OPTIMIZATION OF COOLING TOWER PERFORMANCE ANALYSIS USING TAGUCHI METHOD

by

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Original scientific paper
DOI: 10.2298/TSCI110528024R

This study discuss the application of Taguchi method in assessing maximum cooling tower effectiveness for the counter flow cooling tower using expanded wire mesh packing. The experiments were planned based on Taguchi's L27 orthogonal array .The trail was performed under different inlet conditions of flow rate of water, air, and water temperature. Signal-to-noise ratio analysis, analysis of variance and regression were carried out in order to determine the effects of process parameters on cooling tower effectiveness and to identity optimal factor settings. Finally confirmation tests verified this reliability of Taguchi method for optimization of counter flow cooling tower performance with sufficient accuracy.

Key word: *optimization, cooling tower, performance, Taguchi method, uncertainty, efficiency*

Introduction

The cooling tower is a steady flow device that uses a combination of mass and energy transfer to cool water by exposing it as an extended surface to the atmosphere. The water surface is extended by filling, which presents a film surface or creates droplets. The air flow (AF) may be cross flow or counter flow and caused by mechanical means, convection currents or by natural wind. In mechanical draft towers, air is moved by one or more mechanically driven fans to provide a constant air flow. The function of the fill is to increase the available surface in the tower, either by spreading the liquid over a greater surface or by retarding the rate of fall of the droplet surface through the apparatus. The fill should be strong, light and deterioration resistant. In this study, expanded wire mesh was used as the filling material. Its hardness, strength, and composition guard against common cooling tower problems resulting from fire, chemical water treatment, and deterioration. The operating theory of cooling tower was first suggested by Walker *et al.* [1]. Simpson and Sherwood [2] studied the performances of forced draft cooling towers with a 1.05 m packing height consisted of wood slats. Kelly and Swenson [3] studied the heat transfer and pressure drop characteristics of splash grid type cooling tower packing. Barile *et al*. [4] studied the performances of a turbulent bed cooling tower. They correlated the tower characteristic with the water/air mass flow ratio.

Bedekar *et al.* [5] studied experimentally the performance of a counter flow packed bed mechanical cooling tower, using a film type packing. Their results were presented in terms of tower characteristics, water outlet temperature and efficiency as functions of the water to air flow rate ratio. Goshayshi and Missenden [6] also studied experimentally the mass transfer and

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the pressure drop characteristics of many types of corrugated packing, including smooth and rough surface corrugated packing in atmospheric cooling towers. Their experiments were conducted in a 0.15 m × 0.15 m counter flow sectional test area with 1.60 m packing height. From their experimental data, a correlation between the packing mass transfer coefficient and the pressure drop was proposed. Kloppers and Kroger [7] studied the loss coefficient for wet cooling tower fills. They tested trickle, splash and film type fills in a counter flow wet cooling tower with a cross sectional test area of 1.5 m × 1.5 m. Energy and exergy analysis was conducted in cooling tower, from this result in let air wet bulb temperature is found to be the most important parameter than in let water temperature (WT) and also variation in dead state properties does not affect the performance of wet cooling tower [8]. Abo Elazm and Elsafty [9] studied the cross-flow water cooling tower problem, and found an empirical correlation's controlling heat and mass transfer coefficients as functions of inlet parameters to the tower. Lemouari and Boumaza [10] used this packing in an evaporative cooling system to study its thermal and hydraulic performances. Lemourai *et al*. [11] and Lemourai and Boumaza [12] experimentally investigated the thermal performance of a counter flow wet cooling tower filled with a vertical grid apparatus type packing. In most of the literature surveys, optimization techniques were used in the cooling tower for cost analysis, heat transfer, design, performance *et al.*, and the optimization techniques has been developed as mathematical modeling and simulation and that is being compared with already existing experimental work from the literature itself [8, 13-16].

In the experimental study, the operating parameters were optimized using Taguchi method and that optimized parameters were used in our experimental setup to find the cooling tower performance. Better cooling tower performance was achieved with optimum operating parameters.

