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Research on using resistant sensor to predict corrosion under insulation of carbon steel

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Abstract: Corrosion under insulation (CUI) is very common and severely occurs in chemical/oil and gas industries, however, it is difficult to detect this corrosion by non-destructive testing (NDT) techniques. Carbon steel resistant sensors were used to determine CUI in this research. The output voltage values of the sensor were measured over time and from which the corrosion loss in sensor's thickness was calculated. Carbon steel samples were exposed to the sensors under the same conditions for the same periods, and the corrosion loss of the samples was determined by weight loss. The results show that when the sensors were corroded within 10-20 % the corrosion loss of carbon steel samples is equivalent to that calculated from the output data of the sensors with a standard deviation of 6 - 24 %. These results demonstrate the high potential of resistance sensors in determining CUI and predicting damage of industrial components and pipes.

Keyword: resistant sensors, corrosion under insulation (CUI), non-destructive testing (NDT), corrosion loss.

Classification numbers: 2.9.1, 2.10.1, 3.7.3.

1. INTRODUCTION

Corrosion under insulation (CUI) is very common and severely occurs with industrial equipment devices and components. It is estimated that 40-60 % of total maintenance costs are spent on overcoming the consequences of CUI [1]. This type of corrosion is hardly detected by non-destructive testing (NDT) techniques [2]. There are many NDT methods used to detect CUI, including using ultrasonic probe sensors to monitor CUI [3,4], however their sensitivity is not high.

In general, the resistance of a material is directly proportional to the length and inversely proportional to the cross-sectional area of the material; in other words, for the same length of a material, the larger the cross-sectional area (S), the smaller the resistance (R) and vice versa [5].

$$\frac{R1}{R2} = \frac{S2}{S1} \tag{1}$$

$$U = IR \tag{2}$$

If the metallic component is uniformly corroded, there would be a loss in its thickness and consequently the cross-section is decreased, making the resistance increased in comparison to the original one. It is known that the resistance of a conductor is related to the voltage (U) between the two ends and the current flowing in the conductor according to formula (2) [5], based on which resistant sensors were used to investigate corrosion [6]. A resistant sensor has two circuits: the first circuit is painted to prevent corrosion (compared circuit), and the second one is bare metal that will be corroded. When applying DC current to the sensor, the measured voltage signals U1 and U2 will reflect the resistances in the circuits and the corrosion behavior of the sensor (Fig. 1).

Figure 1. The structure of resistant sensor.

Resistant sensors have been well using to monitor atmospheric corrosion [7]; however, there has been no publication on using resistant sensors to detect CUI. In this study, carbon steel resistant sensors and carbon steel samples were put together into a system for CUI testing in order to figure out the relation between the corrosion loss calculated from the sensor's output data and corrosion loss determined by the weight loss of the samples. Our results would pave the way for the development of resistance sensors in detecting CUI for the chemical/oil and gas industry.

2. MATERIALS AND EXPERIMENTAL METHOD

2.1. Materials

The material used is group B carbon steel according to ASTM standard – A106/A106M with chemical composition shown in Table 1.

The research samples have a donut shape with a width of 20 mm, cut from standard steel pipes with a diameter of 60 mm and a thickness of 4.75 mm.

The shape of a resistance sensor is shown in Fig. 1 with each circuit size being 102 x 3 x 0.53 mm.

The insulation material is standard rockwool used for steel pipes of 60 mm diameter. The technical parameters of the rockwool are as follows: density 120 kg/m^3, inner diameter 76 mm and thickness 50 mm.

Table 1. Chemical composition of the steel samples (wt.%).

	C	Mn	Si	S	P	Cr	Cu	Mo	V	Ni	Fe
wt.%	0.201	0.43	0.24	0.0123	0.0115	0.03	0.01	0.009	0.0026	0.0237	98.87

2.2. Experimental method

The CUI test was carried out according to ASTM G189 [8] - Fig. 2, the carbon steel sample and carbon steel resistant sensor were put into the same CUI testing system in order to compare the corrosion loss of the sensor and the sample. The testing system was assembled as in Fig. 2. The tests were performed at 50 °C , 80 °C and 120 °C temperatures with 0.1 %, 0.5 % and 1 % (wt) NaCl solutions. Relative humidity was maintained at > 80 %.

