Inspection Technique for CUI (Corrosion under Insulation) by Using Fiber Optical AE Sensor

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Corrosion under insulation (CUI) is one of the degradation phenomena that have become a serious problem in recent years especially in chemical plants that have been operating for a long time. Development of a CUI inspection technique which doesn't require the removal of insulation and which is applicable to explosion-proof petrochemical plants is strongly needed. So we focused attention on optical fiber Doppler sensors which already have the explosion-proof characteristics, and we tried to develop a new CUI inspection technique using them. The development of this new inspection technique is explained.

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Introduction

1. Handling of Corrosion Under Insulation in Japan and Overseas

Corrosion under insulation (CUI in the following) started getting close attention in chemical plants, petroleum refineries, power generating facilities and other plants in the developed nations in Europe and the Americas as well as Japan in the 1980s. This was due to the fact that insulation that had previously been used in locations at 149°C or higher started being used in temperature ranges of 100°C or lower after the first oil crisis in 1973. In Japan, the High Pressure Gas Safety Institute of Japan issued a report on external corrosion in 1988, and the Engineering Advancement Association of Japan (ENAA in the following) carried out an investigation into the application of nondestructive testing techniques and monitoring techniques from 2007 through 2011. According to a 2007 ENAA report, guided wave ultrasound, real time radiography and pulsed eddy current nondestructive inspection techniques have been developed and applied at working sites, but they are not yet complete. Therefore, establishing priorities and visual inspection where the insulation is peeled off of the entire length of all surfaces are recommended.[1)]

2. Handling of Inspections at Sumitomo Chemical

The following shows how inspections have been handled by the Sumitomo Chemical Process & Production Technology Center since 2007. In 2007, we fabricated a mock-up pipe (pipe simulation) as shown in **Fig. 1** and conducted an investigation into applying detection of corrosion swelling using a fiber optic acoustic emission (AE in the following) sensor. Starting in 2008, we began working on the development of environmental noise separation techniques that included on-site applications. In 2008, we also investigated insulation structures for corrosion resistance (exterior plate structures), and we have carried out investigations into the selection of optimal undercoating materials for a temperature range of 60°C to 100°C. We continued these investigations in 2009, but we will discuss the status of development of inspection methods using fiber optic AE sensors here.

Fig. 1 Photo of the mock-up pipe

Development of CUI Inspection Techniques Using Fiber Optic AE[2)]

CUI in carbon steel equipment and pipes has become a deterioration phenomenon that has intensified in recent years particularly in chemical plants that have been operating for many years. In particular, exterior visual inspection of pipes installed outside in pipe racks that are in high places is difficult, and also, since the total distance is large, no CUI inspection methods have been established that are more effective than visual inspection with the insulation removed. In addition, the fact that 70 to 80% of the costs for these inspections is scaffolding and tearing down the insulation is one major problem. Therefore, there was a strong requirement for development of CUI inspection techniques for pipes that did not require the work of removing the insulation and worked for plant facilities requiring protection from explosions. We focused on fiber optical Doppler (FOD in the figures) sensors, which have explosion prevention properties from the beginning and attempted to develop new CUI inspection techniques.

1. Comparison and problems in CUI inspection methods for conventional pipes

Table 1 gives the characteristics of various inspection methods that have been applied to pipes up to now. Methods that have good inspection accuracy can only carry out inspections at short distances, and methods capable of long-distance inspections (approximately 5m) have poor inspection accuracy. Therefore, most operations carry out inspections where the insulation is removed as described previously, but even if complete teardown inspections are carried out at great expense, corrosion is only found in 2 and 3 systems out of every 1000 systems. The problem is that the efficiency is very poor.

Table 1 Comparison of the CUI inspection technique for pipes

Inspection method	Ultrasound Testing (UT)	Eddy Current Testing (ECT)	Radio graphic Testing (RT)
	Ultrasonic guided waves	Pulsed ECT	Real-Time RT
Influence of internal fluid	YES	NO	YES
Inspection of long distance	Applicable	Not Applicable	Not Applicable
Removal of insulations	Need	No need (Less than 80mm in thickness)	No need
Corrosion can be detected	localized corrosion (10% depth level of sectional area)	General corrosion like concave	localized corrosion (ϕ2mm through wall hole)
Inspection accuracy	Not good	Not good	Good

2. Principles of AE monitoring using fiber optical Doppler[3)]

We focused on the relationship between corrosion and AE to establish an inspection method that was effective for pipe CUI. **Fig. 2** is a conceptual diagram of the AE generating mechanism. First of all, peeling and cracking of local corrosion products (corrosion swelling) occur because of the progress in active corrosion. At this time, the strain energy that has accumulated inside is released as minute elastic waves. Since these elastic waves are comparatively low frequency elastic waves from the audible to 500kHz, it is known for propagating in a wide range. Therefore, the presence of corrosion can be sensed by detecting the AE caused by the peeling and cracking of the corrosion using an AE sensor to detect the elastic waves as AE. In other words, we can consider improving the CUI inspection efficiency by tearing down the insulation and carrying out visual inspections only on pipes where AE has been observed.

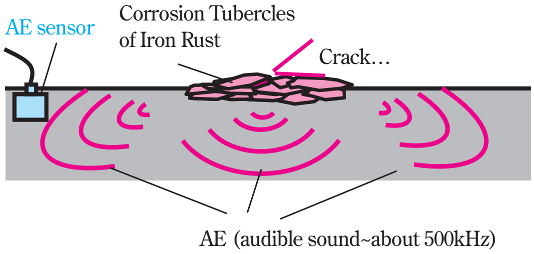

Fig. 2 Image of AE technique

The AE method is superior for monitoring corrosion, and it is already being applied in some places such as evaluation of corrosion damage on the bottoms of tanks, but there are actually various of problems. Up to now the AE method has used piezoelectric sensors, but there are problems such as: (1) they are easily affected by wind, vibration, noise, abrasion noise from the fluid inside, etc. (2) If attempts are made at increasing the sensitivity of the sensor, the range of measurement becomes a narrow band, so separation is impossible when it overlaps with a noise frequency band. (3) Since the resistance to electromagnetic noise is poor in cables, use for long distances is impossible. (4) They do not have explosion prevention properties. (5) The range of temperature applications is limited. To solve these problems, attention has been given to the fiber optic AE technology that has been developed in recent years.

