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Corrosion Rate Optimization of Mild-Steel under Different Cooling Tower Working Parameters Using Taguchi Design

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ABSTRACT

This study investigates the implementation of Taguchi design in the estimation of minimum corrosion rate of mild-steel in cooling tower that uses saline solution of different concentration. The experiments were set on the basis of Taguchi's L16 orthogonal array. The runs were carried out under different condition such as inlet concentration of saline solution, temperature, and flowrate. The Signal-to- Noise ratio and ANOVA analysis were used to define the impact of cooling tower working conditions on the corrosion rate. A regression had been modelled and optimized to identify the optimum level for the working parameters that had been founded to be 13%NaCl, 35^{O}C, and 1 l/min. Also a confirmation run to establish the precision of the Taguchi design for optimization the corrosion rate in cooling tower with high reliability. The contour plot had been applied to understand how it can be in finding the relation between the corrosion rate and the working parameters of the cooling tower.

Keywords: Taguchi, corrosion, mild-steel, cooling tower.

امثلية معدل التآكل للفولاذ الكاربوني تحت تأثير ظروف عمل مختلفة لابراج التبريد باستخدام التصميم التجريبي لتاكوشي

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الخلاصة

في هذه الدراسة تم تطبيق طريقة تاكوشي لتقدير معدل التآكل الاوطئ للفولاذ الكاربوني في ابراج التبريد التي تستخدم مياه مالحه بتراكيز مختلفة. تم هذا باستخدام مصفوفة رياضية L16 . تم اجراء التجارب تحت تأثير ظروف عمل مختلفة منتركيز المحلول الملحي و درجة حرارته و معدل الجريان الحجمي له. تم دراسة نسبة الاشارة الى الضجيج (S/N) وتحليل ANOVA لتحديد

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تأثير ظروف عمل برج التبريد على معدل التاكل للفولاذ الكاربوني. تم ايجاد تعبير رياضي يربط بين المتغيرات و معدل التاكل و تم ايجاد الظروف المثلى للحدود المدروسة و كانت عند تركيز 13%NaCl و درجة حرارة 35^{O}C و معدل جريان 1l/min . تم اجراء تجربة اضافية للتأكد من دقة استخدام طريقة تاكوشي لايجاد معدل التاكل في ابراج التبريد. ايضا تم دراسة المقطع السطحي للرسوم ثلاثية الابعاد لفهم كيفية استخدامها لايجاد العلاقة بين معدل التآكل و ظروف العمل في برج التبريد.

الكلمات الرئيسية: تاكوشي, تآكل, الفولاذ الكاربوني, ابراج التبريد.

1.INTRODUCTION

Large amount of heat is liberated in industries that needed to be disposed through the use of cooling towers that are one of the widely used equipment in industry. Cooling towers are very encounter to corrosion due to the appropriate environment inside the cooling tower like the flow of solution that contains dissolved salts, the temperature, the microbiological growth… etc. **(Muslet, et al., 2009)**. Throughout the operation, water can dissolve many substances, including salts and gases like oxygen. As a result, water can cause corrosion of metals used in cooling systems as evaporation continue **(Safadi, et al., 2018**). Recently, a lot of power plants are using seawater as a cooling medium as a once through process to avoid the accumulation of salts when being re-cooled inside cooling towers. But in fact there are evidence that solution of higher NaCl solution can cause the improvement of power generation efficiency and economize the cost of cooling utility to 49.69% **(Nápoles-Rivera, et al., 2013)**, also the use of this type of solution leads to the prevention of the microbial growth inside the system, but with the use of once-through operation there will be an increase in the warming pollution ecosystem due to the direct throw of the hot water to the water surface. For this reason, the recirculated cooling tower process are recently become of growing interest with this type of solution, but researchers recommended for further researches to investigate the corrosion behavior inside these type of towers.

Corrosion of metals in cooling water systems is an electrochemical process that occurs because of a difference in potential onpoints at the metal surface. Mild steel refers to low carbon steel and it is the less costly material, and commonly used in cooling water system that is most susceptible to corrosion due to cooling tower environments and its tendency toward thermodynamic stability.

Corrosion is the cause of three major problems in cooling towers. The first is of the failure in cooling towers operation, all the types of wet cooling towers are suffering from this failure even the cooling towers that are built from reinforced concrete **(Mitzithraa, et al., 2015),** and this will cause an increase the operation cost. The second problem is the loss of thermal efficiency due to the presence of corrosion products. The third one, is due to the loss of structural integrity of the walls and basins. Many different types of corrosion are taking place inside cooling towers, but the most widespread types are distinguished as general and localized corrosion.

