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The Development of a Laboratory Simulation to Study the Surface Temperature Effect On Corrosion Under Insulation Formation

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Abstract: Corrosion under insulation (CUI) refers to external corrosion that appears between carbon steel piping or pressure vessels' external surfaces underneath jacketed insulation. There are many factors affecting the CUI corrosion rate. The chance of CUI exhibits a higher value between 50ºC and 175ºC. Understanding the corrosion rate at critical temperatures is important in assessing insulation performance and preparing maintenance plans. It is challenging to predict the CUI rate in a real working pipeline. A laboratory simulation following ASTM G189-07 is a laboratory scale to study and provide an alternative method for determining CUI corrosion rate at a controllable working temperature. At 80ºC, the CUI corrosion rate is lower than the CUI rate at 75ºC. The result shows that the corrosion rate on the carbon steel pipeline is not perpendicular to temperature.

Keywords: CUI, carbon steel, pipeline, mineral wool insulation

1. Introduction

Insulation is introduced in hot and cold piping systems to reduce heat loss during operation. The significance of insulation in refineries, petrochemical plants, or liquefied natural gas (LPG) terminals is crucial to protect against direct heat hazards for workers working close to hot surfaces. Plants with pipeline surface temperatures above 60°C are recommended for insulation as a safety precaution and to conserve heat above 93°C. In refrigeration and dehumidification systems, insulation systems are applied to reduce heat loss or to conserve cold heat. Usually, plants with operating pipelines below 10°C are recommended for insulation as a conservation method. Furthermore, insulation works as a condensation control on the surface of the pipe. Noise and vibration produced from the in-flow material are reduced by having insulation and protecting personnel from harmful acoustic levels.

Corrosion under insulation (CUI) refers to external corrosion that appears between carbon steel piping or pressure vessels' external surface underneath jacketed insulation. The National Association of Corrosion Engineers (NACE) defines corrosion as the deterioration of metal and its properties because of a reaction with the environment. However, the CUI occurs when trapped water inside the insulation completes the electrochemical cycle. The process of corrosion may happen regardless of wet or dry atmospheric conditions. The severity of corrosion in insulated components is greater than that of non-insulated components exposed to similar environments and conditions [1]. Trap water evaporates when

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sufficient heat comes from the pipe wall and condensates when the temperature reduces but remains in the insulation and initiates corrosion.

High temperatures play a significant role in CUI formation. An 80 ˚C pipeline surface temperature may alter the cathodic protection (CP) performance on steel pipelines [3] and reduce the effectiveness of the coating system [4]. However, the definition of high temperature here is dissimilar to high-temperature corrosion (HTC). HTC referred to corrosion appearing at temperatures over 204 ˚C [5].

1.1 Critical CUI Temperature Range

The corrosion rate increases with an increase in surface temperature. The temperature is the most significant design-related parameter contributing to CUI formation [6]. The critical point is when the temperature reaches boiling point and water starts to evaporate [7]. For insulated carbon steels, the risk of CUI is higher between temperatures of -12 ˚C and 175 ˚C [8]. Table 1 shows the temperature range suitable for CUI formation on typical pipeline materials.

Table 1 - Temperature and risk of CUI on typical pipeline materials [7]

Pipeline Materials	Temperature Range
Carbon Steel, Low Alloy Steel and 400 Series SS	-5 ˚C - 175˚C
300 Series SS	60 ˚C - 175˚C
Duplex SS	140 ˚C - 175˚C

The critical temperature range for CUI is important in evaluating the performance of the insulation system and preparing maintenance plans. It provides an early assumption on the corrosion rate. However, having a large and different temperature range left estimating the corrosion rate with higher uncertainty. Different ranges of temperature pose different CUI risk threats, as shown in Table 2.

