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Research Article

Risk Assessment Strategy for Corrosion Under Insulation of Nano Technology Insulation on Geothermal Pipeline

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Abstract

Pipelines system are important in geothermal and most of the carbon steel pipe materials are insulated. Pipe insulation that is often used in general is prone to wetness, heat loss, and corrosion. Corrosion is a problem especially Corrosion Under Insulation (CUI). This type of corrosion affected surface degradation and pipeline integrity. The selection and application of nano-tech insulation is a mitigation strategy to reduce CUI to maintain service life. The simulation and research line pipe material were substituted by JIS S45C. 1×1 cm specimen size insulated with nanotechnology insulation covered by aluminum foil perforated and tested by dripping 3.5% NaCl for 3 days test duration in open environment and room temperature. Test result shown roughness, metallographic analysis, and corrosion rate were sought so that, the average surface area corroded was 2.22 mm^2. The original roughness value is 0.528 - 1.725 μm, the corrosion rate was 0.0894 mpy or 2.2707 x 10^{-3} mmpy. Nanotechnology insulation reduces wetting time contact between pipe surface and insulation to mitigate the formation of CUI.

Keywords: *Corrosion Under Insulation (CUI), Nano-tech, Insulation, Corrosion Rate, Geothermal*

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INTRODUCTION

Based on a performance report in the third quarter of the Directorate General of EBTKE (renewable energy division) 2021, Indonesia is one of the countries with the largest source of geothermal power in the world. Geothermal energy resources in Indonesia are estimated to reach around 28.5 GWe from 11.073 MW of resources and 17.453 MW of reserves [1]. Listed in the General Planning of National Energy (RUEN) that Geothermal Power Plant (PLTP) is expected to be able to make a major contribution in the effort to achieve a new renewable energy (EBT) mix target of 23% by 2025 [2]. This thing needs to be followed up with good management so that the utilization of geothermal energy is more optimal and sustainable. In a geothermal power generation system, the type of steel pipe material used for the piping system is a crucial and very important factor because energy problems can also result from production cost and maintenance issues related to the use of steel pipes, in addition to problems with energy production [3]. One instrument on PLTP, there are many geothermal pipes manifold steel carbon insulated [4]. To guard geothermal pipe quality using proper insulation becomes the solution. Insulation is used to keep heat from moving from the pipe (steam) to the environment. Besides that, insulation could however part of major material on pipe insulation used moment this prone to wetting, heat loss as well as energy, poor process control, and corrosion. CUI tends to remain undetected until the insulation and cladding or jacketing are removed to allow inspection or when leaks to atmosphere occur. CUI is not a new problem in the oil, gas, and geothermal industry, however, can become an integrity threat. CUI can cause a big incident if not overcome fast [5]. The ability of insulation in withholds heat depends on the composition constituent, which is due to from difference in conductivity of every insulation material [6]. The use of nanotechnology materials as insulation in geothermal pipes are the optional solution for external pipeline integrity.

Geothermal Pipe

The most frequent phenomenon found below geothermal fluid conditions is uniform level corrosion, which is frequently seen on carbon steel pipelines. In a variety of geothermal fluid conditions, steels with medium to high carbon and alloy strength are susceptible to sulfide stress cracking. The pipe for two-phase operating in the transportation industry experiences erosion and corrosion [7]. Processing geothermal from well going to processing with using a special pipe that is two types i.e. flow pipe steam and flow pipe water vapor. The pipeline means transportation silence that works for distributing fluid goods in liquid or gas form [8]. Geothermal energy resource from geothermal production well, processing by separator and dry steam transported to steam turbine by geothermal pipe system for electric power generation, in Indonesia called PLTP (Geothermal Power Plant) [9].

