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AN EXPERIMENTAL ANALYSIS USING TAGUCHI METHOD IN RESOLVING THE SIGNIFICANT FACTORS SUBJECT TO CORROSION UNDER INSULATION

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ABSTRACT

Corrosion under insulation (CUI) is a gradually vital issue for piping in industries especially petrochemical and chemical plants due to its astonishing catastrophic disaster and automatic impact on the environmental problem. To ensure this CUI problem does not spark sudden surprise in plants, indeterminate factors that contribute to the deterioration of CUI should be recognized and taken care seriously. Thus, this research will unearth the most influential factors for the CUI deterioration using Taguchi method for design of the experiment. Result analysed using a signal to noise ratio revealed that most significant factor for CUI occurrence is insulation type followed by service temperature. However, this method also exposes that interactions between factors for CUI are less significant. Meanwhile, the most influential factor for service temperature is 120oC, type of insulation are perlite and calcium silicate while cycle type is isothermal wet/dry. This will help as an acceptable guideline for inspection planning purpose and priority in the maintenance schedule.

Keywords: taguchi method, corrosion under insulation, ASTM G189-07, signal to noise ratio.

INTRODUCTION

Corrosion under insulation (CUI) is localized corrosion attacking the interface of metal between the metal surface and its insulation. Insulation is frequently applied to maintain process temperatures that reduce energy loss and associated costs including precaution for safety issues. CUI is typically difficult to perceive until it becomes a serious problem, especially in petrochemical or chemical plants that have been operating for decades [1]. These failures can be catastrophic in the environment or, at least, have undesirable economic effect during downtime and restoration.

In 2003, Exxon Mobile Chemical indicated the highest incidence of leaks in the refining and chemical industries is due to CUI [1]. The piping maintenance costs are concerning 40% to 60% for CUI detection and cure for CUI occurrence. Afterward in 2008, National Association of Corrosion Engineers (NACE) fulfils a survey, out of 30 facilities, 17 experiences CUI as the main challenge they have to encounter. Furthermore, NACE Corrosion Costs Study in 2011 states that corrosion costs in the US are approaching \$1 trillion annually, and expected to exceed that unfortunate milestone in future [2-5]. To ensure this CUI problem does not spark sudden surprise in plants, factors that contribute to the deterioration of CUI should be recognized and taken care of seriously.

APPLICATION OF TAGUCHI METHOD

Taguchi method

Taguchi method is robust engineering. This method aims to develop outcomes that worked distinctly in spite of natural variation. Traditionally, Taguchi method proposes two-level, three-level, and mixed-level fractional factorial designs in orthogonal arrays. However, the approach of signal and noise factors, inner and outer arrays, and signal to noise ratios make this method unique [6, 7]. This study will only focus on signal to noise ratio.

Signal to noise ratio (S/N ratio)

Signal factors are system control inputs known as an inner array, while outer array, which is made up of noise factors are variables that are habitually difficult or expensive to manipulate. A signal-to-noise ratio is a statistic function calculated over an entire outer array. Its formula contingent on whether the investigational goal is to minimize, maximize or match a target assessment of the quality characteristic of interest [8, 9]. This study will emphasize on maximizing the CUI rate using Equation. (1) where n is some observations, and y is the observed data as used in [9, 10].

$$S/N = - 10 \log 1/n (\Sigma y^2) \quad (1)$$

This S/N ratio for CUI rate formula is the performance statistic computed to maximize the resulted value, which is –10 times the common logarithm of the average squared reciprocal. The mathematical expression of this methodology can be retrieved in [8].

ALTERNATIVE ANALYSIS

To calculate either CUI parameters are significant or not to CUI rate, and the value lay in the acceptable range, Pareto statistical analysis of variance (Pareto ANOVA) analysis is used. This method is commonly used to analyse data for process optimization [9,10]. Pareto ANOVA is an abridged ANOVA technique which uses Pareto principles and requires neither ANOVA table nor the F-tests. It is an easy way to analyse results of parameter design and reliable application for industrial practitioners and engineers. Particular in this Pareto ANOVA analysis, Sum of Squared Differences (SSD) formula is used as in Equation. (2) [9].

$$SSD = \sum(s\eta 1\ (i,j) - s\eta 2(x + i,\ y+j))^2 \qquad (2)$$

In SSD, the sum of squares exemplifies a portion of deviation or variation from the mean. It is intended as a total of the squares of the variances from the average. Calculation of the randomness of error and sum of squares of the factors are both considered as the total amount of squares.