- Internal heater and temperature controller: the temperature on the outer surface of the sample was achieved via an immersion heater located inside a tube filled with heat transfer oil stable at the maximum intended testing temperature. The testing temperature was controlled with a deviation of ± 5 °C.

- The humidity controller: the NaCl solution is fed continuously to the CUI-system by a water feed hole with an on/off regulation valve to control the amount of solution in the system, maintaining the relative humidity of the CUI-system > 80 % (Fig. 2).

- The temperature of the testing sample and the relative humidity of the testing CUI system were measured using a Hioki temperature and humidity sensor, located near the test samples under insulation.

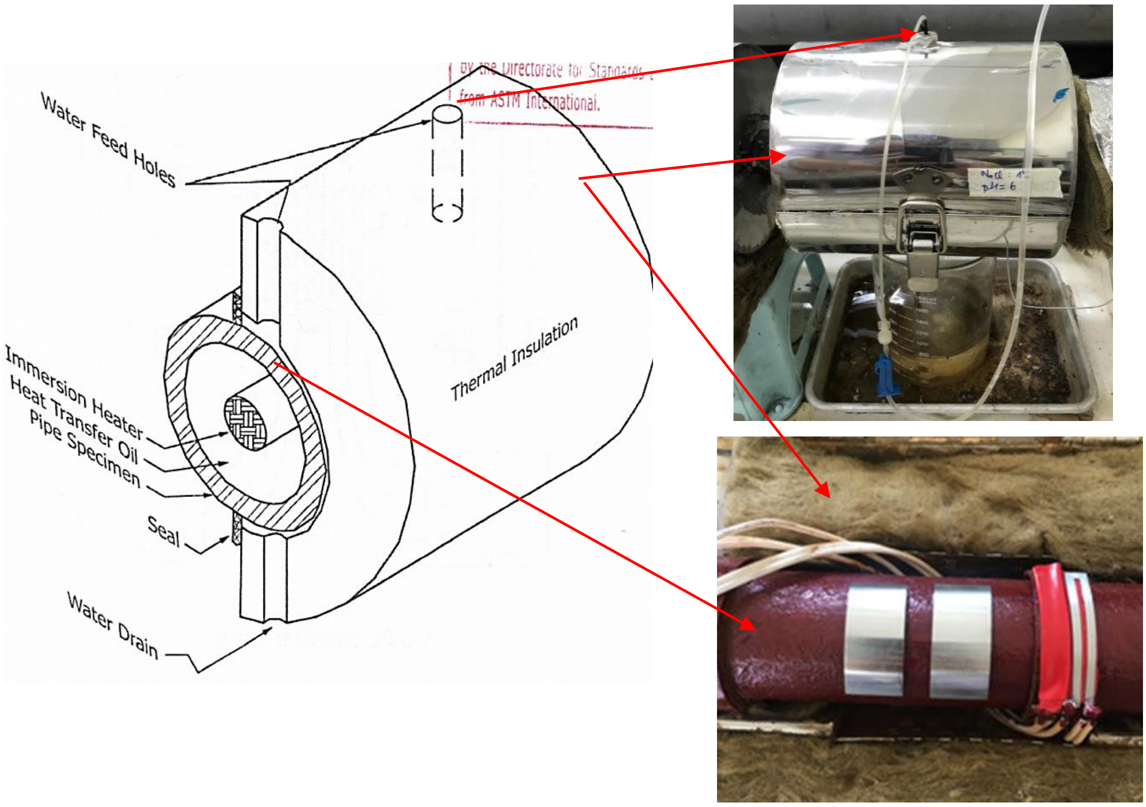


Figure 2. CUI testing system after assembling and position of the sensor and sample under insulation.

Corrosion loss of the steel sample was determined according to ISO 8407 and ISO 9226 [9,10]. The voltages U1 and U2 of the resistant sensor were determined when applying a current of 1.5 A to the sensor. This signal was measured daily until the voltage ratio U1/U2 was between 0.8 - 0.9 (corresponding to the corrosion thickness of the resistant sensor that reached about 10 - 20 % of the original thickness). At the end of the test, the thickness losses of the sample and the sensor were compared to evaluate the reliability of the resistance sensor in detecting CUI corrosion.