Generally, the system geothermal in Indonesia is a high-temperature hydrothermal systems (>225°C) and only some medium temperatures (150-225°C) [10]. Geothermal resource power produces fluid that carries many impurities chemicals that can damage construction generals like metal and cement. Oxygen (which is present in very small amounts due to the environment's reducing agent), hydrogen ions (pH), carbon dioxide, species hydrogen sulfide, ammonia, chloride ions, and sulfate ions are among the caustic substances [7, 11]. The majority of the geothermal fluid's concentra-

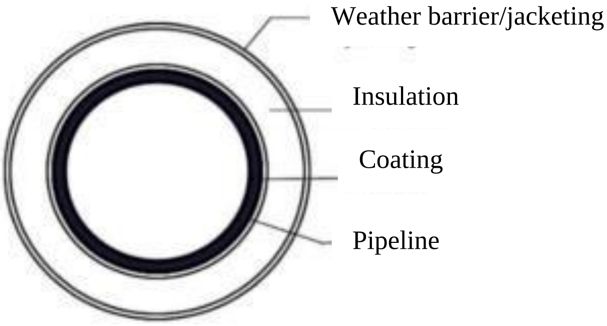


Figure 1. Cross-section of an insulated pipe [12]

tion chemistry has not altered with the process flow. The natural physical fluid, however, might experience the change, particularly if the temperature and pressure are reduced. Corrosion may result from temperature and pressure changing the pH of geothermal fluid [12].

Figure 1., shown cross-section transverse from an insulated pipe system. In recent years, the insulation industry has created elements that provide additional insulation and are beneficial for ensuring efficient energy saving. System insulation is recognized as an element or material combination that functions to lessen the heat transfer from fluid-filled materials to cold areas, such as pipes and the environment. There are several ways that heat can move, including conduction, radiation, convection, and combinations of these. The term "thermal insulation" typically refers to system insulation employed in equipment whose operating temperatures range from -75°C to 815°C. Insulation usage reduces the amount of energy used by every system. Compared to surfaces that are not insulated, insulating materials can decrease undesired heat transmission by at least 90% [12]. Proper insulation material selection and insulation installation methods significant and urgent role in managing integrity and process efficiency.

Corrosion under insulation

Corrosion is the result of a metal environment influencing its physics, chemistry, or electrochemical processes, which results in the deterioration of the metal qualities. Something metal could corrode because of an electrochemical process that requires anode, cathode, path of electron, and lines current ionic to produce cell corrosion as shown in Figure 2 [5].

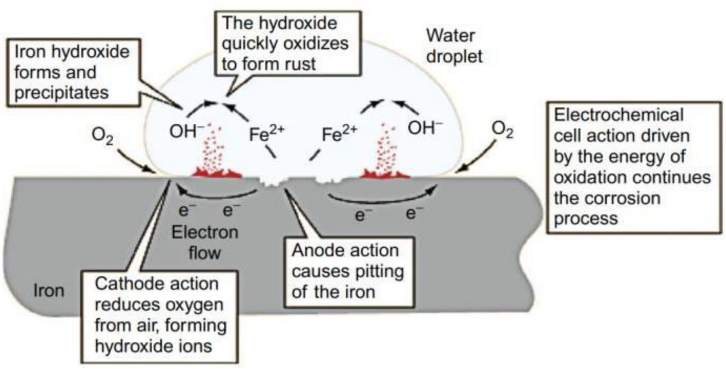


Figure 2. Mechanism formation corrosion [5]

Table 1. Risk occurrence of CUI based on operating temperature [14]

Operation Temperature (° C (° F))	CUI Risk
<-5 (25)	**Low**
>175 (347)	**Low**
-5 to 49 (25 to 121)	**Medium**
50 to 175 (122 to 347)	**Medium-High**
Cycling temperature between -20 and 320 (-4 and 608)	**High**

Corrosion result metal base is at the anode [13]. Iron metallic from steel oxidized for produces ferrous ions and electrons released according to equation:

Reaction at Anode : $Fe \rightarrow Fe^{2+} + 2e^{-}$ (1)

Reaction Cathode : $O_2 + 2H_2O + 4e^{-} \rightarrow 4(OH)^{-}$ (2)

Current electricity and current electron move among anode and cathode through a medium called an electrolyte. Existing pores in an insulating material that contains water are used in the case of CUI serving as an electrolyte. Because of the condensation process from environment, electrolytes will create an atmosphere that is corrosive. Combined oxidation and reduction processes convert metallic iron to hydroxide [13].