The image of telecommunications systems is strong for fiber optics, but optical fibers can be used as sensors by using their Doppler effect. Now, when light waves from light source with acoustic velocity C and frequency f_0 are incident to an optical fiber, we let the optical fiber be extended length L at velocity v (see **Fig. 3**). Letting frequency f_0 be changed to f_1 because of the Doppler effect at this time, frequency f_1 following the change can be expressed as in Eq. 1 by the formula for the Doppler effect.

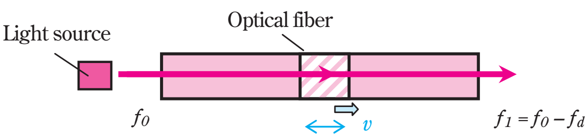

Fig. 3 Model of Doppler effect of optical fiber

$$f_1 = \frac{C - v}{C} f_0 = f_0 - \frac{v}{C} \cdot f_0 \qquad \text{(Eq. 1)}$$

Therefore, if we consider modulation of frequency f_1 following the change from frequency f_0 prior to incidence by f_d, we get Eq. 2.

$$f_d = f_0 \cdot \frac{v}{C} \qquad \text{(Eq. 2)}$$

f_d can be expressed as in Eq. 4 using the formula for the wave given in Eq. 3.

$$C = f_0 \cdot \lambda \qquad \text{(Eq. 3)}$$

$$f_d = f_0 \cdot \frac{v}{C} = \frac{f_0}{C} \cdot v = \frac{1}{\lambda} \cdot \frac{dL}{dt} \qquad \text{(Eq. 4)}$$

Eq. 4 shows that the rate of expansion and contraction of the optical fiber can be detected as and frequency modulation of the lightwave.

In other words, we can detect the strain (elastic waves, changes in stress, etc.) applied to the optical fiber by reading the frequency modulation f_d of the optical fiber. Fiber optical Doppler sensors have been developed for sensors that make use of the Doppler effect when these optical fibers expand and contract (see **Fig. 4**). To increase the sensitivity of these sensors and make reception from all directions possible, the optical fiber is wound into a coil; therefore, the it has the characteristics of being able to obtain an output proportional to the rate of expansion and contraction of the fiber, having a broad receiving band of 1 Hz to 1 MHz and having a broad temperature range of –200°C to 250°C.

In addition, advantages of fiber optical Doppler sensors include (1) having high insulation properties, (2) having high resistance to electromagnetic noise, (3) having explosion prevention properties and not generating electrical sparks, (4) being capable of long distance measurements and (5) having a broad range of applicable environments. Therefore, disadvantages (2) through (5) for the conventional piezoelectric AE sensors described previously can in principle be resolved by using fiber optical Doppler sensors.

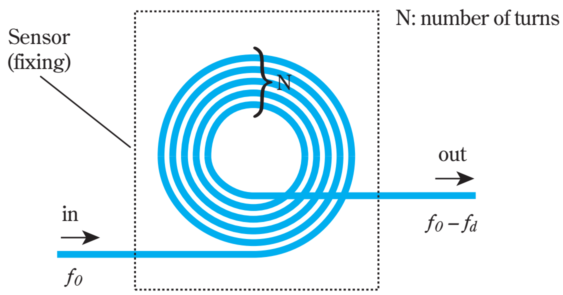

Fig. 4 Principle of FOD sensor

Fig. 5 is a conceptual diagram of a fiber optic AE monitoring system for pipe CUI. First, frequency f_0 lightwaves from a laser Doppler vibrometer light source in a measurement circuit are introduced into the to the optical fiber. The frequency of the lightwaves that are incident to the fiber optical Doppler sensor receive the AE arising because of the corrosion flaking and cracking and are modulated to f_0 through f_d. On the other hand, the amount of frequency modulation is detected using the heterodyne interferometric method. Specifically, a reference light with frequency f_M (80MHz) is added using a frequency modulator (AOM), creating $f_0 + f_M$ modulation. Furthermore, the difference in frequency $f_M + f_d$ of the laser light from the sensor and the laser light from the measurement circuit is introduced and f_d is detected. It is converted to voltage V by a frequency-voltage converter and output. A frequency analysis (FFT) is used on the original waveform data obtained at this time, and it is converted into extracted data such that the horizontal axis is frequency and the vertical axis is spectral power. This waveform analysis is important as a technique for discriminating noise and the AE caused by corrosion.