Three factors are to be considered in this study with four levels for each of them. The usual method to apply multi-parameters with multi-levels to each of them is complex and requires large number of experiments, and they increase with the increase in the number of the parameters or their levels. To minimize the number of experiments, a helpful method had been designed by Taguchi. Taguchi method is a robust engineering and it fox to develop outcomes of the work regardless the variation in some natural parameters. This method processes of many levels fractional factorial design in orthogonal array specially designed to study all of the used parameters levels in small number of experiments **(Ramkumar and Ragupathy, 2013) (Antony and Kaye, 2000).** Taguchi method had got high ability to be embraced and had gained successful in engineering experiments. In this technique, the arrays are chosen based on the degree of freedom needed for any experiments.

This method had been applied widely in studying the corrosion rate of metals to minimize the required number of experiments, especially that the corrosion investigation required long time of study. **Mohammad, et al., (2017)** had used Taguchi design to investigate minimizing the corrosion rate of dissimilar metal in the joint using L9 orthogonal array. **Naser, et al., (2016)** investigated

two types of cathodic protection to reduce the corrosion rate of steel via applying of Taguchi method to minimize the number of experiment and to study the signal-to-noise ratio, and they also analyze the results using Minitab software**. Rashid, et al., (2017)** had used the Taguchi design to find optimum level of pomegranate peel extract to minimize the rate of corrosion of Mild-steel in a solution of phosphoric acid. They embraced the results for the signal-to-noise ratio analysis and processed the results with Minitab-17 to find the optimal condition.
In the current study, the combined effect of the working parameters inside the cooling tower that mutually affect the corrosion of mild-steel had been studied by using weight loss technique to see the change of the thickness of the samples with them. These factors are: the weight percent of the NaCl content in the working solution, its flowrate, and its temperature, each of them in four levels. The experimental set-up was designed using Taguchi's L_{16} orthogonal array and then the results were modelled to form a regression that describe the behavior and then optimized to achieve the levels that gives the minimum corrosion rate. The S/N ratio, the ANOVA analysis, and the contour plot had been also discussed in this work.

2. EXPERIMENTAL WORK

Samples of mild steel of (5*3*0.2 cm) in dimension (with total surface area of about 33.2 cm^2) were prepared to this study, each one of them had been drilled hole of 2 mm. The specific composition of working mild steel sample as provided by the supplier is given in **Table 1**. The exposed surface of each test specimens was initially treated, before being exposed to the desired study variables in bench-scale cooling tower. The treatments were done by polishing the samples using a group of successively smother grades of silicon carbide abrasive papers. Firstly, 80 grade silicon carbide (SiC) paper was used for the initial grinding, and then a set of progressively smother abrasive grades were employed down by the 400,600 and 800 grade, which was used to give the final polishing. The polished spacemen then degreased in ethanol, washed with distilled water and finally dried.
The surface treatment was accomplished immediately before each run of corrosion tests or stored in a desiccator before use for very short time (not more than 10 min). The samples had been weighed and then placed in the cooling tower system (**fig.1**). Samples were removed for the tower at the end of the each run (five days), cleaned by the use of acids (500 ml of HCL and 20 g of hexamethylenetetramine in 1 liter of distilled water) as mentioned by **ASTM G1(1999)**. After the complete removal of corrosion product, the samples were rinsed then dried and weighed again to determine the loss in weight in each run.

The corrosion of mild steel was examined for five working days in different environments of the cooling tower operation (NaCl solutions of concentrations 0-13%, inlet salt-water temperature 35-50^{O}C, flow rate of salt-water 1-2.5 l/min). The corrosion rate of mild steel samples was measured by using weight loss technique which was calculated with the use of Eq.1 **(Song, et al., 2017).**

$$C.R.(mmpy) = \frac{3650*\Delta W}{A*t*\rho} \quad (1)$$

Where
t – time of immersion in the working solution, days
A – surface area of the sample, cm^2
ΔW – average loss in the weight of the sample in the solution (measured as difference of initial mass and mass after corrosion time), g
ρ– specimen density, $g \cdot cm^{-3}$

The Taguchi design of experiments had been used to make benefits of the analyzing method that introduce. The three parameters that had been studied and their four levels are shown in **Table 2**. By using Taguchi experimental design for the three factors with their four levels, L_{16} standard orthogonal array shown in **Table 3** was applied which is the most suitable array depending on the degree of freedom.