$Fe + ½\ O_2 + H_2O_2 + 2e^{-} \leftrightarrow Fe^{2+} + 2(OH)^{-} + 2e^{-}$ (3)

$Fe + ½\ O_2 + H_2O \leftrightarrow Fe^{2+} + 2(OH)^{-}$ (4)

$Fe^{2+} + 2(OH)^{-} \leftrightarrow Fe(OH)_2$ (5)

The mechanism of the formation of CUI can be seen in Figure 3. Risk the occurrence of CUI at operating pipe temperature 50 - 175°C than temperature work other with the same conditions. Risk The occurrence of CUI is also increasing significantly with the increased existence possibility of insulation *leaks*/blister and causing water and air to penetrate into the insulation and reaction with the pipe surface [14]. For monitoring the risk due to corrosion based on the temperature operation shown in Table 1.

In general, CUI does not occur in the main geothermal pipelines due to the high operating temperature of around 200°C. However, there is a CUI situation that can occur in the geothermal X field shown in Figure 4., where some piping is operated intermittently such as auxiliary pipe or drill pipe, bleed line from wellhead to flash-tank/sumps, drain line from well piping to flash - tanks/sumps, blowdown lines in separators, drains from separators, etc. In addition, a special case is the potential CUI damage to a 30"/24" insulated air duct, from field X-1 to field X-2, which is functionally converted as a condensate line operating at temperatures around 50°C (within the CUI temperature range) [15].

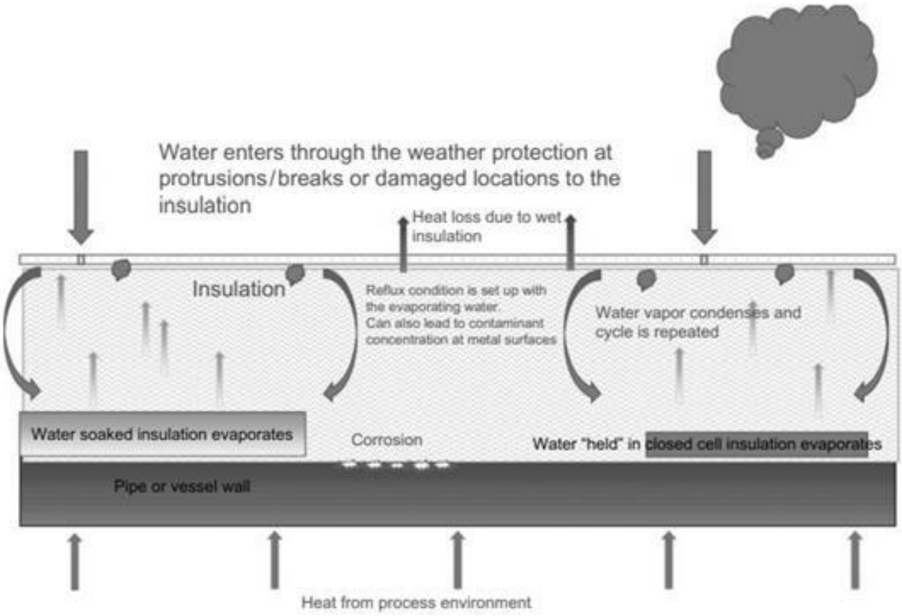


Figure 3. Mechanism formation of CUI [5]

Figure 4. CUI indicates on the pipe in the X field [15]