Table 2 - Likelihood risk of CUI on carbon steel pipe

CUI Risk	Temperature Range		
	API [8]	NACE [9]	CINI [10]
Medium Risk	-12 ˚C to 77 ˚C 110 ˚C to 175 ˚C	-4 ˚C to 50 ˚C	-5 ˚C to 50 ˚C
High Risk	77 ˚C to 110 ˚C	50 ˚C to 175 ˚C	50 ˚C to 175 ˚C

2. Material and Methods

2.1 Benefits of CUI Laboratory Simulation

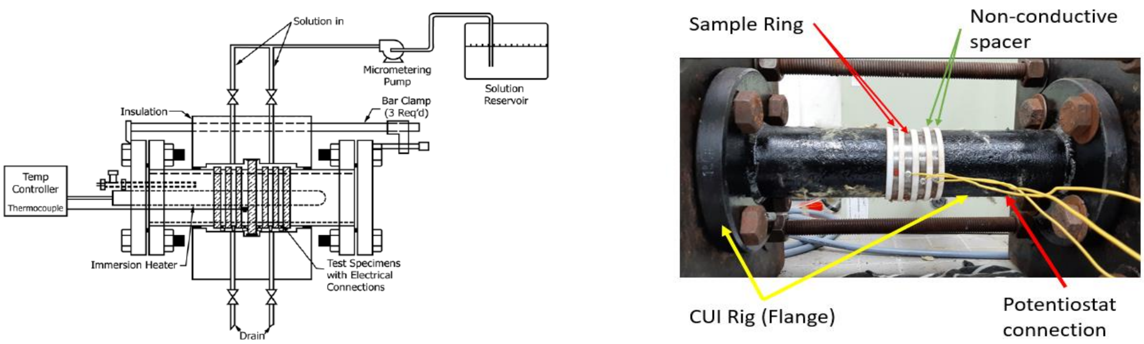
Corrosion behavior data is important to determine the CUI corrosion rate. Industrial is not keen to conduct in-situ monitoring and data collection due to the cost of insulation removal. However, the only effective way to conduct a visual inspection on CUI is by removing the insulation and external jacketing or cladding [11]. Indeed, much of the currently available CUI data is based on field and in-plant measurements of wall thickness reduction.

A CUI laboratory simulation is a laboratory corrosion test that can fulfil the limitations of a simple immersion test. Corrosivity caused by leachants in thermal insulation is usually measured using immersion tests. The test, however, does not present the actual CUI in the pipeline. Differences in exposure geometry, cyclic temperature, temperature, and wet or dry conditions in the environments need to be considered. The significant aspect of utilizing CUI laboratory simulation is the capability to replicate CUI exposure conditions.

CUI laboratory simulation is capable of idealizing annular geometry between outer pipe and inner insulation surfaces. The internal heating element produces a hot wall surface on which sets of operating temperatures can be put in place. Furthermore, the temperature controller connected to the CUI test rig leaves the test condition either isothermally or cyclically. Another important aspect of the CUI simulation test is the introduction of ionic solutions. An ionic solution prepared to replicate environmental conditions was dripped into the annular cavity between the piping and insulation. The solution is to hold inside insulation and release it through a valve at the bottom. The condition has made the wet and dry tests possible.

2.2 CUI Laboratory Simulation

A laboratory CUI simulation has been conducted to study the effect of temperature on corrosion rate. The arrangement and setup of the experiment are according to ASTM G189. The CUI simulation arrangement consists of a CUI rig, insulation, cladding, potentiostat, micrometer pump, heater, temperature controller, sample material, spacer, environmental solution, and mineral oil. Fig. 1 shows a schematic layout of CUI simulation equipment.



(a) **(b)**

Fig. 1 - (a) Schematic layout of CUI simulation equipment [10]; (b) sample ring and spacer position

Samples of carbon steel pipe were cut to become several pieces of rings. The ring's nominal diameter is 50.8 mm (2-inch) and 4.75 mm (0.187-inch) in thickness. The rings are cut equally to 6.35 mm (0.25-inch) in width. A small hole using the drill and tap method was made on the specimen ring surface as a potentiostat connection socket. A non-conductive spacer (Teflon) ring was put in between the ring specimens. Its surfaces should be ready with interlocking surfaces to assist in sealing mineral oil inside the test rig.