Table 1. The Composition of Mild-Steel.

%S	%C	%Mn	%Cr	%Cu	%P	%Si	The Balance is Fe
0.017	0.098	0.071	0.043	0.092	0.011	0.019	

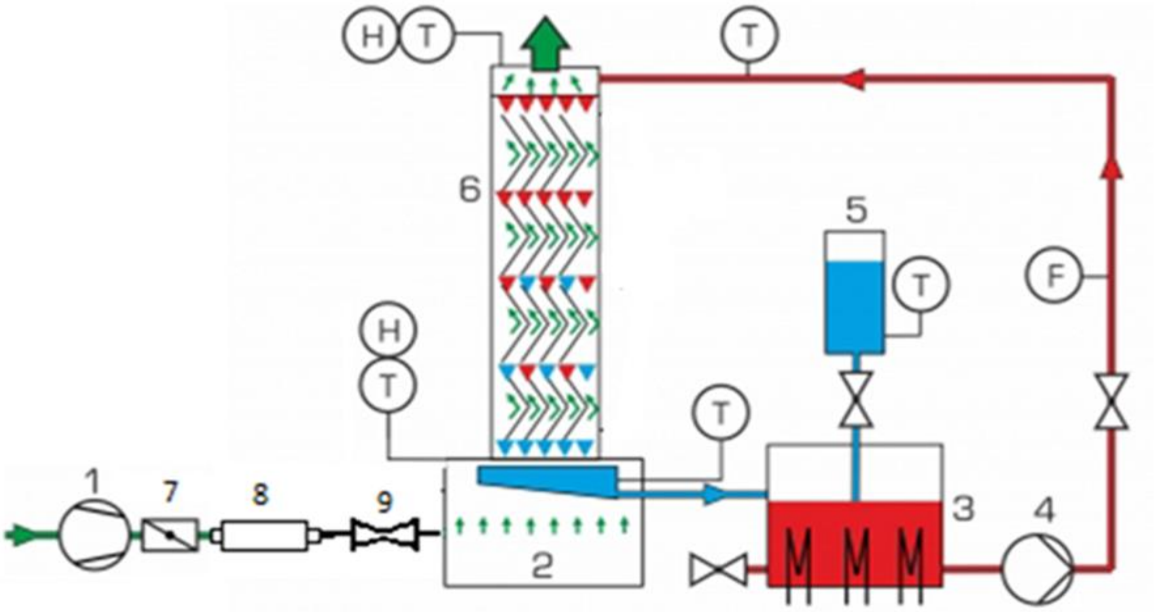

Figure 1. Schematic Diagram of the Cooling Tower System that Consist of; (1) air-blower, (2) distribution chamber, (3) vessel contains heaters, (4) liquid pump, (5) make-up tank, (7) humidity controller, (8) controller system, (9) venture-meter.

Table 2. Control Factors and their Levels Used in the Taguchi Experiment Design for Corrosion Rate of Mild-Steel in Cooling Tower.

Level	% NaCl	T_w ^oC	Q_w (l/min)
1	0	35	1
2	3.5	40	1.5
3	10	45	2
4	13	50	2.5

Table 3. Taguchi L_{16} Orthogonal Array for Mild-Steel Corrosion Rate in Cooling Tower.

No. of run	% NaCl	T_w ^OC	Q_w (l/min)
1	0.0	35	1.0
2	0.0	40	1.5
3	0.0	45	2.0
4	0.0	50	2.5
5	3.5	35	1.5
6	3.5	40	1.0
7	3.5	45	2.5
8	3.5	50	2.0
9	10.0	35	2.0
10	10.0	40	2.5
11	10.0	45	1.0
12	10.0	50	1.5
13	13.0	35	2.5
14	13.0	40	2.0
15	13.0	45	1.5
16	13.0	50	1.0

3. RESULTS AND DISCUSSIONS

Table 4. represents the L_{16} orthogonal array results of corrosion rate of mild-steel that was calculated using Eq.1 The analysis of these results is made by using MINITAB-18 software package.

Table 4. Taguchi Design of L_{16} Orthogonal Array with Corrosion Rate Response and (S/N) Ratio to each Set of Parameters.