Nanotechnology Insulation

Polyurethane, fiberglass, and ceramic insulation are often used extensively in the thermal industry [16]. Nanotechnology-based thermal insulation materials typically have superior thermal insulation properties to conventional materials. Traditional thermal insulation has three heat transfer methods namely: thermal conduction (molecular vibrations within the cell wall), convection (between air particles enclosed in a cell), and radiation (between opposite cell walls) [17]. In general, the thermal conductivity value for insulation is about 0.05 W/mK. Thermal conductivity levels for insulating materials have recently dropped much below 0.02 W/mK. There are many other properties that are important to consider when evaluating an insulating material namely adaptability to the building site, mechanical strength, fire reaction, protective behavior, durability, resistance to weathering, air resistance, environmental hazard impact, human health, and cost [18]. Thermal insulation materials based on nanotechnology are a new invention that can prevent to heat transfer. The best criteria insulation is good adhesion, self-healing, corrosion resistance, and protection can be achieved with nanoparticle-based coatings [19].

Aerogel is a very porous synthetic substance with nanostructures. Aerogel was created by replacing the liquid gel component of gel with gas, which resulted in smoked and dry solids as the final product. Because of the production process, silica aerogel can

Table 2. Aerogel insulation vs. conventional insulation [20]

	Aerogel	Microporous Materials (Silica + Opacifiers)	Mineral Wool / Rock Wool	Ceramic Fiber	Calcium Silicate	Perlite
						
Cost	$$$	$$$$$	$	$$	$$	$$
		Thermal				
K-Value @ 200°C (W/m-K)	0,028	0,026	0,064	0,052	0,063	0,088
Max Use Temp (°C)	650	1,000	650	1,260	650	650
		Phyisical				
Material Flexibility	Flexible	Moulds: Not Flexible Mats: Flexible	Flexible	Flexible	Not Flexible	Not Flexible
Material Form	Blanket	Compact Powder in moulds or custom made stitched mats	Slabs, moulds & wired mats	Blanket	Rigid preformed moulds or slabs	Preformed pipe section or blocks
Installed Weight for equivalent thermal performance	Light	Light	Medium	Medium	Heavy	Heavy
Density (kg/m^3)	200	220	114	128	240	208
Damage Tolerant	High	High	Low	Medium	Low	Medium
Hydrophobicity	Yes Very hydrophobic	No	No	No	No	Yes Moderately Hydrophobic
Storage / Space	Low	Moulds: medium Mats: Less	Medium	Medium	Very High	Very High
Flame Spread / Smoke Index	0/0	0/0	5/0	0/0	0/0	0/0
Installation and Labor Skill	Easy – Minimal Skilled labor	Hard – Competent Skilled labor	Easy – Minimal Skilled labor	Easy – Minimal Skilled labor	Hard – Competent Skilled labor	Hard – Competent Skilled labor
		Environmental				
Disposal	Landfill	Landfill	Process Waste	Landfill	Process Waste	Landfill

exhibit hydrophobic or hydrophilic properties. The silanol group (Si-OH) in the aerogel network causes water to be absorbed, which results in a hydrophilic characteristic. However, the addition of nonpolar side surface pore function, such as material silica, can provide hydrophobic behavior. Its hydrophobic properties minimize the amount of water that enters geothermal pipelines [18].

When compared to other types of insulation as shown in Table 2, a low K-value, one of the aerogel's exceptional qualities, enables the aerogel insulation system to have a thin profile. Aerogel is additionally more versatile because it is simple to cut into different sizes and forms. The aerogel's hydrophobicity can keep air from leaking through the insulation, preventing the development of CUI, while its respiratory characteristics can let vapors pass through as the equipment heats up [20].

Aerogel has various types, one of them is “nanotechnology additive insulation” is shown in Figure 5. In the final report issued by Aerogels vendor, it is stated: that nanotechnology insulation material has a level of high-water resistance through test use ASTM C1511 method with results shown in Table 3.