2.3. Theoretical basis

The main cause of CUI is the penetration and existence of moisture/aerated water (oxygen) and corrosive agents through the insulation at the cracked/broken sites (Fig. 3), or water leakage from water traps on the pipeline system, or from damaged seals/buffers causing water infiltration, 1, etc. [1, 2, 11]. Corrosion due to oxygen depolarization is usually uniform corrosion. However, due to occurring in narrow gap conditions, with the simultaneous presence of some other corrosive agents such as chloride ions, sulfide ions, etc., as well as due to the effects of stress, vibration, etc., during operation, CUI usually shows a localized mode of corrosion such as pitting corrosion, stress corrosion cracking, intergranular corrosion, fatigue corrosion, etc. [12 - 16]. For carbon steel pipes, CUI is mainly uniform corrosion.

In this study, the resistant sensor was installed under the insulation layer together with the carbon steel sample. The CUI corrosion tests were conducted to determine the correlation between the data obtained from the sensor and the test sample, thereby aiming to apply the sensor in CUI prediction.

According to formula (2), the resistance of the conductor is directly proportional to the voltage, when the constant current is applied to the measuring system. Formula (3) is obtained by combining formulas (1) and (2).

$$\frac{U1}{U2} = \frac{S2}{S1} \tag{3}$$

The widths of sensor circuits are equal, so formula (3) is rewritten as follows:

$$\frac{U1}{U2} = \frac{d2}{d1} \tag{4}$$

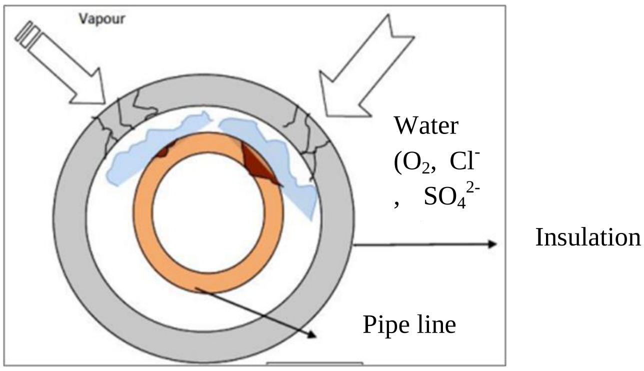


Figure 3. Infiltration of moisture and corrosion agents through the insulation layer [2].

In which U1 and U2 are the voltages measured on the painted and unpainted circuits of the sensor, respectively; while d1 and d2 are the original thickness and the remaining thickness of the sensor after corrosion, respectively. The voltage ratio will thus indicate the percentage of the sensor thickness that has been reduced due to the corrosion process. The CUI test will end when the ratio (U1/U2) in formula (4) has a value from 0.9 to 0.8.

3. RESULTS AND DISCUSSION

3.1. Test results on carbon steel samples

At the end of the test, except for the samples examined at 50 °C with 0.1 and 0.5 % NaCl solutions, the remaining steel samples were uniformly corroded with the corrosion product covering almost the entire surface. Except for the samples tested at 50 °C with 0.1 and 0.5 % NaCl solutions (Table 2), the corrosion depths of the carbon steel samples increase with the temperature and NaCl solution concentration (Table 3).

Table 2. The appearance of the surface sample after CUI test.

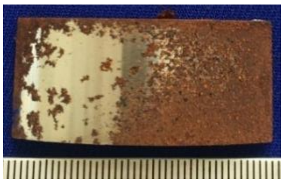
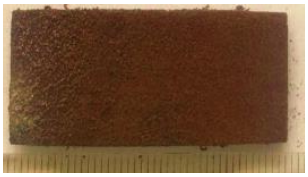
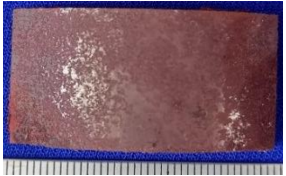
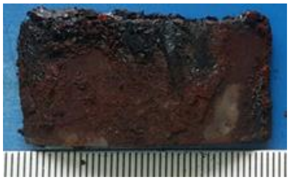
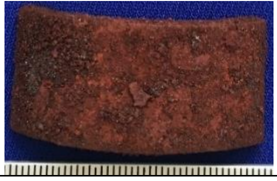
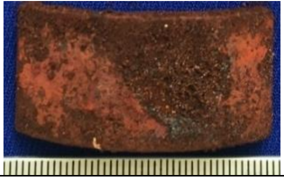
Testing temperature °C	Surface of carbon steel samples after CUI test		
	0.1 % NaCl Solution	0.5 % NaCl Solution	1 % NaCl Solution
50			
80			
120			

Table 3. Corrosion depth of carbon steel samples after CUI test.