EXPERIMENTAL DETAILS

ASTM G189-07

This ASTM standard is an official guide for laboratory experiment of corrosion under insulation [12]. This guide is broad and can incorporate many specifications in a range of material, environments and conditions depending on the desired experiment needed. However, there is limited research or implementation of the testing using this ASTM G189-07 and the analysis commonly restricted to get the corrosion rate only. Thus, in this paper, ASTM G189-07 is applied to obtain the utmost influential factors in CUI incident. The design of the experiment is enabled using Taguchi method and the analysis using S/N ratio. Three factors are selected based on the general field factors that contribute to CUI. They are service temperature, insulation type, and cycle type. Table-1 presents those elements and designation used in the experiment. For this study, ASTM A106, Grade B carbon steel pipe is bound by blind flange pipe segment with same material specification on both ends [12]. Supplementary, to retain the test environment, thermal insulation is laid on the testing section to grant annular space. As we can observe in Figure-1, six carbon steel ring specimens in this CUI cell are parted by insulation spacers. The ring specimens act as test electrodes in two separate electrochemical cells. Other than that, corrosion measurements are generated using both electrochemical polarization resistance (EPR) and weight loss measurement.

Cui rate measurement

For further result analysis in this study, only weight loss method is used, and the average weight loss of each run is taken since result from such measurement technique resembles more to actual plant CUI rate data [13]. For this weight loss reading, a sample size of 3 rings is use for each experimental run. Fundamentally, all ring specimens as demonstrated in Figure-1 are evaluated using mass loss method prescribed in ASTM G01-03, and those results are then applied to Equation. 3 to determine the CUI rate [14].

$$\text{CUI rate} = (K \times M) / (A \times T \times D) \qquad (3)$$

Where K is constant of 8.76×10^{-4} mm/year, M is a mass loss in gram, A is an outer surface area of the ring specimens exposed to the solution in cm^2, T is an exposure time in hours while D is the density of the material in gram/cm^3. After all the corrosion rates are determined, average CUI rate based on weight loss for each run is computed as tabulated in Table-2. Likewise, although experiment uses electrochemical polarization resistance (EPR) method for other three rings, the CUI rate based on this EPR are not considered in the result analysis as it has the limitation of altering the measured current by inducement of controlled potential [15]. Thus, EPR is only used to monitor the progress and variation of CUI during the experiment.

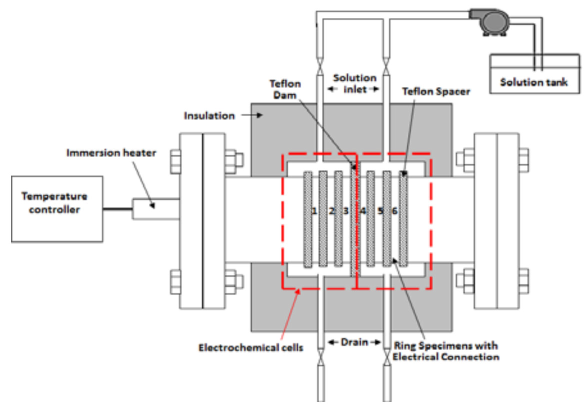

Figure-1. Schematic diagram of CUI cell experiment.

Design of experiment

In this experiment, standard L_{27} (3^{13}) orthogonal array is used in the fractional factorial design to discover interaction of each factor. It is three factors with three elements each. Features of each element are represented by '0' or '1' or '2' and the factors represent by symbol 'A', 'B', or 'C' as designed in Table-1. Detail of experimental run is schedule as shown in Table-2.

In this experiment, each run has three rings for weight loss measurement as mean value novelty to get a precise estimate for weight loss and to estimate experimental error. This replication is an essential substance for the design of experiments. Subtotals of six samples are considered at each run resulting in 162 total samples.

Table-1. Factors and designation used in result analysis.

Symbol	Factor	Designation		
		0	1	2
A	Service Temperature	60°C	90°C	120°C
B	Insulation	Calcium Silicate	Perlite	Rockwool
C	Cycle Type	Isothermal	Isothermal wet/dry	Cyclic

RESULTS AND DISCUSSION

The principal objective of the experimental work is to maximize the CUI rate thenceforth reveal the most influential elements in each factor. Table-2 shows the actual result for CUI rate along with their computed S/N ratio.