Experimental set-up

A schematic diagram of the experimental apparatus is shown in fig.1(a) and 1(b). The main part of the installation is the cooling tower, 1.5 m in height and 0.3 m × 0.3 m in cross-section. The tower structure is made of steel frames. The sides and rear side of the test section are made of sheet metal, and front side is transparent and is made of Acrylic plate of 5 mm thick. The front plate is removable, so that the easy access to interior of tower is possible in order to replace packing, as well as to enable the access of various measuring probes. Water is transported by pump through flow regulated valve. The water flow (WF) rate is measured by flow meter and distributed through spray nozzles. Water is distributed in the form of falling films over the expanded wire mesh fill. The water distribution system consists of six numbers of 2 mm diameter nozzles. By using this system water is directly distributed over the EWM packing, and the films of falling water were uniform across the whole surface of packing. The pressure drop at fill zone is measured by U-tube manometer. Chromel-alumel thermocouples were used to measure water inlet and outlet temperature and measure the WT in fill zone area. All thermocouples were connected to a 24 point digital temperature recorder. Both dry bulb and wet bulb temperature of air are measured at the inlet and exit of the cooling tower. A forced draught fan was used to provide air flow to the tower. The air enters into

Figure 1(a). Snap shot of the experimental set-up of forced draft cooling tower

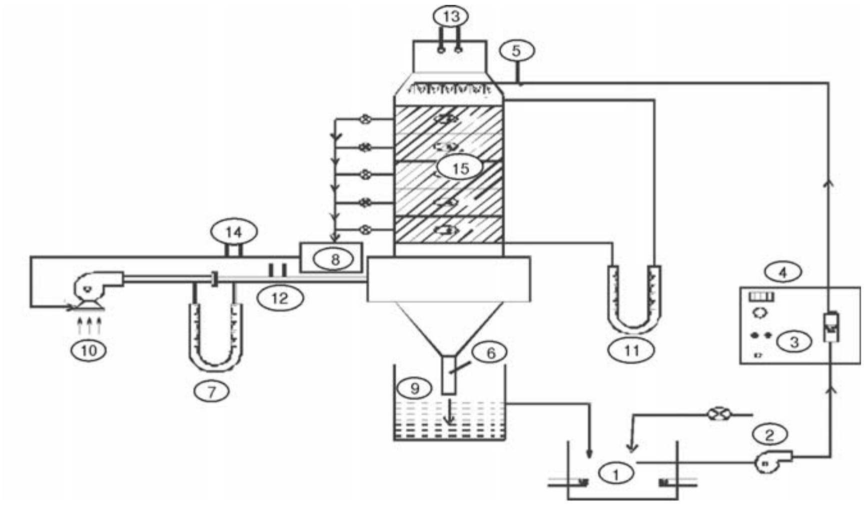

Figure 1(b). Line diagram of the experimental set-up of forced draft cooling tower
(1) water heater, (2) pump, (3) flow meter, (4) temp display and control unit, (5) hot water thermometer, (6) coldwater thermometer, (7) U-tube manometer air flow, (8) psychometric gun, (9) receiving tank, (10) forced draft fan, (11) U-tube manometer- cooling tower, (12) air inlet temperature (T_{DB1} T_{WB1}), (13) air outlet temperature (T_{DB2} T_{WB2}), (14) psychometric gun temperature, (15) expanded wire mesh fill

tower, passes the rain zone, fill zone, spray zone, and leaves the tower. In the present experimental work many parameters affecting the performance of counter flow wet cooing towers are investigated. These parameters and their corresponding range are given in tab. 1.

The cooling tower effectiveness is the ratio of range to the ideal range.

Table 1. Cooling tower operating parameters and range

Parameter	Range
Water flow, [kgh^{-1}]	100-200
Air flow [kgh^{-1}]	100-200
Inlet water temp. [°C]	40-48

$$\text{Effectiveness } (\varepsilon) = \frac{\text{Range (R)}}{\text{Range (R)} + \text{Approach (A)}}$$

$$\varepsilon = \frac{T_{\text{wi}} - T_{\text{wo}}}{T_{\text{wi}} - T_{\text{wbi}}} \tag{1}$$

$$R = T_{\text{wi}} - T_{\text{wo}} \tag{2}$$

$$A = T_{\text{wo}} - T_{\text{wbi}} \tag{3}$$

Uncertainty analysis

Standard uncertainty

"The objective of a measurement is to determine the value of the measurand, that is, the value of the particular quantity to be measure. A measurement therefore begins with an appropriate specification of the measurand, the method of measurement, and the measurement procedure. In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate" [17]. Through there are many factors in the measurement uncertainty, in this study, it is assumed that the major factors of resolution or detection of sensors and the variation of the measured data during repeated tests at the test condition. It defined the measurand, the output quantity as a function $Y = \mathrm{f}(X)$ of the input quantities X.