No.	%NaCl	T_w ^OC	Q_w (l/min)	C.R. (mmpy)	Signal-to-Noise Ratio
1	0.0	35	1.0	0.0232	32.6902
2	0.0	40	1.5	0.0333	29.5511
3	0.0	45	2.0	0.0374	28.5426
4	0.0	50	2.5	0.0418	27.5765
5	3.5	35	1.5	0.0913	20.7906
6	3.5	40	1.0	0.1039	19.6677
7	3.5	45	2.5	0.1426	16.9176
8	3.5	50	2.0	0.1249	18.0688
9	10.0	35	2.0	0.0765	22.3268
10	10.0	40	2.5	0.0999	20.0087
11	10.0	45	1.0	0.0783	22.1248
12	10.0	50	1.5	0.1011	19.9050
13	13.0	35	2.5	0.0132	37.5885

14	13.0	40	2.0	0.0278	31.1191
15	13.0	45	1.5	0.0289	30.7820
16	13.0	50	1.0	0.0119	38.4891

There is a statistical measurement of performance in the Taguchi method that is called signal-to-noise ratio (S/N), where the signal is refer to the desirable value (the output characteristic) and the noise refer to undesirable value (the square deviation of the output characteristic). Therefore, it is ratio of the mean square of deviation. This ration is used to specify the levels of the control factors that reduce to minimum the variance of the resulted response that are caused by the noise factor. This ratio depends on standard for the quality that we want to optimize. There are mainly three different types of signal to noise ratio that are applicable in most situations: larger is better (LTB), smaller is better (STB), and nominal is better (NTB). In this study, the quality that wanted to be optimized is the corrosion rate. The used type of signal to noise ratio is smaller better (STB). Equation 2 is used to calculate the ratio.

$$\left(\frac{S}{N}\right)_{STB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (2)$$

Table 4. shows also in the last column the S/N ratio that had been calculated using Eq. 2 for the corrosion rate out-put that are calculated for all experiments. **Table 5**. clarify the effect of each of the studied factors on the corrosion rate, these out-put are shown in **fig. 2**. From **fig.2**, it can be seen that the temperature and flowrate of salt solution have negative influence on the corrosion rate of mild-steel, while the most negative influence of % NaCl is between 0 and 3.5% due to the increase in the working solution conductivity, followed by positive effect due to the decrease in the solubility of the oxygen in the solution. It had been recorded that the % NaCl have the largest effect on the corrosion rate of mild steel in cooling tower, followed by the salt-water inlet temperature, and the entering salt-water flowrate as shown in **fig.3**.

Table 5. Response for S/N Ratio for the Corrosion Rate of Mild-Steel

Level	%NaCl	T_w ^{O}C	Q_w (l/min)
1	29.59	28.35	28.24
2	18.86	25.09	25.26
3	21.09	24.59	25.01
4	34.49	26.01	25.52
Delta	15.63	3.76	3.23
Rank	1	2	3