Testing temperature, °C	Corrosion depth, mm		
	0.1 % NaCl solution	0.5 % NaCl solution	1 % NaCl solution
50	0.0079	0.0334	0.1774
80	0.0568	0.0718	0.1889
120	0.0967	0.1489	0.2212

3.2. Test results of the resistant sensors

The CUI testing results of the resistant sensors are given in Figs. 4 and 5, as well as in Tables 4 and 5. Similar to the steel samples, the sensors were uniformly corroded with corrosion product covering almost the entire surface (Table 5). Time by time, the U2 value will increase, reducing the U1/U2 ratio, and this ratio will change markedly when the sensors are corroded with a large enough area. The depth of corrosion calculated from the measured signals of the sensor according to formula (4) tends to increase with the temperature and concentration of the test solution (Table 4). The time duration until the ratio U1/U2 reaches 0.8 ÷ 0.9 varies depending on the temperature and concentration of the test solution, thus the testing time is shorter when increasing the testing temperature and the concentration of NaCl solution put into the insulation layer (Figs. 4 and 5).

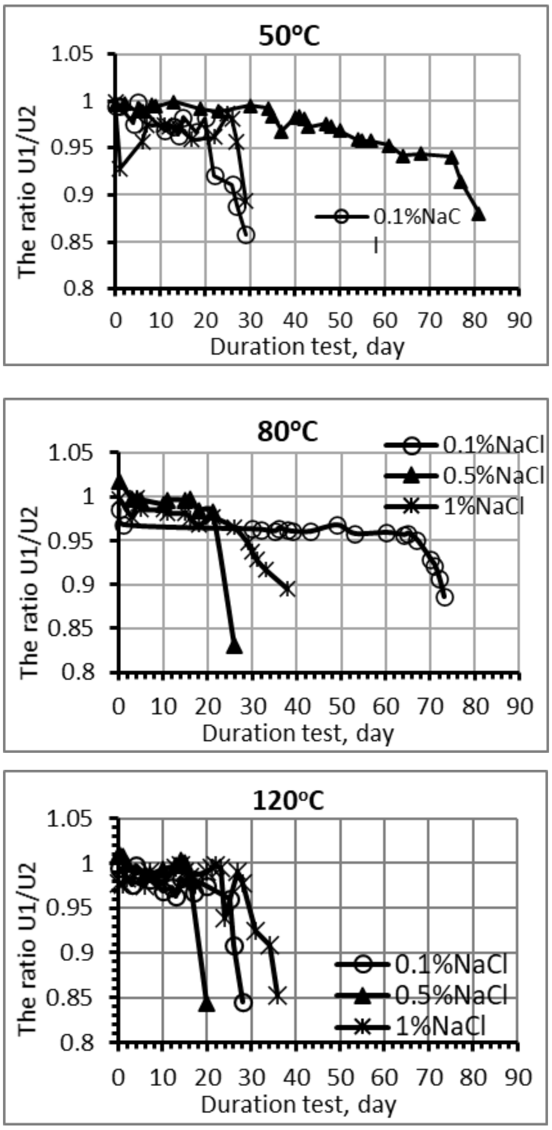


Figure 4. Change in U1/U2 ratio of resistant sensors depending on testing time and concentration of NaCl solution at different testing temperatures: 50 °C, 80 °C and 120 °C.