The uncertainties of the measured data were calculated by combining the type A and B [18].The type A uncertainty was evaluated by statistical analysis of series of observation of the 50 times sampled data and the type B uncertainty was calculated by previous measurements, specifications from the manufacturer, hand-books, calibration certificates, *etc.* [19]. The standard uncertainty was computed as root mean square (RMS) error of the type A and B uncertainties. Table 2 shows the uncertainty estimation of each measured parameter and 50 samples were collected in each test [19].

Table 2. Uncertainty estimation of variables

Variables	Unit	A-type	B-type	u(y)
Temperature (T)	°C	1.51e-2	1.00e-2	1.01e-2
Water flow meter (F_w)	l/h	3.522e-2	1.00e-2	2.25e-2
Air velocity (v)	m/s	1.583-1	1.00e-1	2.01e-1
Air pressure drop	mm of water	1.325	1.00	2.25
Orifice diameter (d)	m	–	1.45e-5	1.33e-5
Pipe diameter (D)	m	–	1.23e-5	1.35e-5
Drag coefficient (C_d)	–	–	3.32e-3	3.63e-3

Combined uncertainty

Combined uncertainty is an application of the law of propagation of uncertainty [15] in measurement on the function $Y = \mathrm{f}(X) = \mathrm{f}(X_1, X_2, X_3,...)$ and it is shown in eq. (4) and (5)

$$u_c^2(y) = \sum c_i^2 u^2(x_i) = \sum \frac{\delta Y}{\delta X_i} u^2(x_i) \tag{4}$$

$$c_i = \frac{\delta Y}{\delta X_i} \approx \frac{\Delta Y}{\Delta X_i} = \frac{y(1.01 x_i) - y(x_i)}{1.01 x_i - x_i} \tag{5}$$

where $u(x_i)$ is the standard uncertainty of input variable, $u_c(y)$ – the combine uncertainty, and c_i – the sensitivity coefficient.

In eq. (5), the sensitivity coefficients of the each variable were approximated as the effect on the function when the variable changed by 1%. The combined standard uncertainty was computed as a RMS of each multiplication of sensitivity coefficient and the standard uncertainty of the variable [20]. In this study, the combined standard uncertainty of water flow and air flow were calculated from the standard uncertainty of measured parameters.

Table 3 present sensitivity coefficients and uncertainties of the input variables, and calculated combined standard uncertainties of the WF and AF for the cooling tower. If the cooling tower test condition is changed, combined standard uncertainties analysis should be recalculated because of the characteristic of the test facility. At the different test condition, the type uncertainties of the measured parameter would change, and that results in the change of the combined standard uncertainties. In this study, Monte Carlo simulation (MCS) for the AF rate, WF rate were conducted and the results were used to verify the combined standard uncertainties. In the MCS, commercial software (at Risk-trial version) was used, and the same standard deviation and limits of resolution of sensor of the input variables as previous uncertainty analysis were used. The validation of the combined uncertainty by the uncertainty analysis and the standard deviation by the MCS for the WF and AF errors were 0.079% and 0.043%. Results agree with errors are less than 0.1% and the errors could be caused by the approximation used in the uncertainty analysis.

Table 3. Combined standard uncertainty

Input	Sensitivity coefficient	Uncertainty	Percentage
Water flow	4.29e-4	2.101	0.0721
Air flow	5.25e-5	4.325	0.0653

Application of the Taguchi method

First proposed by Taguchi in 1960, the quality design is widely applied because of its proven success in improving industrial product quality greatly [21, 22]. The Taguchi approach was used as a statistical design of experiment technique to set the optimal welding parameters [23]. Taguchi method was applied to optimize ultrasound thermal process for extracting caffeine and flavor from coffee. The use of ultrasound has abridged experiments in cost, energy loss and time [24]. In the literature surveys, parameters were optimized and the system performance was enhancing using Taguchi method [25-28]. In addition to this, minimum trail numbers, obtaining the effect of process parameters on quality characteristics and their optimum levels have easily increased its popularity [29]. There are ten steps in a systematic approach to the use of Taguchi's parameter design methodology. Figure 2 shows the detailed procedure of Taguchi design methodology.

In this study, the effect of process parameters, such as flow rate of inlet water, air and WT, on the tower effectiveness have been determined and optimum factor levels have been obtained by applying the steps given above. The specified factors and their levels are depicted in tab. 4.

