrasonic waves generated from changes in the water flow due to changes in the thickness of the scale adhering to the inside of the pipes and the ultrasonic waves propagated from the change locations of the metal surface, and this enabled us to confirm the buildup of scale using an acoustic emission (AE) sensor [12]. As a result, the ultrasonic waves captured by the AE sensor are output from the AE sensor as AE signal waveforms, and we found that the amplitude of the AE signal waveform that was output correlated with increases in the scale thickness.

Experimental and setup

Figure 1 shows the overall schematic diagram for the experimental equipment. As shown in this figure, carbon steel pipes (SGP; JIS G 3452:2002) 40A were used for building the experimental equipment as a model for the steam well pipes in a geothermal power generation station. The experiment was conducted by directly connecting water pipes with a constant water flow rate to 145 L / min throughout to the steel pipes.

Figure 2 shows an overview of the experimental steel pipes used in the experiment. To simulate the adhesion of scale inside the steel pipes, five steel pipes were prepared

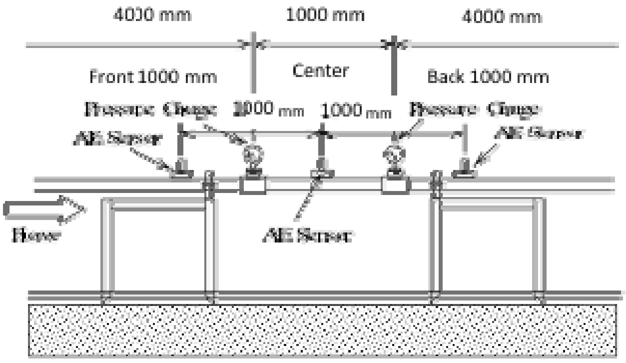


Fig.1. Experimental setup

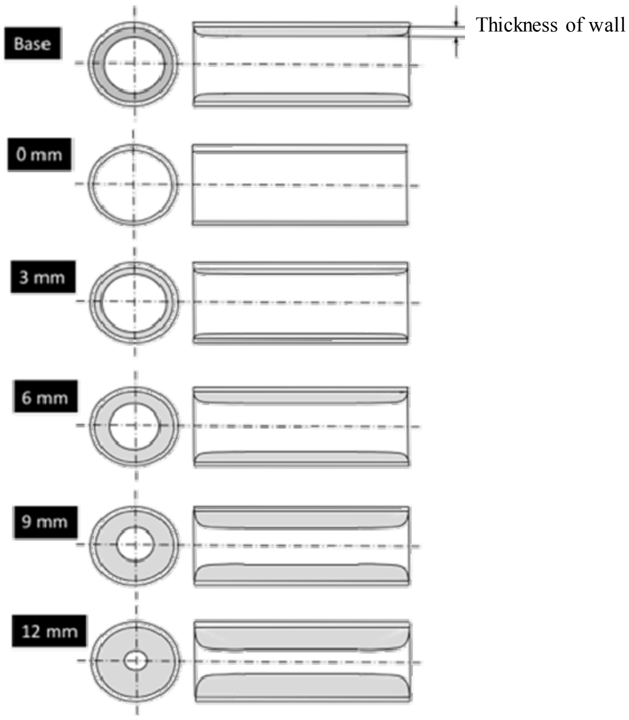


Fig.2. Schematic of experimental iron pipe models.

where uniform non-hardened putty (Mortar) was applied to the entire interior surface (0 -12.0 mm) of the steel pipes (600mm). The ultrasonic signals generated from the change in water pressure and water flow due to the putty inside the steel pipes were captured by an AE sensor (NF Corporation; AE-900S-WB), and the AE sensor output signal was amplified by a pre-amplifier (NF Corporation; 9917), and the result was recorded to a digital oscilloscope (Hantek; DSO5202B) as a signal waveform.