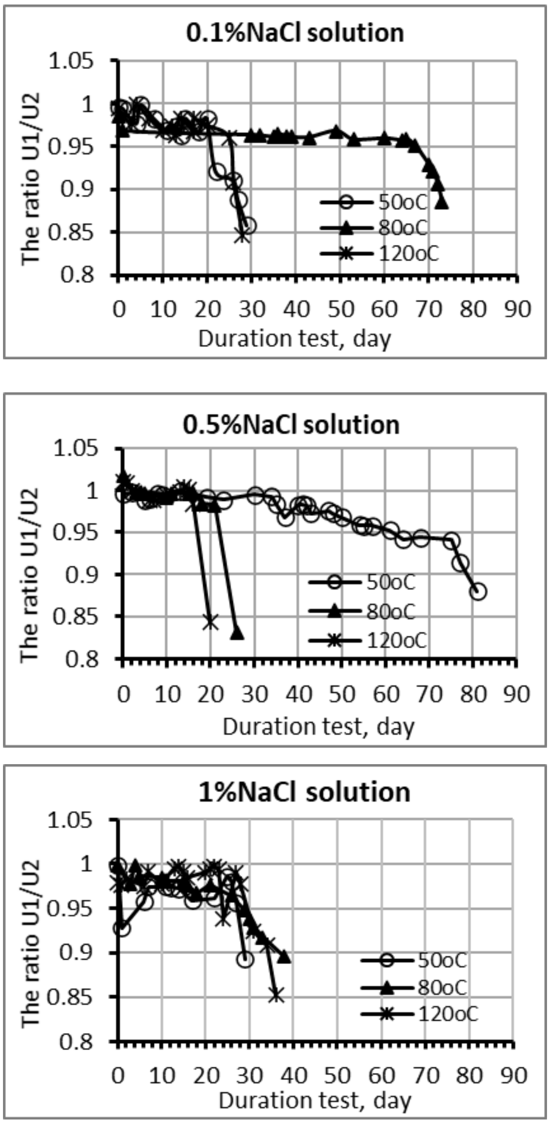
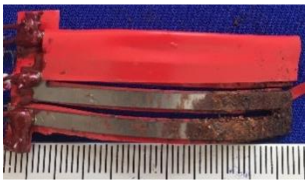
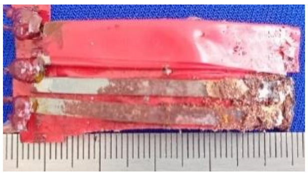
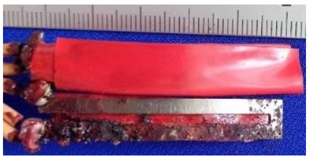


Figure 5. Change in U1/U2 ratio of resistant sensors depending on testing time and testing temperatures at different concentrations of NaCl solution: 0.1 %; 0.5 % and 1 %.

Table 4. Corrosion depth of the sensors after CUI test.

Testing temp, °C	Corrosion depth, mm		
	0.1 % NaCl solution	0.5 % NaCl solution	1 % NaCl solution
50	0.0753	0.0632	0.0945
80	0.0606	0.0895	0.0553
120	0.0817	0.0831	0.0783

Table 5. Corrosion behavior of the sensors surface after CUI test.

Temperature, ^{o}C	Sample surfaces after CUI test		
	0.1 % NaCl	0.5 % NaCl	1 % NaCl
50			
80			
120			

3.3. Discussion

The resistant sensors were tested in parallel with the carbon steel sample in the same corrosive environments under the insulation. At the end of the test, the same uniform corrosion mechanism was observed on the steel samples and the resistance sensor. Therefore, resistant sensors can be used to detect the corrosion of carbon steel under the insulation layer.

According to [6], the depth of corrosion has a strong influence on the accuracy of the measured signal from the resistant sensors, accordingly the corrosion depth of the sensors needs to be less than 1/3 of the original thickness of the sensor. As seen in Table 6, when testing the sensors with 1 % NaCl solution, the ratio of the corrosion depth after testing to the original thickness is 0.53 mm which is greater than 1/3, so the corrosion depth of the carbon steel sample and the corrosion depth calculated from the sensor signals are not similar (Fig. 6). Therefore, it is necessary to design the sensor with a larger thickness in order to increase the accuracy of the sensor when testing in harsh corrosive environments.