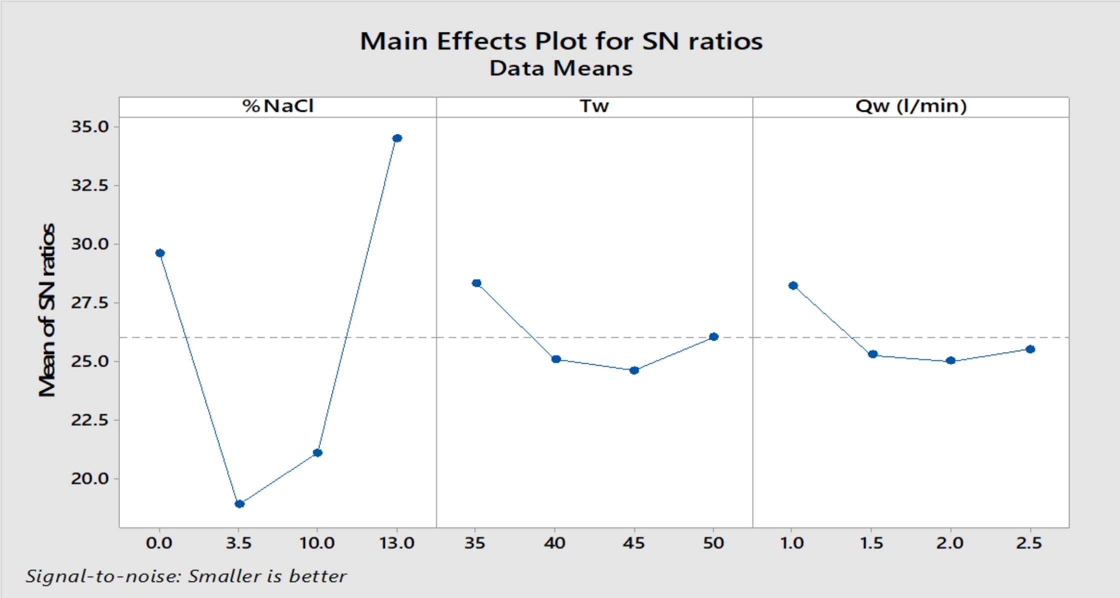

Figure 2. Main Effects for the S/N on the Corrosion Rate of Mild Steel.

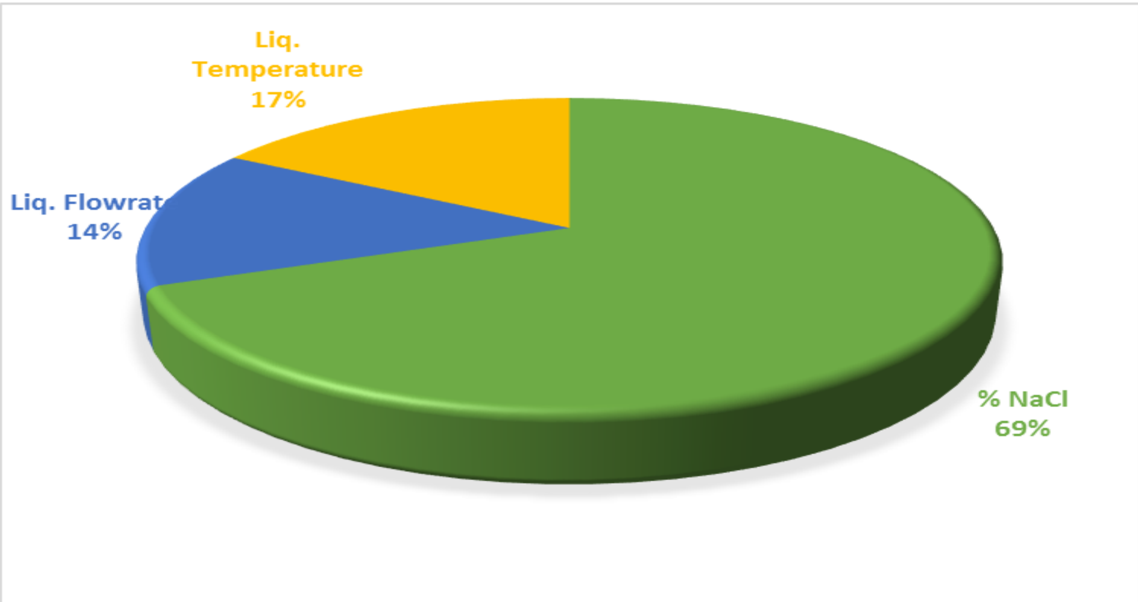

Figure 3. Influence of Cooling Tower Working Parameters on Corrosion Rate Obtained from S/N Ratio.

ANOVA is a technique widely used that can inform us some important statistical results based on analyzing the out comes from the experiments. This collection of statistical models had been developed in 1918 to study the effect of some calculated parameters on the chosen responses by calculating the sum of square (SS) which clarify the deviation from the mean, the means of square (MS) which is calculated by dividing the SS value by the DF, degree of freedom (DF) calculated by subscribing one from the number of levels. The F-value is a value that determine the effect of each parameter on the desired quality **(Mohammad, 2016)**. **Table 6 &7**, show the ANOVA results for the S/N ratio and the mean respectively. It is also clear from those tables that the NaCl have the largest effect among the process parameters.

Table 6. Analysis of Variance for S/N Ratio of Corrosion Rate.

Source	DF	Sum of Squares SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
%NaCl	3	640.43	88.97%	640.43	213.475	67.57	0.000
Tw ^{O}C	3	33.34	4.63%	33.34	11.113	3.52	0.089
Qw (l/min)	3	27.13	3.77%	27.13	9.042	2.86	0.126
Error	6	18.96	2.63%	18.96	3.159		
Total	15	719.85	100.00%				
Model Summary							
S	**R-sq**		**R-sq (adj)**	**PRESS**		**R-sq(pred)**	
1.77743	97.37%		93.42%	134.784		81.27%	

Table 7. Analysis of Variance of Means of Corrosion Rate.