Also, by capturing the ultrasonic waves by the AE sensor, the AE signal waveform that was output undergoes spectral analysis using Fast Fourier transform (FFT) method, and the spectral changes for each frequency were confirmed. It was transformed to spectrogram by the using algorithm from MATLAB for analysis. The article describes the method of fault detection using the spectrogram-based binary image and presents technique for detection of mortar thickness in iron tube [13][14]. The spectrogram using FFT and sound technique algorithms to transform AE sensor signal. The spectrogram also allow us to detect faults of mortar thickness in iron pipe [15-17]. However, 2D spectrogram can be distracted by ambient noise. It is very important, because the 2D spectrogram is more difficult to recognize. Therefore, 2D spectrogram changed to 3D spectrogram of mortar thickness in iron pipe. The vibration of AE sensor signal with 3D spectrogram by sound technique algorithms was easies analysis.

In the same way, the data analysis of the recorded AE signal waveform used the Mahalanobis distance [18], which is a mathematical technique that is frequently used for variations in characteristic value distributions for different groups. The Mahalanobis distance d^2 is an index using correlation between variables, and it is a distance metric that indicates the distance from the reference space of the target data. Normally, in discriminant analysis using the Mahalanobis distance, the group where the target object belongs is identified from the attribution to the characteristic value space created by the reference data.

Generally, a value near 1.0 is obtained when near the reference space, and as the difference from the reference space becomes larger, the values become significantly larger than 1.0. For this reason, the Mahalanobis distances from the references spaces for the data that needed to be identified were calculated, and this enabled us to determine that data belonged to the reference space giving the minimum Mahalanobis distance. If we take the explanatory variable as *x*, then by expressing the variables for the number of data points *N* and the degree of freedom *T* in terms of x_{ij}, (*i* :1-*N* or *j* :1-*T*) we can define the Mahalanobis distance d^2 using the following formula (1).

Equations

For equations it is recommended to use standard equation editor existing in Word editor (usually it is Math Type editor). The equation editor is defined as follows: font Times New Roman italic, matrix bold, for letters font 10, for index 8, for symbol 12. For example, typical equation should be as:

$$d_{ij}{}^2 = \frac{1}{T}\sum_{l=1}^{T}\sum_{k=1}^{T}\left(X_{il} - X_{jl}\right) S_{lk}^{-1}\left(X_{ik} - X_{jk}\right) \quad (1)$$

Here, *S* is the standardized variance-covariance matrix shown in formula (2).

$$S_{lk} = \frac{1}{T}\sum_{i=1}^{T}(X_{il} - \bar{X}_l)\,(X_{ik} - \bar{X}_k) \quad (2)$$

Also, *X* is the result after standardization of *x* using the following formula (3) [19].

$$X_{ij} = \frac{x_{ij} - \bar{x}_j}{\sigma_{xi}} \quad (3)$$

Figure 3 shows the AE signal waveforms obtained when the ultrasonic waves were measured by an AE sensor for a constant water pressure in the five types of simulated steel pipes. As shown in this figure, the AE signal waveform shows no changes when there is no scale in the steel pipe.

Also, this shows a clear increase in the amplitude of the AE signal waveform as the thickness of the scale in the steel pipe increases. For example, when comparing the changes in the AE signal waveform for scale thicknesses of 3.0 mm and 12.0 mm, in proportion to the increase in the simulated scale thickness in the steel pipe, it was found that the peak value of the AE sensor signal waveform increased to 2x.