According to [6], resistant sensors are not suitable to determine localized corrosion, because the sensor surface is only partially corroded, thus the corrosion depths will be different from area to area, which causes the resistance of the material to also vary between positions on the sensor. Therefore, the measurements of the sensor are not as accurate as in the case of uniform corroded surfaces. Tables 4, 5 and 6 show that the sensors tested at 50 ^{o}C with 0.1 % NaCl and 0.5 % NaCl solutions have not yet been corroded on the entire surface, but they were strongly corroded at the sensor edges, consequently, the corrosion thickness loss calculated from the sensor's measurement signals is much larger than that of the carbon steel sample tested under the same conditions. In this case, the ratio of the corrosion thickness loss to the original thickness of the sensor (Table 6) is less than 0.1. The effect of the edge corrosion on the measuring signal can be reduced using the sensor with a larger width, and simultaneous proper protection of sensor edges against corrosion.

When the sensors were tested at 80 °C with 0.1 % NaCl and 0.5 % NaCl solutions or at 120 °C with 0.1 % NaCl solution, the ratio of the corrosion depth to the original thickness of the sensor ranges from 0.1 to 0.2, the values of corrosion depth on the test steel samples and on the resistance sensor are relatively similar (standard deviations are 6 ÷ 24 %, calculated from Tables 3 and 4).

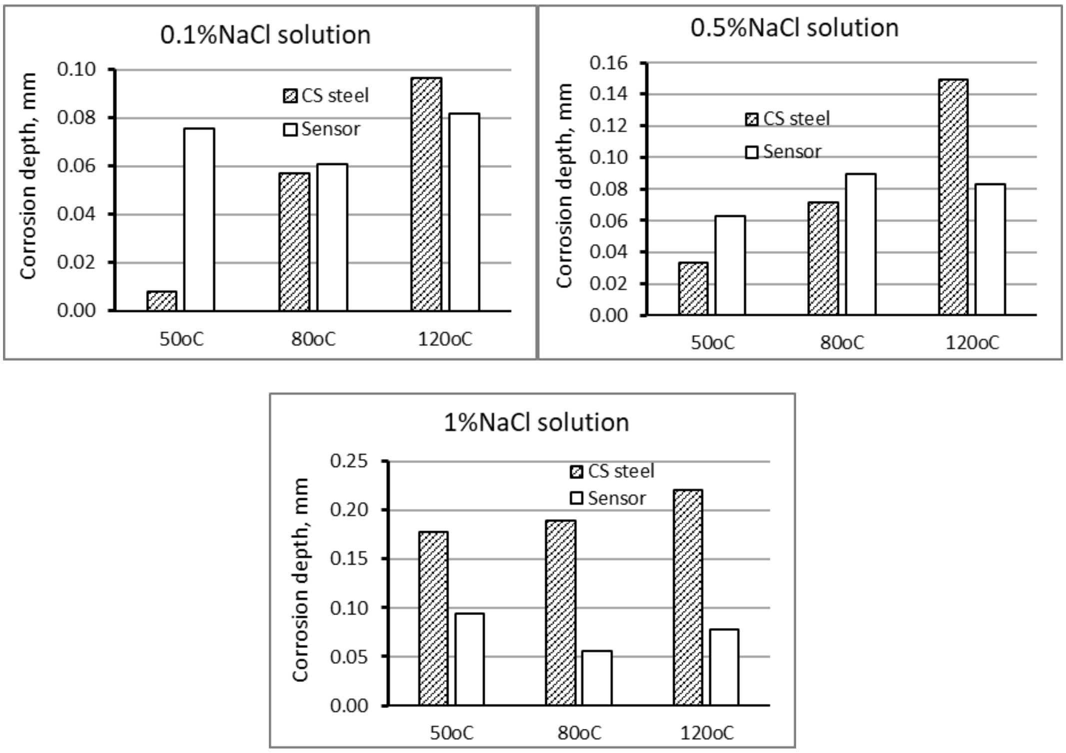


Figure 6. Comparison of corrosion depth of CUI test carbon steel sample and corrosion depth calculated from the observed data of the resistant sensor.

Table 6. Ratio of corrosion depth after CUI test to original sensor thickness.