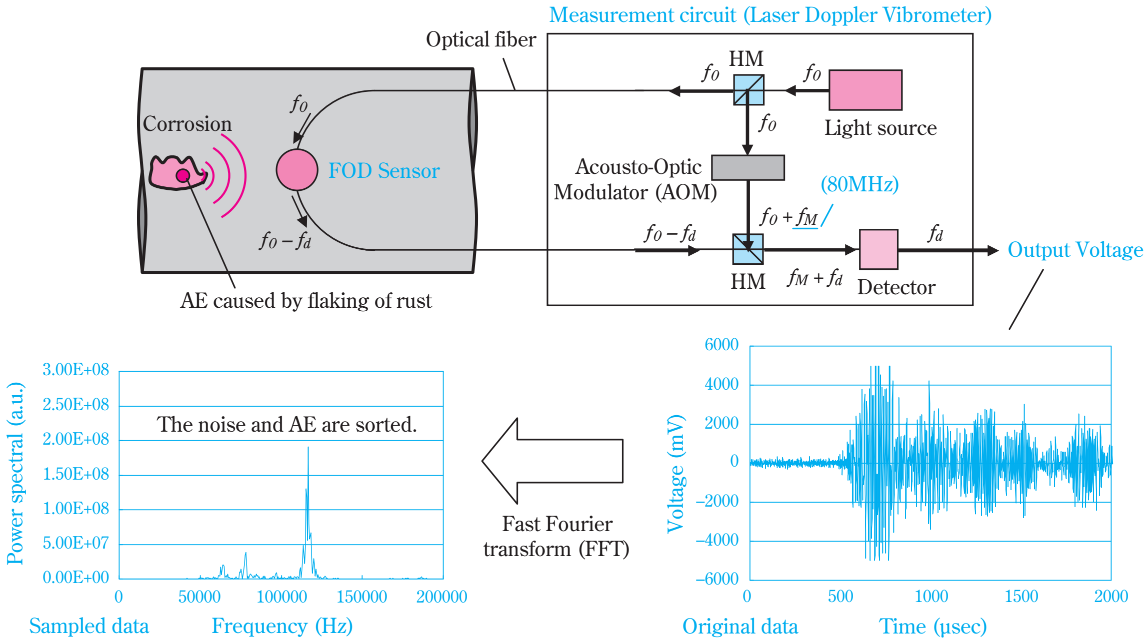

Fig. 5 Image of optical fiber of CUI

3. Mock-up piping for investigating CUI inspections

Up to now there have been actual records of fiber optic AE evaluations of areas with loosening base rock that accompanies underground storage tank excavation, but there are no records of use in CUI evaluations. Therefore, we fabricated mock-up piping like that shown in **Fig. 6** to investigate the possibilities of developing CUI inspection technology using fiber optic AE. Insulation was applied to a 5m carbon steel pipe, and heated silicon oil was circulated inside the pipe by a heating device. In addition, corrosion was accelerated artificially by pure water and salt where the amount dripped was finely adjusted to an extent giving rise to wetting and drying to efficiently generate CUI and further by heating to 60 to 70°C using silicon oil. A fiber optical Doppler sensor is positioned at any location on this mock-up piping and data collected regarding AE from this corrosion site.

In this investigation, we used a commercial layered fiber optical Doppler sensor that was a 65m optical fiber wound into a layered coil shape (see **Fig. 7**). This sensor is characterized by having an increased sensitivity because the optical fiber is installed in a layered form. Even though it has a broad band, it has the same or greater receiving sensitivity than a narrow band conventional piezoelectric AE sensor. When the layered fiber optical Doppler sensor is installed on the piping, it

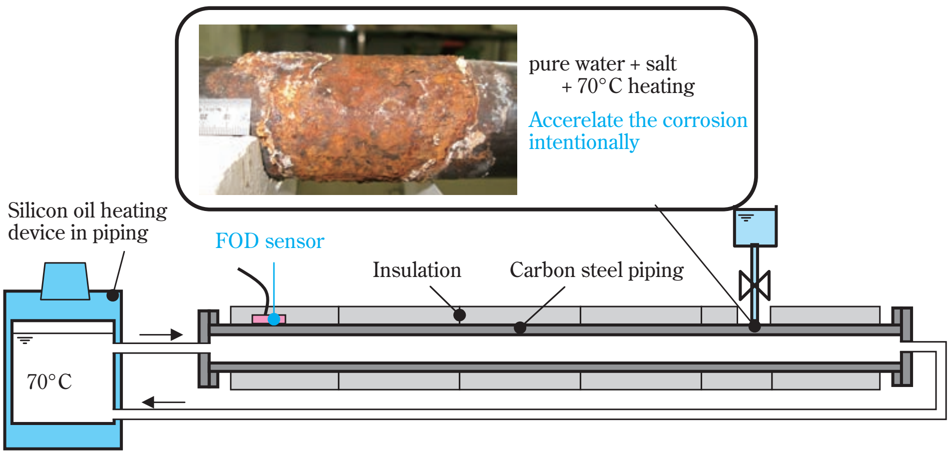

Fig. 6 Mock-up piping for CUI inspection investigation

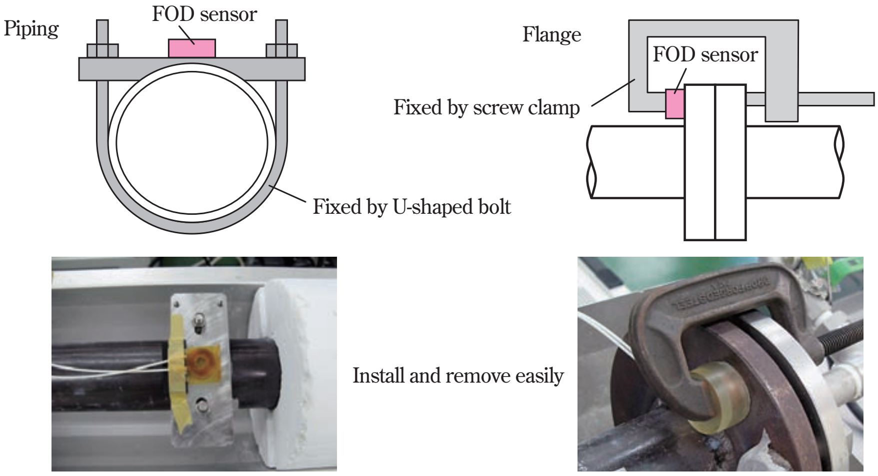

Fig. 7 FOD sensor installation

is secured using a U-bolt, and when it is installed on a flange, it is secured with a clamp. Either is extremely easy to install and remove, and like piezoelectric AE measurements, sending and receiving is possible through a commercial contact medium.

4. Results of measurements with mock-up piping[4)]

(1) Results of AE detection investigations at the initial stages of corrosion

We carried out tests investigating AE detection in the initial stages of corrosion in November 2007. The state of corrosion on the piping at this time is shown in **Fig. 8**. Corrosion swelling has yet to arise, and the parts that look white are salt that has recrystallized. The fiber optical Doppler sensor was installed at a position 300mm from the site of the corrosion. The AE detection results are shown in **Fig. 9**. The bar graph shows the number of AE hits per hour, and the plotted line shows the cumulative AE hits.