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Table-2. Experimental results and their corresponding S/N ratio.

Experimental Run	Service temperature A	Insulation B	Cycle type C	Designation	Mean CUI rate (mm/year)	Mean S/N ratio
1	0	0	1	$A_0B_0C_1$	1.644	4.318
2	0	0	2	$A_0B_0C_2$	1.821	5.204
3	0	0	0	$A_0B_0C_0$	1.331	2.483
4	0	1	1	$A_0B_1C_1$	1.766	4.941
5	0	1	2	$A_0B_1C_2$	1.531	3.701
6	0	1	0	$A_0B_1C_0$	1.417	3.029
7	0	2	1	$A_0B_2C_1$	1.538	3.738
8	0	2	2	$A_0B_2C_2$	0.958	-0.371
9	0	2	0	$A_0B_2C_0$	1.122	0.999
10	1	0	1	$A_1B_0C_1$	1.894	5.549
11	1	0	2	$A_1B_0C_2$	1.929	5.709
12	1	0	0	$A_1B_0C_0$	1.620	4.189
13	1	1	1	$A_1B_1C_1$	1.828	5.240
14	1	1	2	$A_1B_1C_2$	1.893	5.543
15	1	1	0	$A_1B_1C_0$	1.711	4.665
16	1	2	1	$A_1B_2C_1$	1.015	0.129
17	1	2	2	$A_1B_2C_2$	1.257	1.986
18	1	2	0	$A_1B_2C_0$	0.785	-2.101
19	2	0	1	$A_2B_0C_1$	2.203	6.859
20	2	0	2	$A_2B_0C_2$	2.163	6.702
21	2	0	0	$A_2B_0C_0$	2.216	6.910
22	2	1	1	$A_2B_1C_1$	2.620	8.366
23	2	1	2	$A_2B_1C_2$	2.247	7.032
24	2	1	0	$A_2B_1C_0$	2.224	6.942
25	2	2	1	$A_2B_2C_1$	1.989	5.971
26	2	2	2	$A_2B_2C_2$	1.569	3.915
27	2	2	0	$A_2B_2C_0$	1.310	2.346

To simplify the tabulated result, Taguchi recommends analyzing mean of S/N ratio for each element and factor using the graphic. Hence, the significant factors can be visualized and easily identified. To illustrate and plot the graph, mean of S/N ratio is calculated and tabulated in Table-3. The interaction between factors also calculated as demonstrated in J.A. Ghani *et al.* [11]. Afterward, the findings are plotted and illustrated in Figure-2 and Figure-3.

Table-3. Response table for average S/N ratio.

Symbol	Mean S/N ratio A	Mean S/N ratio B	Mean S/N ratio C	Max - min	Sum of Squared Differences (SSD)	Contribution ratio (%)
A	28.043	30.908	55.042	26.999	16.291	31.212
B	47.923	49.459	16.611	32.847	25.454	48.769
C	29.462	45.111	39.420	15.648	4.647	8.903
B x C	13.582	18.546	5.529	13.017	3.197	6.125
A x B	12.006	15.448	12.232	3.443	0.275	0.526
A x C	6.512	10.918	17.649	11.137	2.330	4.464

Higher subtraction value of maximum and minimum S/N ratio means the factor is more significant on the CUI rate though a lower value of maximum and minimum S/N ratio means the aspect gives less impact on the CUI rate. From Table 3, the most significant factor is insulation type with a total value of 32.847 followed by service temperature with 26.999. The contribution ratio between those influential factors is then analyzed using Sum of Squared Differences (SSD) as in Table-3 and then plotted in Figure-2 to evaluate the percentage held of CUI influential factor.

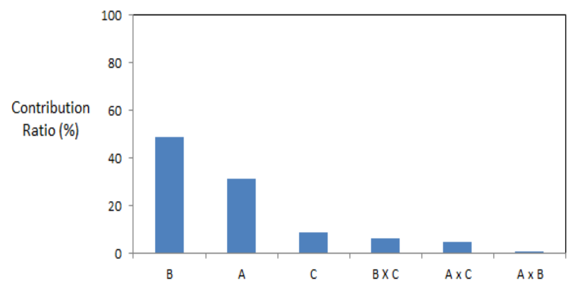

Figure-2. Pareto ANOVA analysis for CUI influential factor.