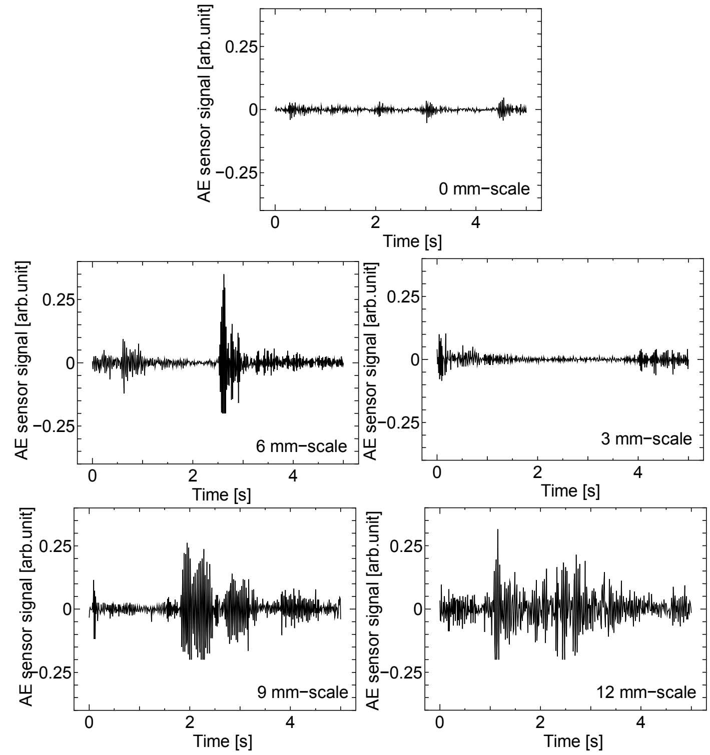


Fig.3. Waveforms of AE sensor signals

Figure 4 shows the relationship between the scale thicknesses and the peak values of the AE signal waveform obtained from Fig.3. In this figure, the blockage ratio [20] in the steel pipe and because using only the scale thickness was unclear, the blockage ratio was also included in the figure. As shown in this figure, we were able to find a clear increase in the peak value of the AE signal waveform based on the scale thickness. For these measured AE waveforms, it is thought that the impact energy due to the steel pipes caused the generated ultrasonic waves to propagate within the steel pipes, which were picked up by the AE sensor. We found a clear correlation between the peak value of the AE signal waveform and the blockage rate within the steel pipes.

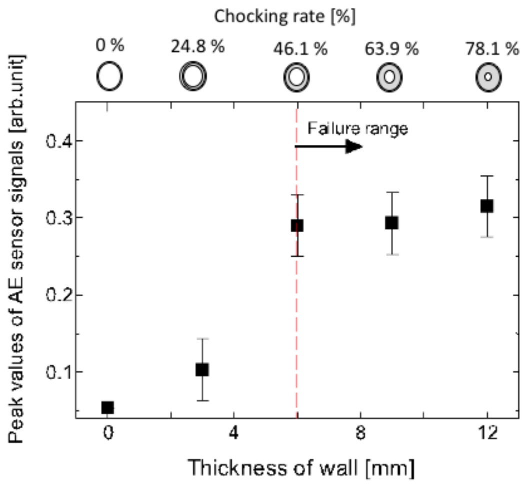
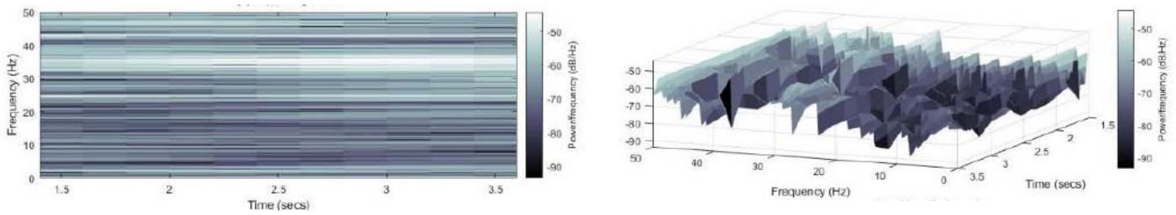


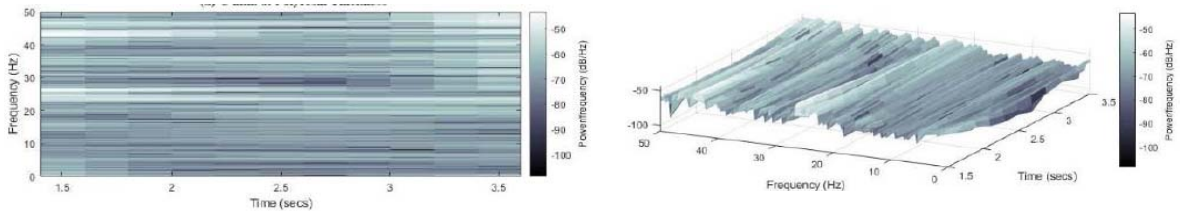
Fig.4. Relationship between thickness of wall and peak value of AE sensor signals.