This proves that AE measurements are possible at initial stages of corrosion like this. In addition, there

Fig. 8 Corrosion of piping (1st monitor: 11/2007)

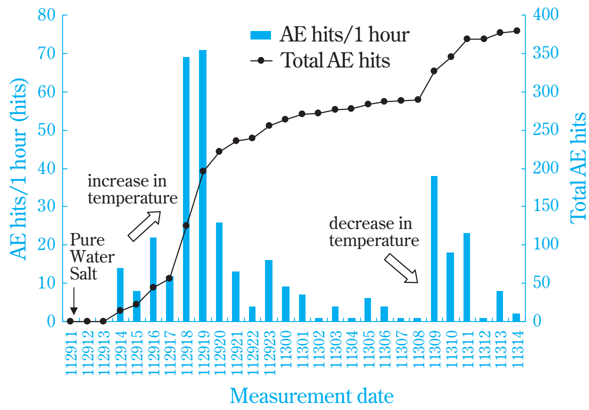

Fig. 9 AE hits by initial corrosion

was an abrupt increase in AE after the start of the pure water and salt dripping and after the increase in temperature. In addition, the AE converges after a certain amount of time, and the AE increases when the oil temperatures lowered. The increase in the number of AE hits when the wetting and drying and changes in temperature are applied in this manner is a major characteristic of AE.

In addition, the AE waveforms recorded at this time are grouped into three patterns, ones that have frequencies exceeding 100kHz, ones at 50 to 100kHz and ones at 10 to 50kHz as shown in **Fig. 10**. These results can be said to be due to the fiber optic AE being able to receive a broad band. In measurements on actual equipment, it is important to selectively receive the AE in a frequency band from these three patterns of frequencies that does not overlap measurement noise. In addition, the lower the frequency for the AE, the further the propagation is, but since it is easy for management noise to arise on the low frequency side, it is necessary to measure the AE

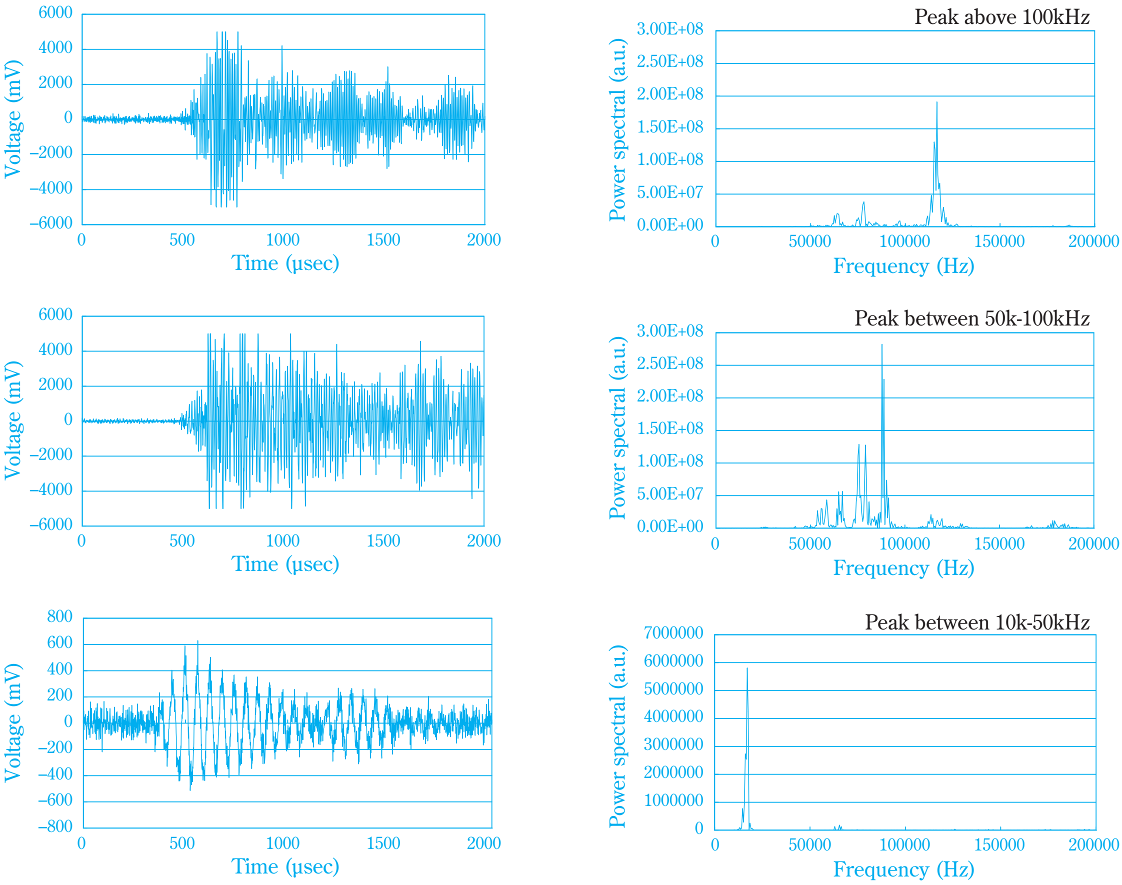

Fig. 10 Data of original AE and Frequency spectrum pattern

pattern at as low a frequency as possible that does not overlap with the noise.

(2) Results of investigations into distances where AE is detectable

In January 2008 we conducted verifications of the distances at which AE could be detected. The state of corrosion on the piping at this time is shown in **Fig. 11**. Corrosion swelling has arisen, and in the progress of the corrosion can be seen. We installed the fiber optical Doppler sensor at positions 2,000mm, 3,000mm and 3,900mm from the site of the corrosion. **Fig. 12** shows the AE detection results at the 3,900mm position. In this manner we confirmed that it was possible to detect AE at a sufficient sensitivity even at maximum distance of 3,900mm. In addition, we found that the 50k to 100kHz frequencies were detected the most out of the three AE patterns. If no noise is present in this range of frequencies in measurements on actual equipment, which are a problem we will take up later, we can efficiently detect AE caused by corrosion.