Source	DF	Sum of Squares SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
%NaCl	3	0.024367	90.63%	0.02437	0.00812	77.42	0.000
Tw	3	0.001065	3.96%	0.00107	0.00036	3.39	0.095
Qw (l/min)	3	0.000825	3.07%	0.00083	0.00028	2.62	0.146
Error	6	0.000629	2.34%	0.00063	0.00011		
Total	15	0.026886	100.00%				
Model Summary							
S	**R-sq**		**R-sq (adj)**	**PRESS**		**R-sq(pred)**	
0.0102424	97.99%		94.15%	0.004476		83.35%	

The ANOVA analysis is shown in **Fig.4** had to be explained. In this figure there are four sub-figures. For the normal probability plot it noticed that it follows a straight line and there is no skewness, this mean that there are no outlier points. The histogram plot represents the normal distribution of the results about the mean of zero, and since they are near to each other with no spaces between them this also confirm that there are no outlier points. The residual versus fits is used to see if the residual is randomly distributed or not. It must be spread randomly about the zero-line, if not this will be a sign for an error. The residual versus order plot is used to check out the assumption of independency of residuals from each other. If there is a repeating pattern or a sudden shift, this gives an indication that the residuals may dependent on each other **(Zainab, 2018)** which is noticed in the mentioned figure.

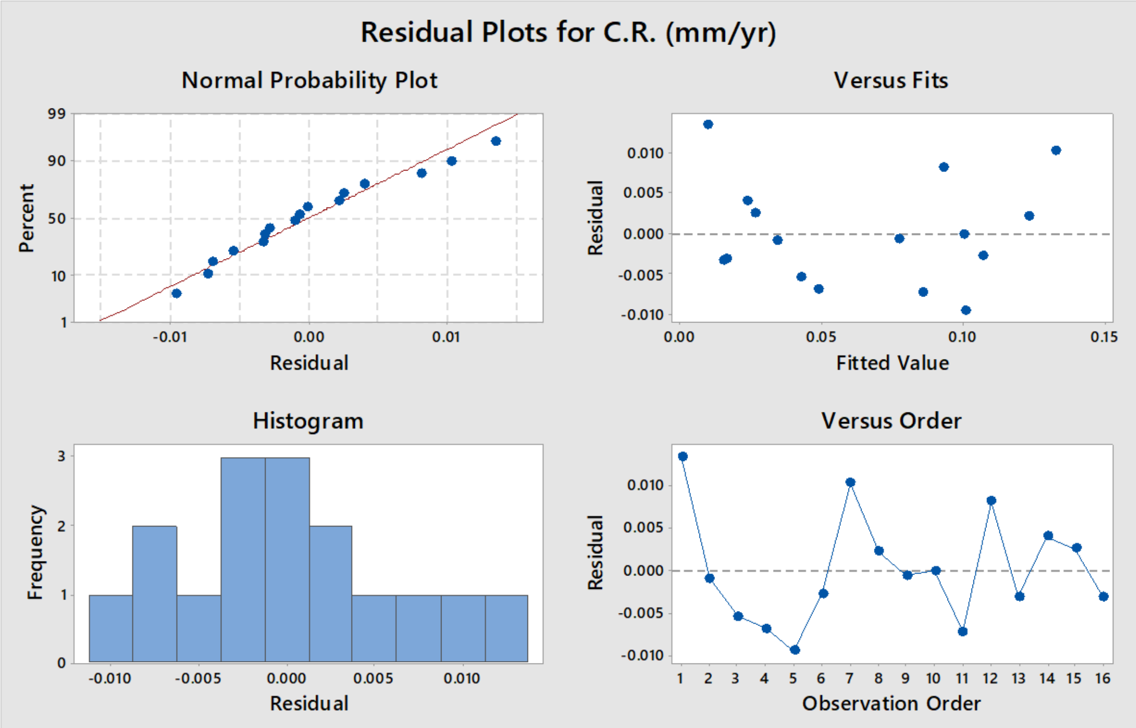

Figure 4. Residual Plots of ANOVA Analysis for Corrosion Rate of Mild-Steel.