Fig. 5 shows the spectrogram image of 2D in the lift side and 3D on the right side for AE sensor signals (5-type) when using FFT method. The X-axis and Y-axis of spectrogram image of 2D was time and frequency, respectively where intensity bar in the right side of 2D-image shows power fluctuates (dB/Hz) when using FFT analysis. The black to white color of intensity bar on 2D-image was the level of decibel. However, the 3D image of spectrogram was allowed for easier analysis with presentation of power range and peak level in both time and frequency. The 3D spectrogram generates by using sound technique algorithms to transform AE sensor signal to sound, compute and plot the Power Spectral Density (PSD). The distribution of the signal power collision of the flowing water with the scale thickness adhering inside the over the frequency interval (0-50) was shown in Fig 5. The vibration signal present peaks of differences of acoustic signals around -90 dB/Hz in 1.75-3.75 second of testing time. The Fig. 5(a) shows that the signal power fluctuates, it was found that the signal power decrease or increase suddenly all testing time. Besides, Fig. 5(b) and 5(c) show spectrogram with 3.0 mm and 6.0 mm, it was found that the vibration signal has PSD between -40 to -65 dB/Hz which it was confirmed that the signal power was distributed relatively stable. On the other hand, the signal power in Fig. 5(d) and 5(e) was no stable which observed that the PSD was between -25 to -85 dB/Hz. Especially, the 9 mm in Fig. 5(d) has significant power shooting at 30 Hz due to resin in the iron pipe started to become damaged. Finally, the signal power in 12 mm in Fig. 5(e) was results in fluctuates in a wide range.

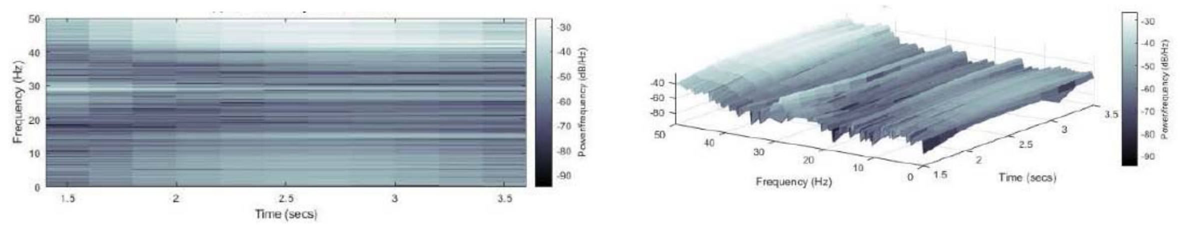
Figure 6 shows an example of determining the acquisition range from the AE signal waveform for creating a reference space from the scale thicknesses in the Mahalanobis distance. In this figure, the maximum value was found from the amplitude values of the measured AE signal waveforms, and the range from 30 % (Maximum value of 30 %) of the maximum value to the maximum value was plotted on a Gaussian distribution. Also, the scale thickness of 3.0 mm within the steel pipes was set for the respective reference spaces (four pattern: 30, 60, 90, 120 mm).