Fig. 11 Corrosion of piping (2nd monitor: 01/2008)

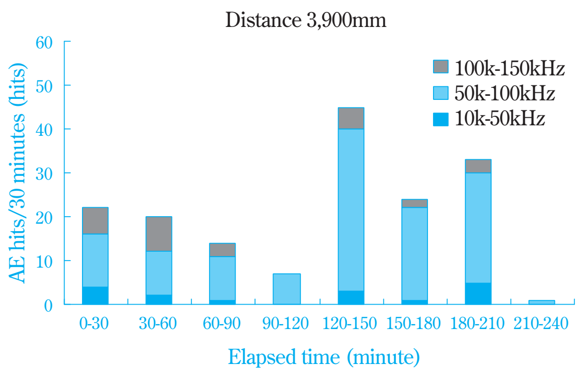

Fig. 12 AE hits by corrosion progress at 3,900mm

(3) Comparison of AE detection results on the piping and flange parts

In March 2008 we compared AE detection on the piping and flange parts. The state of corrosion on the piping at this time is shown in **Fig. 13**. The corrosion swelling has grown further, and cracking heads appeared in part of the corrosion swelling. Fiber optical Doppler sensors were installed on the pipe at 3,900mm and on a flange part at 3,950mm from the site of the corrosion is shown in **Fig. 14**.

Fig. 13 Corrosion of piping (3rd monitor: 03/2008)

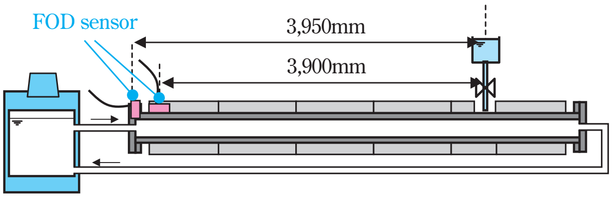

Fig. 14 The position of FOD sensor installation

Fig. 15 shows a comparison of the results for AE detection on the piping and flange parts. While these results show poorer sensitivity than on the pipe itself, we confirmed that there was excellent AE detection on the flange part. If it is possible to detect AE on the flanges, we can expect to only remove the insulation from the flange parts to make AE measurements.

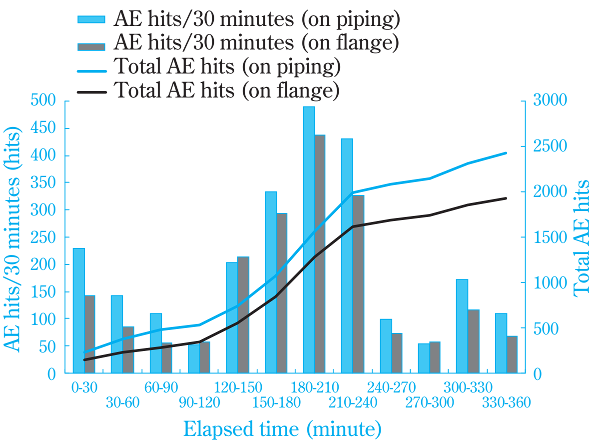

Fig. 15 Comparison of the situation of AE hits piping and flange

(4) Investigation of corrosion progress and number of AE hits

To make a comparison with the number of AE hits from the corrosion site in January 2008 and the number of AE hits from the corrosion site in March 2008 after the corrosion had progressed further, we installed a fiber optical Doppler sensor at the same 3,900mm position and compared the results of measurements. The results of that comparison are shown in **Fig. 16**. However, the AE measurements in January 2008 were only made up to 240 minutes. As is clear from this figure, we can see that the number of AE hits in March has clearly increased with the progress in the corrosion compared with those in January (an approximately tenfold AE hit number at 240 minutes). The AE method cannot quantify the area of the corrosion or depth of material reduction, but if the volume of the corrosion swelling increases, the probability of AE hits increases. Therefore, we can consider the possibility of evaluations using the degree of correlation with the progress of the corrosion by counting the number of AE hits.

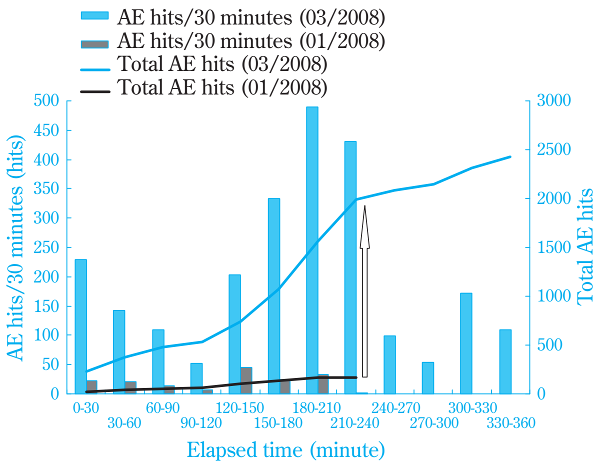

Fig. 16 Comparison of the number of AE hits 01/2008 and 03/2008

Fiber Optic AE Measurements in Actual Equipment[5)]

1. Selection of stationary equipment and environmental noise separation

As was discussed earlier, it is possible to inspect pipes without tearing down insulation even if it cannot be called complete, but there is no method for equipment other than tearing down insulation and visual inspection. Therefore, we selected an operating vertical reactor (3.8m inside diameter, column length approximately 28m) where CUI might be revealed as the equipment to be targeted for measurements. There was a plan for the insulation to be removed from the entire surface of the column in this equipment and to perform the work of eliminating the corrosion that had arisen due to CUI by surface preparation. Therefore, fiber optical Doppler sensors were installed along with this work, and after the corrosion had been removed, AE measurements were made. We investigated the separation of the AE from corrosion under conditions that included the environmental noise due to the fluid inside. Moreover, if a CUI inspection method that is more efficient than visual inspection is established for stationary equipment like vertical reactors, installation of scaffolding and tearing down the insulation will become unnecessary, which has great merit in terms of costs.