Table 3. Water repellency per ASTM C1511 [21]

Material	Average water uptake per ASTM C1511 (wt %)
Nanotech insulation	5
Mineral wool	1100
Calcium Silicate	350
Perlite	8

Figure 5. Nanotechnology insulation material

Roughness Tester

Surface roughness is a measurement or value for how rough a material's surface or surface height is when it is measured from a reference point. The concept of surface roughness can be applied to research the movement of heat and electricity in materials, the idea of friction on a material's surface, the link between two materials, and the area where deformation occurs [22,23], and the study of the corrosion properties of the material [24]. One factor taken into account when assessing the quality of a metal product is the roughness rating of the metal surface. The relationship between surface roughness and the product is produced mechanical, optical, and electrical properties are unquestionably referred to as the product's quality. The method of producing the metal, the process of cutting the metal after it has been created, the provision of metal cutting speed, and the provision of metal cutting angle all have an impact on the roughness value of the metal [25].

Surface roughness is yet another crucial factor in determining the quality of the component surface that is most usually assessed, along with flatness. A mechanical component's functionality within the parameters of its intended use is frequently determined by the roughness of its surface. Models used to estimate the values of these parameters take into account the geometry of the cutting edge and the cutting process parameters, which determine the values of surface roughness parameters [26].

Metallographic Inspection

Analyzing the microstructure of a metal or alloy is one method for observing the mechanical properties of the material. Metallography was done to be able to see the microstructure [27]. Metallographic testing in this study is a test that aims to determine the condition of the metal on a micro basis. This is done to find out how the corrosion conditions formed on the microstructure so that can be the value of the corrosion area that occurs in this test sample. The measurement microstructure used optical microscope with a magnification of 200 X so that the condition of the metal is clearly

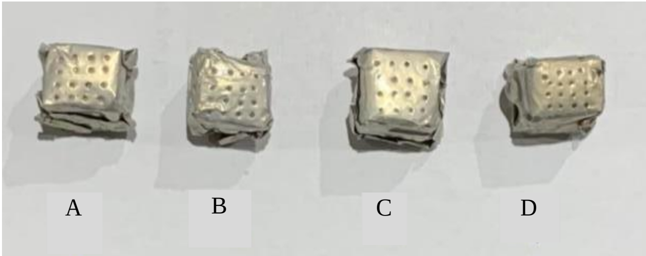


Fig. 6. Insulation specimen.

visible. The result of microstructure can determine the average area of corrosion in the test sample [28].

METHODS AND ANALYSIS

The JIS S45C steel plate measuring 1×1 cm is cleaned with sandpaper according to the Sa 2½ surface standard. This experiment was made of 4 specimens replication (specimens A, B, C, and D) to get the final average value. Surface specimen insulated with nanotechnology insulation 10 mm and aluminum foil perforated are shown in Figure 6., next carried out the testing process corrosion with dripped 3.5% NaCl solution at a room temperature for 3 days with sunlight exposure [29].

RESULTS AND DISCUSSIONS

Roughness Tester

Result data roughness testing with use tool roughness surface tester can be seen in Table 4. Based on the results of the roughness test that has been carried out using the surface roughness test equipment, the specimen roughness value has increased. Where is the increase that occurs 3-6 times from roughness value early. Where on the specimen the first experience an increased roughness value of 1.062 μm then on the specimen second 1.082 μm; specimen third 2.537 μm and specimen fourth 0.132 μm. Geothermal pipes generally have a relative roughness value of 0.025 μm [31]. Corrosion cause the surface roughness to increase as per equation (3), (4), (5).

Metallography

Inspection metallography aims for seeing the wide surface corroded area. Examination metallographic results as shown in Table 5. Based on surface area data corrosion obtained the average area is 2.22 mm^2.

Corrosion Rate

On testing rate corrosion used the weight loss method. Specimen was weight at before and after testing. The specimens weight data are shown in Table 6. Based on weight loss result, the rate value corrosion determined by formula (6).

$$CR = \frac{W \, x \, K}{\rho \, x \, A \, x \, T} \tag{6}$$

Where, CR = Corrosion Rate; W = Weight loss; K = Constanta; ρ = Density; A = Surface area; T = Exposure time. The rate value corrosion as shown in Table 7.