Environmental solutions are required in an accelerated exposure environment. It represents the industrial and coastal environments as having extreme atmospheric conditions. 100 ppm of NaCl dissolved in reagent water is used for this solution. The acidity of the solution was increased by the addition of H_2SO_4 (1M) until the pH value reached 6.0 at room temperature.

Industrial-grade mineral wool insulation with a 101.6 mm (4-inch) thickness was used throughout the experiment. Mineral wool insulation was preferred over pearlite or calcium silicate since it is a common pipeline insulation material. Mineral wools were covered using cladding made from carbon steel to hold insulation in place. The experiment is conducted at three different temperatures, considering only the high-risk CUI range. The risk of CUI is higher at temperatures above 50 ˚C.

2.3 Mass Loss Test

CUI simulation runs at three different temperatures: 65˚C, 80˚C and 95˚C. Temperature selection considers only temperatures in the high-risk CUI range. For each temperature setting, sample rings are exposed to an environmental solution for 72 hours. After completion, rings are taken for a mass loss test.

The corrosion rate for each ring on different operating temperatures was calculated using the mass loss approach. Each sample was measured for any weight loss before the mass loss test was conducted to find out the corrosion rate using Equation (1) below. The initial weight of samples was measured according to ASTM G1-03 prior to simulation.

$$\text{Corrosion rate} = \frac{K \times M}{A \times T \times D} \tag{1}$$

where K is constant (mpy: 3.45 x 10^6; mmpy: 8.76 x 10^4), M is mass loss (g), A is surface area (mm^2), T is exposure time (h) and D is sample's density (gcm^{-3}).

Surface area, A, here is corroded surface area, which is only able to be determined after simulation is done. This differs from the immersion test corrosion rate to which the surface area is exposed. According to ASTM G189, the minimum exposure time, T, for a single simulation is 72 hours. The amount is used for the entire test in this research. The density, D, of carbon steel pipe is 7.86 gcm^{-3} as outlined in ASTM G1-03.

3. Result and Discussions

3.1 Corrosion Rate

The final corrosion rate was calculated after the sample was taken off from the simulation rig and handled according to ASTM G1-03. Fig. 2 shows the condition of ring samples after 72 hours under insulation at an isothermal temperature setting. The uniform corrosion appears on all rigs, almost in a similar pattern. It covers more than 65% of the surface and is concentrated at the bottom of the ring. Visual observation makes it hard to determine which temperature setting produces harsh corrosion.

Fig. 2(a) is a ring connected to a working electrode, *WE*, terminal in a potentiostat set up after CUI simulation at 65˚C. Fig. 2(b) shows rings connected to the *WE* and reference electrodes and the *RE* terminal in the potentiostat set-up. After CUI simulation at 80˚C, uniform corrosion appears around the *WE* surface area. In *RE*, less surface area is covered with corrosion. Meanwhile, Fig. 2(c) shows rings connected to *WE*, *RE*, and *CE*. After the CUI simulation was performed at 95˚C, both *WE* and *RE* were covered with corrosion, while the counter electrode, CE, was less affected. The situation is similar in all temperature settings.