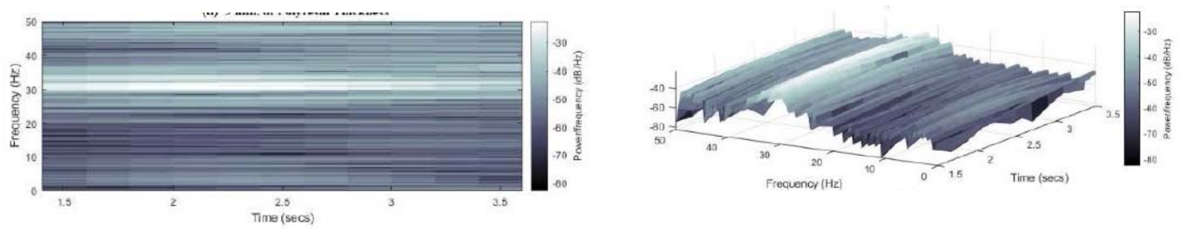
(a) 0 mm



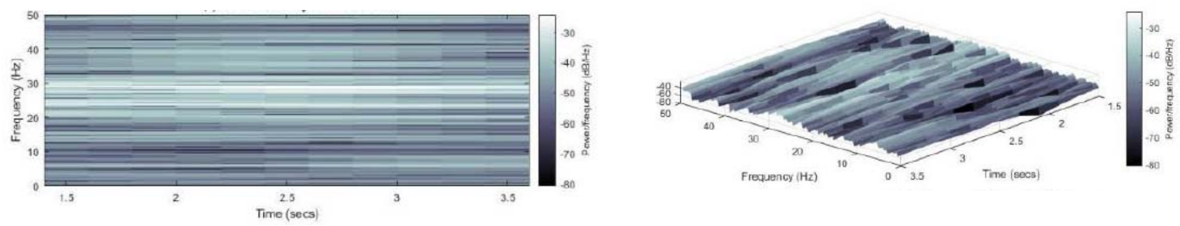
(b) 3.0 mm



(c) 6.0 mm



(d) 9.0 mm



(e) 12.0 mm

Fig.5. 2D and 3D for AE sensor signals (5-type)

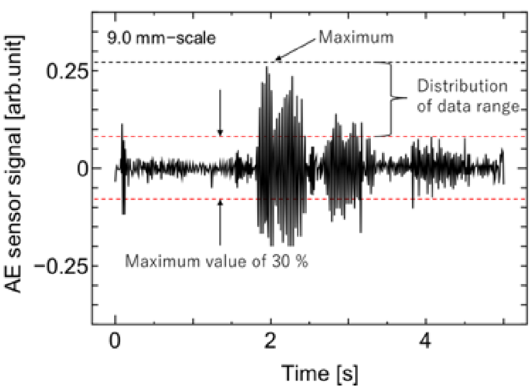


Fig.6. Data acquisition for base-spece in AE sensor signal (Scale: 9.0 mm).

Figure 7 shows the relationship between the scale thickness within the pipes and the Mahalanobis distance for each reference space that was obtained from Figure 6. From this figure, a scale thickness of 3.0 mm was taken as the base for the reference space. In a reference space with scale thickness of 3.0 mm, the Mahalanobis distance converges to a value of about 1.0. When the reference space is set to a scale thickness of 3.0 mm, the value for the Mahalanobis distance at a scale thickness of 3.0 mm showed a value about more than 7x larger than the value for a scale thickness of 6.0 mm. In the same way, when the reference space is set to a scale thickness of 6.0 mm, the value for the Mahalanobis distance at a scale thickness of 3.0 mm showed a value about more than 1/2x larger than the value for the reference space value. As a result, for scale thicknesses of 6.0 mm or more, increasing of the scale thickness and raising of the blockage rate enables us to predict the timing for replacement of the steel pipes.