2. Attachment of fiber optical Doppler sensors to vertical reactor

The positions for attaching the fiber optical Doppler sensors to the vertical reactor are shown in **Fig. 17** and **Fig. 18**. Four (four channels) fiber optical Doppler sensors were attached at intervals of approximately 3,000mm with a pitch of 90° around the circumference positioned vertically at 9,500mm based on the girth line for the lower mirror and body of the main body of the reactor.

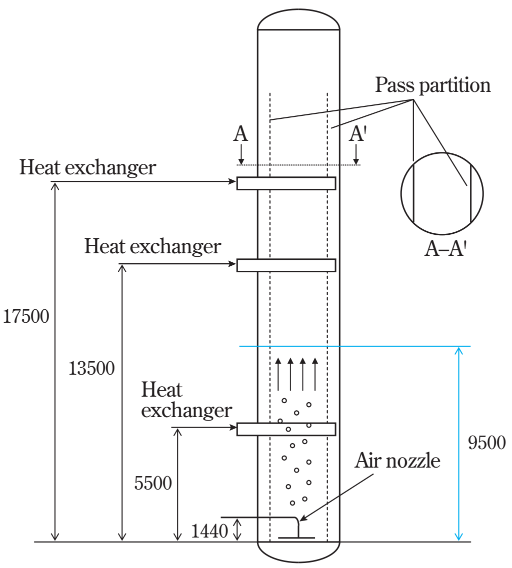

Fig. 17 Structure of the vertical reactor

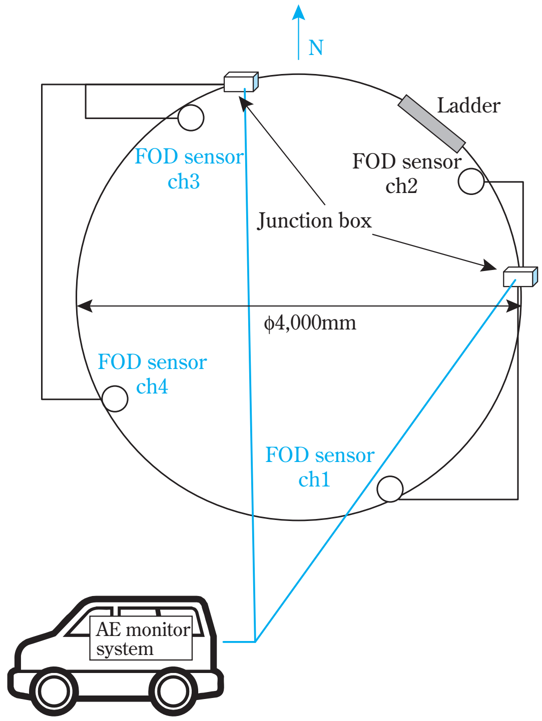

Fig. 18 The position of FOD sensor installation and wiring for signal cable

As is shown in **Fig. 19**, the fiber optical Doppler sensors were protected by a waterproof case. After the surface coating on the outside of the reactor was removed with sandpaper, they were glued using a heat resistant epoxy resin adhesive and secured from the top using aluminum tape. The signal cables extending from the fiber optical Doppler sensors were each collected in a jack box as ch1, ch2, ch3 and ch4 (see **Fig. 20**), and a cable was extended from there to the ground. When AE measurements are made, a terminal box installed on the aboveground part and a fiber optical Doppler interferometer installed in a vehicle are connected by a cable (see **Fig. 21**). One of the major merits of this method is that, once the fiber optical Doppler sensors are connected to the actual equipment, inspections can easily

Fig. 19 The condition of FOD sensor installation on the vertical reactor

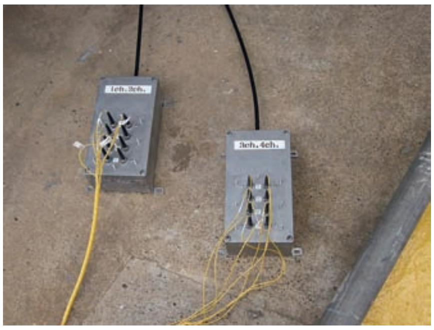

Fig. 20 Connection of 4ch FOD sensor to junk BOX

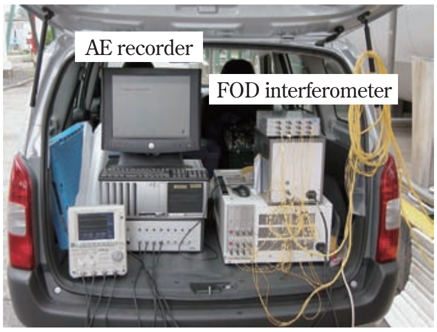

Fig. 21 AE measurement condition in which FOD interferometer and collection analysis device are loaded into car

be carried out from the aboveground part which is at a distance from the sensors.

3. AE measurement results before and after repair of corroded parts

The results of AE measurements before and after the removal of the corrosion due to CUI that had arisen on the equipment by surface preparation are shown in **Fig. 22** and **Fig. 23**, respectively. As a result, a large amount of AE was detected in the state where the corrosion due to CUI was present, and after the corrosion had been removed, the number of AE hits was reduced to approximately 1/10. Therefore, we assumed that we were also able to detect AE that can be thought of as being caused by corrosion on actual equipment. In addition, there was also a large difference in the number of AE detections by each of the sensors before removal of the corrosion. In visual inspections after the insulation was removed, multiple corrosion sites were found to be present in the vicinity of the sensors where there were many AE detections. In this manner, we were able to confirm that there was a good correlation between the state of corrosion and the state of AE detection in tests carried out using actual equipment.