Table 4. Roughness value data specimen before and after test.

Specimen	Roughness Value (μm)	
	Before	After
A	0.526	1.588
B	0.202	1.284
C	0.508	3.045
D	0.851	0.983

Table 5. Surface area data corroded

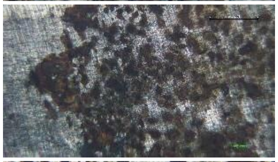
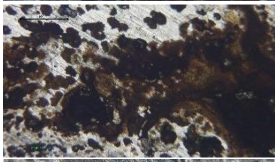
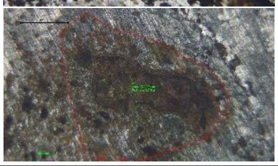
Specimen	Surface Area Corrosion (mm^2)	Surface Drawing
A	0.0545	
B	3.6400	
C	2.6300	
D	2.5500	

Table 6. Weight data specimen

Specimen	Weight Data Specimen (gr)		
	Before Test	After Test	Weight Loss
A	2.3019	2.1197	0.1822
B	2.1941	2.1829	0.0112
C	2.2476	2.2404	0.0072
D	2.2974	2.1218	0.1756

Table 7. Rate value corrosion

Specimen	Rate Corrosion (mpy)	Rate Corrosion (mmpy)	Relative Corrosion Resistance
A	0.1730	4.3942×10^{-3}	Outstanding
B	0.0106	2.6924×10^{-4}	Outstanding
C	0.0068	1.7272×10^{-4}	Outstanding
D	0.1669	4.2392×10^{-3}	Outstanding

Table 8. Glass wool and Aluminum foil vs. Nanotech insulation [20]

Insulation	Maximum weight loss (gr)	Maximum corrosion rate (mmpy)
Glass wool and aluminum foil [30]	0.2647	0.2539
Nanotech insulation	0.1822	4.3942×10^{-3}

After corrosion testing, all specimens have weight loss. This indicates that the specimen was corroded. Because the elements contained in the specimen have reacted with the electrolyte elements a reaction occurs and the surface was degraded, as shown in Table 7, the corrosion rate value for all specimens is <1 mpy [8].

If compared the results of corrosion test simulation with other types of insulation by Faridz (2017), we get the average data for glass wool and aluminum foil insulation materials, with a weight loss is 0.2647 gr (corrosion rate of 0.2539 mmpy) [30]. Based on the data above, the results of the corrosion rate of nanotechnology insulation compared to the results of the corrosion rate of glass wool insulation materials with aluminum foil can be seen in Table 8. With the results of the comparison of weight losses and corrosion rates, nanotechnology isolation has minimum risk of corrosion.

CONCLUSIONS

Presented research gives results in the rate of CUI from corrosion using nano insulation with value first specimen is 0.1730 mpy, the second specimen is 0.1060 mpy, the third specimen is 0.0068 mpy, and the fourth specimen is 0.1669 mpy. Based on the weight-loss method, the data obtained results shows that the weight loss of the first specimen is 0.1822 gr, the second specimen is 0.0112 gr, the third specimen is 0.0072 gr, and the fourth specimen is 0.1756 gr. Based on the roughness test data, the data obtained for the first test object is increased by 1.060 μm, for the second test object is increased by 1.082 μm, the third test object is increased by 2.537 μm, and the fourth test object is increased by 0.132 μm.

The result of a comparative analysis between nanotechnology insulation material and glass wool insulation based on weight loss and corrosion rate showed that the minimal risk of corrosion is in nanotechnology insulation material. Presented research reveals that type insulation is one of the most important factors in CUI. Scarcity of rate data CUI corrosion study is limited in this area. It is expected that these studies could become the initiation for the use of more reliable insulation for mitigating CUI in geothermal industries.

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