In this study, the significant factors and interactions are chosen from leading proportion of contribution ratio that has a cumulative contribution up to 80%. This value will be the benchmark and become the acceptable range to denote the factor as the most influential factor for the CUI rate. Results from Figure 2 shows that Factor B, which is the insulation factor, gives the highest contribution to CUI rate with contribution ratio of 48.769%. The second element, factor A, service temperature is still considered as a high impact factor to CUI rate because the contribution ratio falls in acceptable range with the cumulative contribution of 79.981% by its contribution ratio of 31.212%.

However, the third high SSD value is 4.647 for cycle type factor and contributes only 8.903%. Further SSD value that are 3.197, 0.275, and 2.330 respectively for interactions between factors B x C, A x B and A x C also show minimum contribution ratio with 6.125%, 0.526%, and 4.464%. It means that cycle type factor including all interactions between factors is less significant in CUI rate as a result of the cumulative contribution are out from benchmark range.

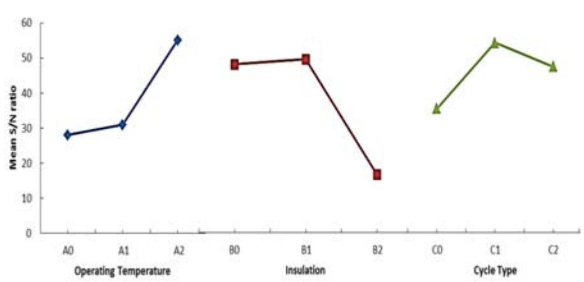

Figure-3. Mean S/N ratio for CUI rate factor.

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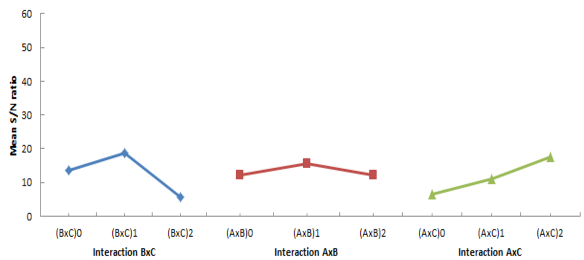

Figure-4. Mean S/N ratio for interactions between CUI factors.

Subsequently, the study of Figure-3 indicates that most influential factor for service temperature (factor A) is A2 while for insulation (factor B) are, B1 and B0 as the readings are very close. Both of these insulations are taken as dominant in promoting CUI, albeit perlite is the most prominent one followed by calcium silicate. For cycle type (factor C), C1 shows the highest S/N ratio. Therefore, the optimal combination within the safe range to get a high value of CUI rate is A2B1C1 and A2B0C1 This means, for factor A, service temperature of 120 °C, for factor B, Perlite and Calcium Silicate insulation whereas for factor C, cycle type is isothermal wet/dry cyclic.

Other than that, the plotted trend and differences between Figure-3 and Figure-4 can be seen clearly. The plot of interaction graph in Figure-4 has smaller mean S/N ratio 0,1 and 2, for all pair of interactions, which gives less significant compared to specific factors in Figure-3. For service temperature 120 °C, the result is substantially corresponding to API Recommended Practice 581, the CUI rate increases with increasing metal temperature up to the point where liquid evaporates quickly [16]. Corrosion turns out to be more severe at metal temperatures between the boiling point, 100 °C, and 120 °C, where the insulation stays wet longer due to less prone for water to vaporize. Thus, the formation of CUI is higher at 120 °C contrasted to CUI at operating temperatures 60 °C and 90 °C.

CONCLUSIONS

The experimental work for CUI based on ASTM G189-07 is successfully designed by Taguchi method and analyzed using S/N ratio analysis. Other conclusions are:

- Result analyzed using the signal to noise ratio revealed that most significant factor for CUI occurrence is insulation type followed by service temperature.
- S/N ratio analysis shows that the optimal combination to acquire the high value of CUI which means the most influential factors for CUI occurrence in this experiment are A2B1C1 and A2B0C1. This designation means for factor A, service temperature of 120 °C, factor B, perlite and calcium silicate insulation, and for factor C, cycle type is isothermal wet/dry cycle.
- However, this method also exposes that interactions between factors for CUI are less significant.

This will be an acceptable guideline for inspection planning purpose and priority in inspections and maintenance schedule.

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