However, the AE shown in **Fig. 23**, which was detected after the removal of the corrosion, is not caused by corrosion. It can be assumed to be environmental noise that could not be eliminated by filtering using current waveform processing techniques. Being able to separate out this environmental noise as precisely as possible is extremely important for using this technology at actual sites.

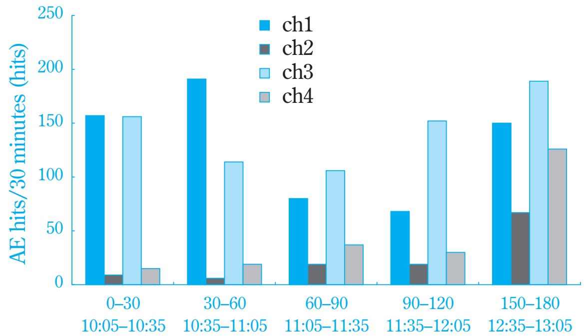

Fig. 22 AE hits/30 minutes before removing rust

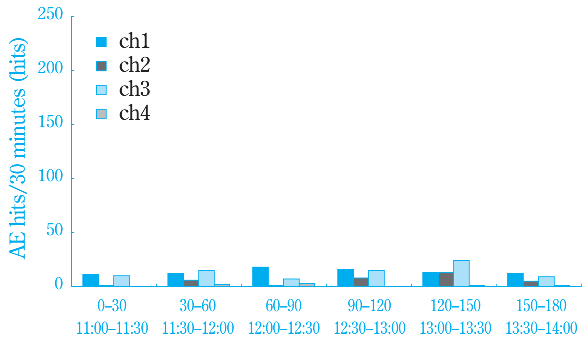

Fig. 23 AE hits/30 minutes after removing rust

4. Investigation of environmental noise separation

The typical AE waveforms detected before and after the removal of the corrosion and the AE waveforms from corrosion that were obtained in the investigations with the CUI mock-up piping are shown in **Fig. 24** through **Fig. 26**, respectively. Since the rise of the waveforms, the duration, etc. have a very similar shape, it can be assumed that separating the environmental noise out using the shape of the waveforms will be difficult.

Next, the frequency distributions for the peak frequency (frequency with the largest amplitude in the frequency spectrum) and the barycentric frequency (frequency that is the center of gravity for the area of the frequency spectrum) for a measurement time of three hours of AE detected before and after the removal

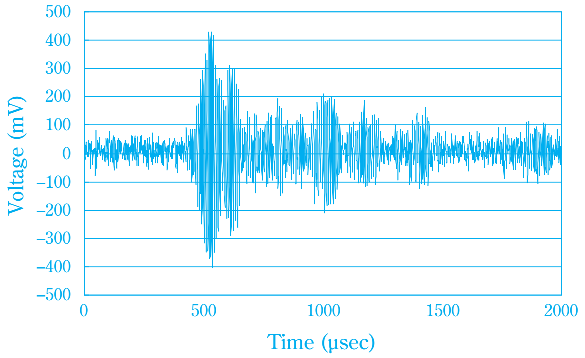

Fig. 24 Representative Waveform of AE obtained before removing rust

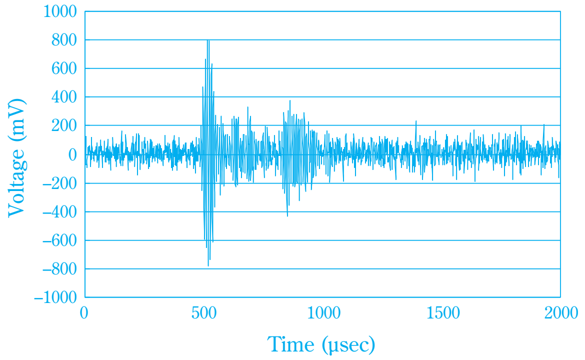

Fig. 25 Representative Waveform of AE obtained after removing rust

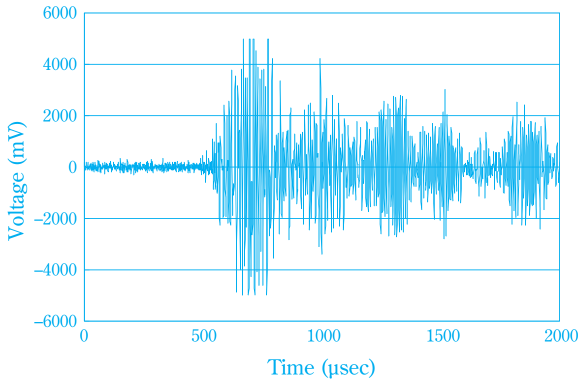

Fig. 26 Representative Waveform of AE obtained from mock-up piping

of the corrosion are shown in **Fig. 27** and **Fig. 28**. Both of the frequency bands are substantially the same as the corrosion AE frequency band (10kHz to 150kHz) obtained in the investigations with the CUI mock-up piping. In addition, since the frequency distributions for the AE peak frequency and the barycentric frequency before and after the removal of the corrosion have very similar distribution shapes, it can be assumed that environmental noise separation by frequency analysis will be difficult.