By using correlation analysis in MINITAB-18, the best regression that fits the responses of corrosion rate of mild steel in cooling tower versus that affecting parameters of % NaCl, salt-water temperature and its flow rate was obtained for the highest R^2 that have P-value less than 0.001 as shown in Eq.3.

$$\boldsymbol{Corr.Rate = -0.0389 + 0.02982 * X_1 + 0.001244 * X_2 + 0.01263 * X_3 - 0.002402 * X_1^2} \quad (3)$$

Where X_1 is the % NaCl
X_2 is the salt-water temperature in ^{o}C
X_3 is the salt-water flowrate in l/min
It had been recorded that the above statistical model can predict the corrosion rate of mild steel in cooling tower with high level of trust depending on the correlation obtained coefficients (R^2=95.59%), and this indicate that the relation between the corrosion rate and the variables is strongly significant.
The minimum corrosion rate for the above founded regression (Eq.3) was founded by using the Minitab-18 optimization tool and it gives that for 13%NaCl, 35^{o}C for inlet salt-water temperature, and 1 l/min flow rate of salt-water.
A confirmation run had been done to test the results at the optimum point to verify the outcomes of the runs according to Taguchi design. **Table 8**. shows the results at the optimum level from both experiment and the application of Eq.2, and the % error between them. From the confirmation run, an error of 2.14 % had been obtained between the results from real run and applying the above regression.

Table 8, Optimal Run Level and a Comparison between the Results.

Run	%NaCl	T_{H2O} ^{O}C	Q_{H2O} (l/min)	Exp. result	Result from Eq. 2	% Error
1	13	35	1	0.0012	$-1.05*10^{-3}$	2.14

In **Fig. 5 & 6** the contour plots of the corrosion rate vs. %NaCl, Temperature and vs. %NaCl, flowrate respectively is shown. From these figures the corrosion rate was at the minimum levels when the salt concentration was very low or higher than 12% for all ranges of temperature and solution flowrate. From these two figures it is to know the range of all the variables that we can work with in to have specific corrosion rate when we have specific level for one of them. For example, in fig.4, when we have 10%NaCl solution we can work with in temperature range between 44-46^{O}C and flowrate of about 1.8-2.3 l/min to have corrosion rate of about 0.06-0.08 mmpy.