Testing temperature, °C	Ratio of corrosion thickness to original sensor thickness		
	0.1 % NaCl solution	0.5 % NaCl solution	1% NaCl solution
50	0.0149	0.0630	0.3346
80	0.1071	0.1355	0.3565
120	0.1824	0.2810	0.4174

4. CONCLUSIONS

Resistant sensors can be used to detect CUI of carbon steel pipes based on a significant decrease in the U1/U2 ratio, corrosion is considered to occur when the U1/U2 ratio reaches 0.9. The corrosion depth is calculated using the ratio of the voltage values obtained from the sensor output and the original thickness of the sensor according to formula (4).

The deviation between the corrosion depth calculated from the sensor output and the corrosion depth determined by the weight loss of the sample depends on the severity of the corrosion environment. When the ratio of corrosion depth to the original thickness of the sensor is in the range of 0.1 ÷ 0.2, the corrosion depth values determined by the weight loss of the testing steel sample are similar to those calculated from the resistant sensor output.

The results of this study show that a resistant sensor with a thickness of 0.53 mm can be used to determine the corrosion depth of carbon steel exposed to the CUI system with 0.1 % NaCl and 0.5 % NaCl solutions at 80 ^{o}C and with 0.1 % NaCl solution at 120 ^{o}C, with the standard deviations of 6 ÷ 24 %.

To realize corrosion measurements using resistant sensors it is necessary to study different types of sensors with different sizes (width and thickness), and also fabrication techniques need to be further studied.

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CRediT authorship contribution statement. Hoang Lam Hong: Methodology, Investigation, Funding acquisition. Nguyen Van Trang: Formal analysis. Dinh Thi Duyen: Formal analysis. Le Thi Hong Lien: Supervision. Pham Thy San: Supervision. Bui Thi Van Anh: Supervision.

Declaration of competing interest. We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

1. Javaherdashti R. - Corrosion under insulation (CUI): A review of essential knowledge and practice, Journal of Materials Science & Surface Engineering **1** (2) (2014) 36-43.
2. James Higgins at TUEV Petro-Chem Inspection Service - Corrosion Under Insulation - Detection Methods and Inspection - NACE Section Meeting, Jun 18, 2013.
3. Corrosion under insulation Guidelines, S. Winnik, 2nd Edition, 2014.
4. Ultracorr® Corrosion Monitoring System- User Manual, Rohrback Cosasco Systems, Inc.
5. https://en.wikipedia.org/wiki/Electricalresistivity and conductivity.
6. Pham Thy San - Research and manufacture sensor used to evaluate the corrosion process of metal materials, Doctoral thesis 2005, pp. 93-94
7. Prošek T., Kouřil M., Dubus M., Taube M., Hubert V., Scheffel B., Degres Y., Jouannic M., Thierry D. - Real Time monitoring of indoor air corrosivity in cultural heritage institutions with metallic electrical resistance sensors, Stud. Conserv. **58** (2013) 117-128.
8. ASTM G 189-07, Standard Guide for Laboratory Simulation of Corrosion under Insulation.
9. ISO 8407, Metals and alloys – procedure for removal of corrosion products from corrosion test specimens.
10. ISO 9226, Corrosion of Metals and alloys – Corrosivity of atmospheres – Determination of corrosion rate of standard speciments for the evaluation of corrosivity.
11. Chloride stress corrosion cracking in austenitic stainless steel: assessing susceptibility and structural integrity. Research Report RR902. Health and Safety Exertive; 2011.

12. Susan Caines, Faisal Khan, John Shirokoff - Analysis of pitting corrosion on steel under insulation in marine environments, Journal of Loss Prevention in the Process Industries **26** (2013) 1466-1483.
13. Suresh Kumar M., Sujata M., Venkataswamy M. A., Bhaumik S. K. - Failure analysis of a stainless steel pipeline, Engineering Failure Analysis **15** (5) (2008) 497-504.
14. Masouri D., Zafari M., Araghi A. - Sulfide stress cracking of pipeline – case history, In: NACE International. Corrosion 2008 Proceedings, 2008.
15. ASM Handbook - In: Becker WT, Shipley RJ, editors. Failure analysis and prevention, 10th ed., vol. 11. ASM International, Handbook Committee, 2002.
16. Geary W. - Analysis of corrosion under insulation failure in a carbon steel refinery hydrocarbon line, Case Studies in Engineering Failure Analysis (1) (2013) 249-256.