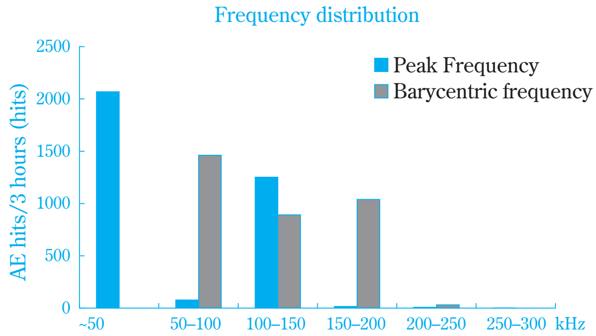

Fig. 27 Frequency distribution of AE obtained before removing rust

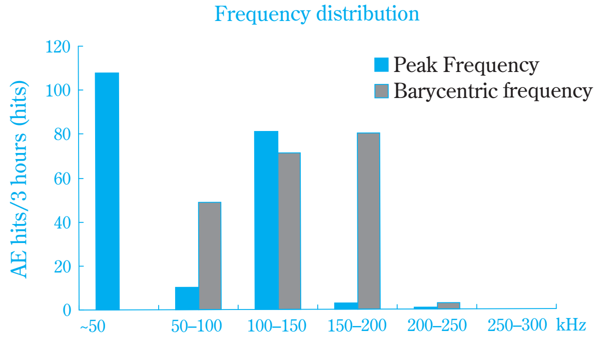

Fig. 28 Frequency distribution of AE obtained after removing rust

Next, the frequency distributions for the maximum amplitude and number of AE hits for a measurement time of three hours of AE detected before and after the removal of the corrosion are shown in **Fig. 29** and **Fig. 30**, respectively. There are many small maximum amplitudes for AE before the removal of the corrosion, and as the maximum amplitudes increase, the number of AE hits decreases. On the other hand, while the shape of the distribution for AE after removal of the corrosion is roughly similar to the AE before removal, a clearly significant difference can be seen in this frequency distribution instead of the small maximum amplitudes being the most common. Therefore, we attempted a comparison using the *m* value (shape parameter for the distribution function) to make a more easily understood numerical conversion for these results. The *m* value is the slope of the distribution graph line obtained when two axes in the graphs for the frequency distributions of the maximum amplitude and hits for AE shown in **Fig. 29** and **Fig. 30** are shown logarithmically. The corrosion AE *m* values obtained for the AE detected before and after the removal of the corrosion and in the investigations with the CUI mock-up piping are shown in **Fig. 31**.

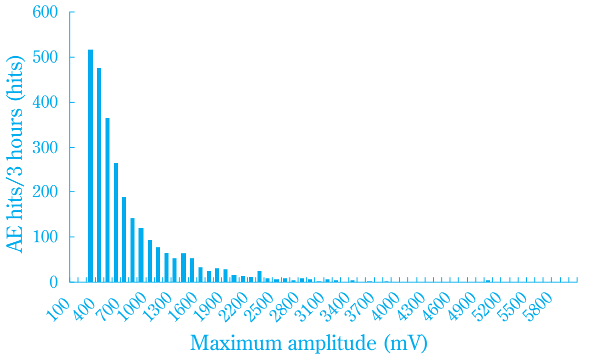

Fig. 29 Distribution of AE hits and maximum amplitude obtained before removing rust

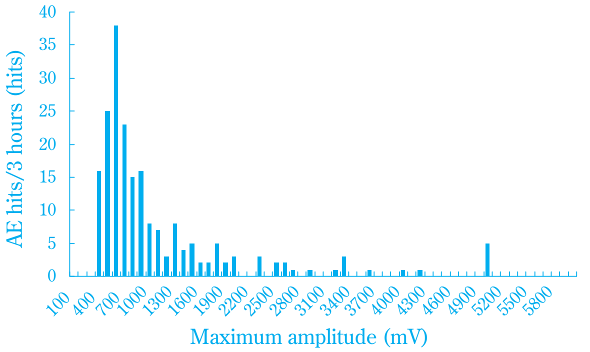

Fig. 30 Distribution of AE hits and maximum amplitude obtained after removing rust

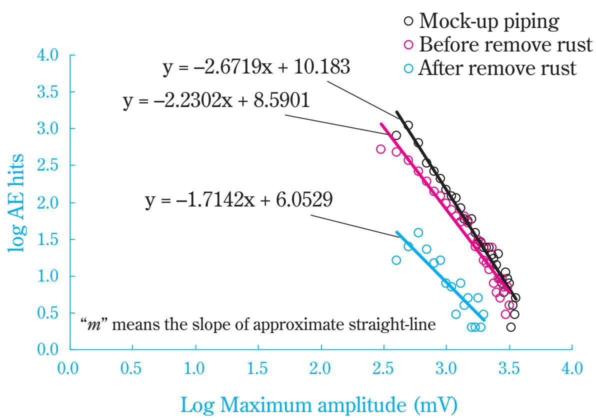

Fig. 31 Comparison by *m* value (Shape parameter)

In these results, the *m* values for AE before and after the removal of the corrosion were –2.23 and –1.71, respectively, and the *m* value for the AE from the corrosion in the CUI mock-up piping was –2.67. It was found that the AE frequency distribution before the removal of the corrosion was very similar to the AE frequency distribution from the corrosion on the CUI mock-up piping and that the frequency distribution of the AE after the removal of the corrosion differed. These results suggested that it would be possible to separate AE due to corrosion and the pseudo-AE due to the environmental noise by finding the *m* value.

However, to use this separation technique at actual sites, we will require the accumulation of more fundamental data based on laboratory results and the accumulation of separation data for AE due to corrosion and environmental noise through the accumulation of tests with actual equipment on site.

Summary

The AE arising from corrosion swelling was captured roughly in the frequency range of 10kHz to 150kHz. In addition, it was shown that AE could be captured even at a maximum length of 4,000mm. This shows that it is possible to inspect a range of 8,000mm left him right with a single sensor, and since there was plenty of margin in the sensitivity, we can assume that even longer distances can be inspected. In addition, even if the sensor was installed on a flange part, it was possible to capture the AE from the pipe part in the same manner. Furthermore, AE that was thought to be caused by corrosion could also be detected in actual equipment, and it was suggested that separation of corrosion AE from environmental noise would be possible by carrying out evaluations of the *m* values (shape parameter). Since fiber optic AE sensors have explosion prevention from the beginning, normal installation of the sensor parts may also be performed in plants that have where explosions must be prevented such as petrochemical plants. We hope to accumulate more data in the future and move toward making this practical rapidly.

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