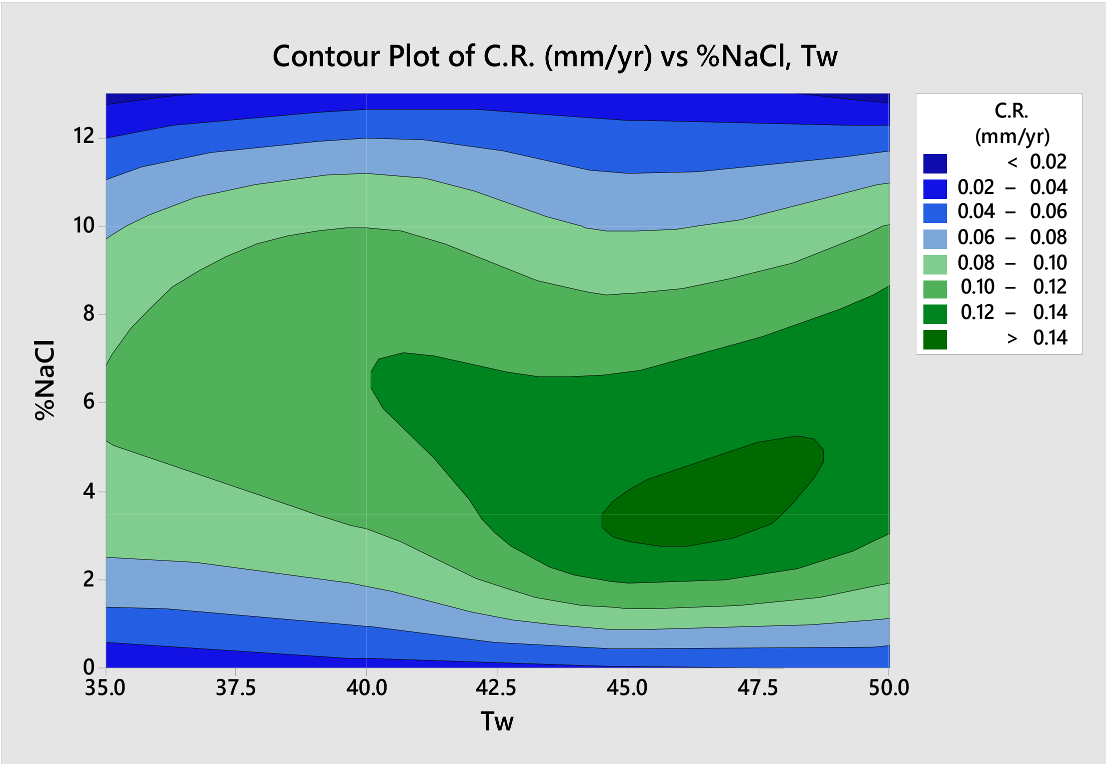

Figure 5. Contour Plot of Corrosion Rate versus %NaCl, Inlet Solution Temperature.

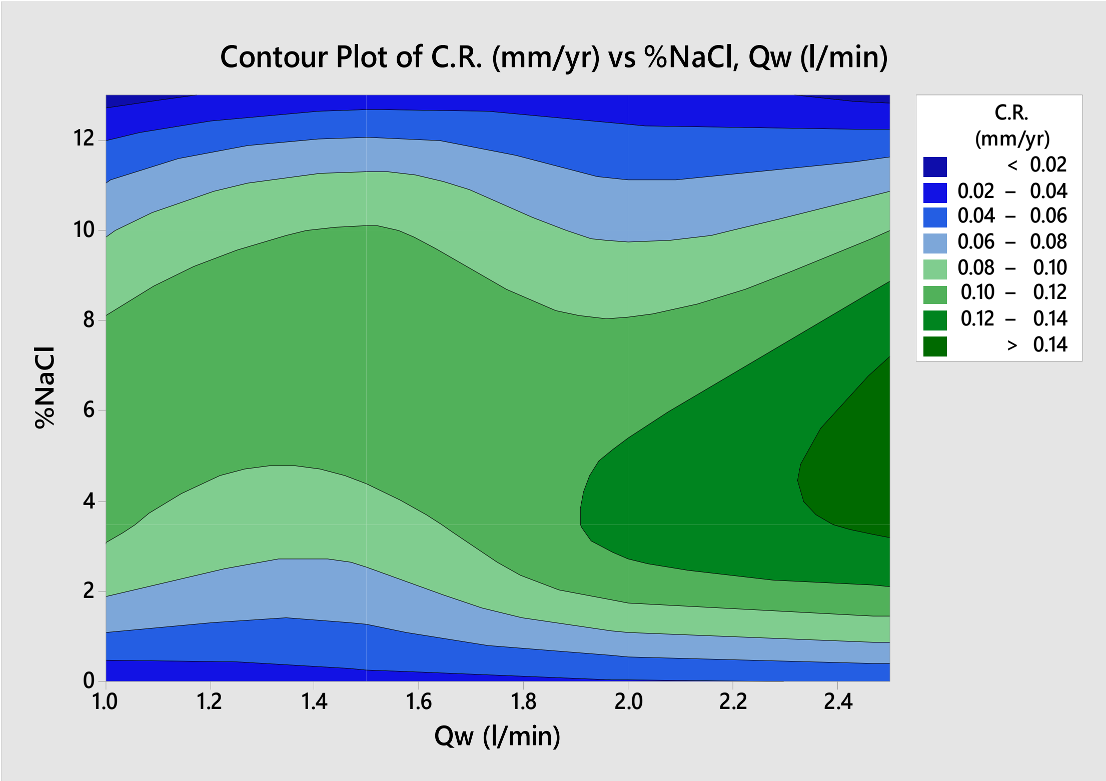

Figure 6. Contour Plot of Corrosion Rate versus %NaCl, Inlet Solution Flowrate.

4. CONCLUSIONS

This paper investigates the implementation of Taguchi design in the estimation of optimum minimum corrosion rate of mild-steel in cooling tower that uses saline solution of different concentration and different working parameters. It had been concluded that Taguchi design prepare a useful methodology for the setup and optimization of corrosion rate with minimum numbers of trials in comparison to other experimental design. It had been also founded that the optimal levels were 13%NaCl, 35^{o}C, and 1 l/min and that the %NaCl content have the greatest effect on corrosion rate followed by the solution temperature and then its flowrate. By using the contour plot, it offer a useful method to know under which ranges we can work to have the desired corrosion rate in the situation of fixing one of the working parameters.

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