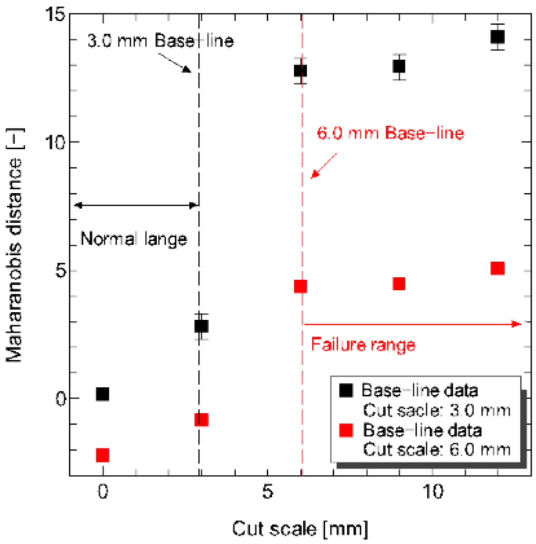


Fig.7. Relationship between Maharanobis distance in typical base-space and scale thickness in iron pipes

Conclusions

This study presents a proposal for a remaining life and deterioration assessment technique using an AE sensor for determining the replacement timing due to scale clogging that occurs in the steel pipes of geothermal power generation steam wells. This technique uses the impact energy between the water flow and scale that is generated from locations where scale adheres to the pipe inner wall, which generates an ultrasonic wave that propagates within the steel pipe. We were able to use an AE sensor to capture this ultrasonic wave. This study obtained the following results:

1) We found that the amplitude of the AE signal waveform that was captured by the AE sensor correlated with the thickness of scale in the steel pipe. Also, after spectral analysis using FFT method, we were able to clearly find a high-level spectrum, and this established the correlation between the amplitude of the AE signal waveform and the scale thickness within the steel pipe. The AE signal waveform present peaks of differences of acoustic signals at -90 db/Hz in 1.75-3.75 sec. of testing time.

2) We set a reference space from the scale thickness in the Mahalanobis distance, and we studied benchmark indices for the replacement timing of steel pipes. As a result, we were able to establish one standard metric for replacement timing of steel pipes for scale thicknesses of 6.0 mm or more when the scale thickness is increased and the blockage rate rises.

Looking forward, we plan to perform further experiments by conducting non-destructive testing using AE sensors for confirming the scale locations within the steel pipes connected to geothermal power generation steam wells in actual geothermal power generation stations for verifying the practical application of this research.

This study was supported by research grant from Japan Power Academy.

***Authors**: dr. Toshifumi YUJI, Faculty of Education, University of Miyazaki, 1-1, Gakuenkibanadai-nishi, Miyazaki, 889192, Japan, E-mail: yuji@cc.miyazaki-u.ac.jp; dr. Hiroyuki KINOSHITA, Department of Mechanical Design Systems Engineering, University of Miyazaki, 1-1, Gakuenkibanadai-nishi, Miyazaki, 889192, Japan, E-mail: t0d165u@cc.miyazaki-u.ac.jp; prof. Toshio BOUNO, Department of Electrical and Electric Engineering, National Institute of Technology, Sasebo College, 1-1, Okishinmachi, Sasebo-city, Nagasaki, 8571193, Japan, E-mail: tsobouno@sasebo.ac.jp; dr. Nuttee THUNGSUK, Department of Electrical Engineering, Dhonburi Rajabhat University Samut-Prakan, 59/1 Moo 14 Bang Pla, Bang Phi, Samut-Prakan, 10540, Thailand, E-mail: nuttee.t@dru.ac.th; dr. Sunun TATI and Thaweesak TANARAM, Faculty of Industrial Technology, Pibulsongkram Rajabhat University, 156 Moo 5, Tambon Phlaichumphon Muang District, Phitsanulok, 65000, Thailand, E-mail: sunun.t@psru.ac.th, tummut@hotmail.com; dr. Narong MUNGKUNG, Department of Electrical Technology Education, King Mongkut's University of Technology Thonburi, 126 Pracha Uthit Rd, Bang Mot, Thung Khru, Bangkok, 10140, Thailand, E-mail: narong_kmutt@hotmail.com;*

REFERENCES

[1] Butler D., "Radioactivity Spreads in Japan", *Nature*, 471 (2011), No.7340, 555-556.