(a) **(b)** **(c)**

Fig. 2 - Sample ring condition after being exposed under insulation at (a) 65˚C; (b) 80˚C and; (c) 95˚C

Corroded surface area, A, is measured after the CUI simulation test is completed and before the ring is cleaned. The ring was put on plain paper, and then a sketch of the ring's shape was made. Carefully observe and determine the corroded surfaces. Then make marks on the sketch as shown in Fig. 3. Use a compass and protractor to plot the angle of the affected area. We used Equation (2) to calculate all the corroded surface areas on each ring. The corrosion result of the CUI simulation is shown in Table 3.

$$A = ring\ width\left(\frac{effected\ angle}{180} \times \pi\right) \quad (2)$$

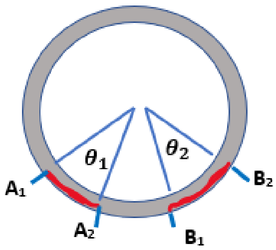
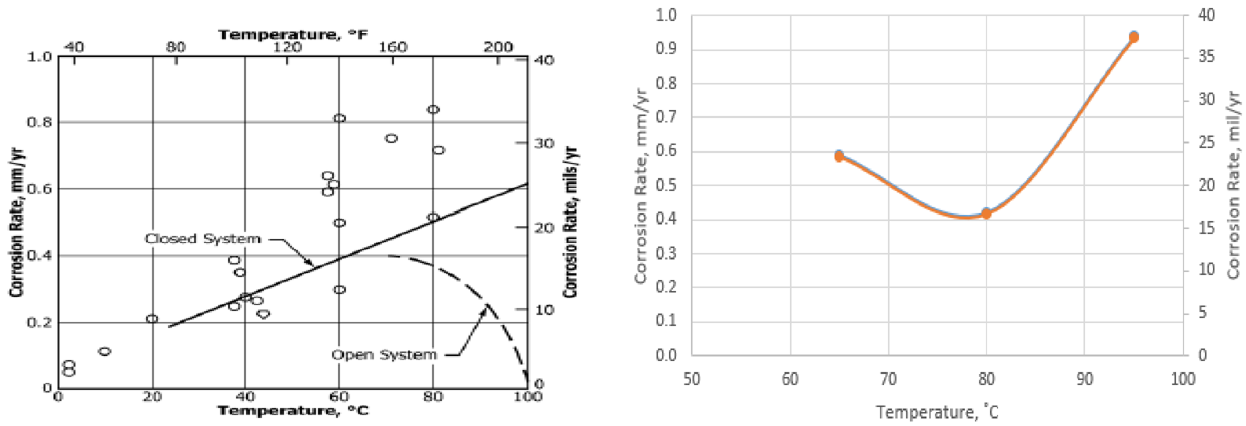


Fig. 3 - Marking the corroded surface area

Table 3 - Corrosion rate at different surface temperature

Corrosion Rate Unit	Temperature 65˚C	80˚C	95˚C
mm/year	0.5893	0.4208	0.9485
mil/year	23.2106	16.5712	37.3543

It is proposed that the actual CUI rate in an open system concaved downward and approached zero as temperature increased. Meanwhile, in a closed system, the corrosion rate gradually increases, depicting a positive gradient line (Fig. 4). In this CUI laboratory simulation, the CUI corrosion rate is following an open system behavior at a temperature below 80˚C. The corrosion rate continues to elevate at higher surface temperatures. The CUI corrosion rate at 65˚C is higher than the corrosion rate at 80˚C. Wetted time exposure contributes significantly to the formation of harsh CUI in a closed system. Indirectly, insulation material that retains water longer will be prone to producing harsh CUI.



(a) (b)

Fig. 4 - (a) Comparison of actual plan CUI corrosion rates measurements (Open Data Points Shown is for Plant CUI) with Laboratory Corrosion data obtained in open and closed systems [11]; (b) CUI corrosion rates obtained using laboratory simulation

4. Conclusion

The CUI corrosion rate is not proportional to the increase in temperature. A specific operating temperature needs to be determined to help in obtaining a much more accurate corrosion rate for monitoring and maintenance purposes. Further investigation is required to understand why the rate is not proportional to the increase in temperature. Even though NACE and CINI (Table 2) suggest CUI is unlikely to form at temperatures over 175˚C, the temperature gradient shows that CUI formation may appear at that temperature range unexpectedly.

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