[2] Jeffrey B. K. and Unesaki H., "Japan's 2014 Strategic Energy Plan: A Planned Energy System Transition", *Journal of Energy*, 2017 (2017), Article ID 4107614.

[3] Williamson K.H., Gunderson R.P., Hamblin G. M., Gallup D. L. and Kitz K., Johnson B., Pike G.E., "Geothermal Power Technology", *Proceedings of the IEEE*, 89 (2001), 1783-1792.

[4] DiPippo R., Geothermal Power Plants: Evolution and Performance Assessments, *Geothermics*, 53 (2015), 291-307.

[5] Ehara S., "Toward the Quantitative Study of Hydrothermal Systems", *J. Hot Spring Sci.*, 60 (2002), 261-271 in Japanese.

[6] Adachi M. and Noda T., "How to Move forward to New Development of Geothermal Power Plants in Japan ?", *J. Geotherm. Res. Soc. Japan*, 31 (2009), No.1, 17-26 in Japanese.

[7] Ricci G. and Viviani G., "Maintenance Operations in Geothermal Power Plants", *Geothermics*, 2 (2002), No.1, 839-847.

[8] Nakashima H., "Current Status and Future of the Geothermal Energy", *Journal of Smart Processing*, 3 (2014), No.2, 108-114 in Japanese.

[9] Stefánsson V., "Investment Cost for Geothermal Power Plants ", *Geothermics*, 31 (2002), No. 2, 263-272.

[10] Haruyama N., Kiyota Y., Bouno T. and Yuji T., "Investigation of Scale Thickness on Measurement Techniques for Geothermal Power Generation Using Iron Pipe", *J. IEIE Jpn.*, 29, (2009), No. 6, 461-462 in Japanese.

[11] Yuji T., Kiyota Y., Bouno T. and, Toya H., "Estimate of Scale Thickness in Iron Pipes Using Acoustic Emission Sensor", *J. IEIE Jpn.*, 33 (2013), No.2, 146-147 in Japanese.

[12] Ouali C., Dumouchel P. and Gupta V., "Efficient spectrogram based binary image feature for audio copy detection", in 2015 *IEEE International Conf. on Acoustics, Speech and Signal Processing* (ICASSP), (2015), 1792-1796.

[13] Tati S., Kijsanayothin P. and Kongdenfha W., 2018, "Song Clustering Using Similarity of Audio Fingerprint", *TNI Journal of Engineering and Technology*, 6 (2018) No 1: January-June, 49-55.

[14] Glowacz A., "Acoustic Fault Analysis of Three Commutator Motors", *Mechanical Systems and Signal Processing,* 133 (2019) 106226

[15] Kuma H., Sugumaran V. and Amarnath M., "Fault diagnosis of bearings through sound Signal Using Statistical Features and Bayes Classifier", *J. Vib. Eng. Technol.*, 4, (2016) N0.2, 87–96

[16] Delgado-Arredondo P.A., Morinigo-Sotelo D., Osornio-Rios R.A., Avina-Cervantes J.G., Rostro-Gonzalez H. and Romero-Troncoso R.D., "Methodology for Fault Detection in Induction Motors via Sound and Vibration Signals", Mech. Syst. Sig. Process, 83 (2017), 568-589.

[17] T. Bouno, S. Arimori, T. Yuji and H. Kinoshita, "Development of Fault Diagnosis Classification Method System using Mahalanobis Distance in Micro Wind Turbine", *IEEJ Trans. on Power and Energy*, 135 (2015), No.9, 577-578 in Japanese.

[18] Iwasaki A., Todoroki A., Shimamura Y. and Kobayashi H., "Daage Indentification by Discriminant Analysis Using Maharanobis Distance", Trans. of the Japan Society of Mechanical Engineers, Series A, Vol.67, (2001), No.659, 1242-1247 in Japanese.

[19] Chung K.-M. and Chen Y.-J., "Effect of High Blockage Ratios on Surface Pressures of an Inclined Flat Plate", *Journal of Engineering and Architecture*, 4 (2016), No.2, 82-92.