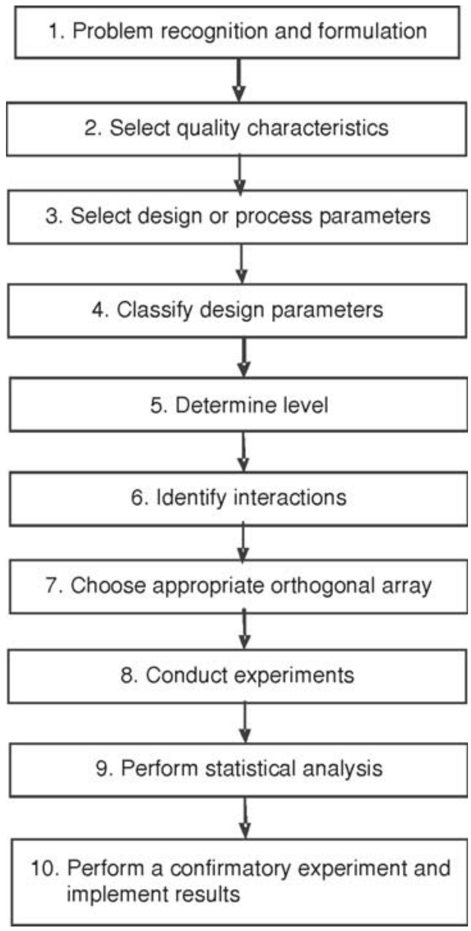

Figure 2. Procedure of Taguchi design methodology

Table 4. Cooling tower parameters and their levels

Factor	Parameter	Unit	Level 1	Level 2	Level 3
A	Water flow (WF)	kg/h	100	150	200
B	Air flow (AF)	kg/h	100	150	200
C	Water temperature (WT)	°C	40	44	48

Based on orthogonal arrays, the number of experiments that may cause an increase in time and cost can be reduced by means of Taguchi techniques. It uses a special design of orthogonal arrays to learn the whole parameters space with a small number of experiments

Table 5. L27 – an orthogonal array (OA) with control factors and interactions assigned to columns

Orthogonal array for L27 Taguchi design													
Expt. no.	1 A	2 B	3 (A × B)	4 (A × B)	5 C	6 (A × C)	7 (A × C)	8 (B × C)	9	10	11 (B × C)	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	2	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	3	1	1	3	2

[30-32]. An orthogonal array can be chosen based on the total degrees of freedom (DoF) required for an experiment. DoF related to a process can be calculated for each factor and each interactions as [33, 34]:

$$\text{DoF} = (\text{number of levels-1}) \text{ for each factor} + (\text{number of level-1}) \times \\ \times (\text{number of level-1}) \text{ for each interactions} + 1$$

In the present study which takes three factors with three levels and their two-way interactions into consideration, the total DCF is 18. Hence, an L27-an OA was chosen which has 27 rows corresponding to the number of parameter combinations with 13 columns as shown in tab. 5. The experimental design consists of 27 trials (each row in the L27 OA and the columned of the OA are assigned to factors and their interactions. As per the linear graph of L27 OA [35] and the fig. 3, the first column is assigned to inlet WT, second column to inlet AF and fifth column to inlet WT and remaining column are assigned to their interactions. If all the factors have interactions in experiments, systems consisting of three factors with three levels are taken into consideration, L27 OA is the most appropriate experimental plan. In addition, as it includes all the combination of factor levels, it is possible to use it in regression and correlation analysis effectively. For analysis of the results and optimization of conditions for setting the control factors, MINITAB-15 software was used. It is the widow version software for automatic design and analysis of Taguchi experiments.

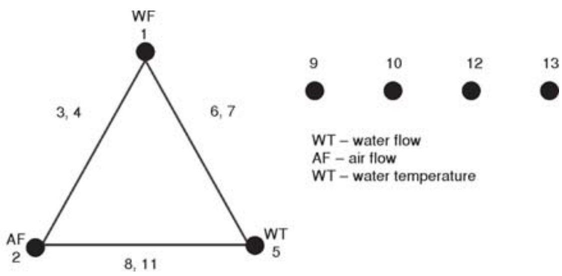

Figure 3. A linear graph of L27 – an OA

Statistical analysis

Statistical analysis – signal-to-noise (S/N) ratio, analysis of variance (ANOVA), regression – are carried out for a significance level of 0.005, *i. e.*, for confidence level of 95%.

Signal-to-noise analysis

Taguchi method employs a S/N to measure the present variation [24, 36]. The definition of S/N ratio differs according to an objective function, *i. e.*, a characteristic value. There are three kinds of characteristics value: nominal is best (NB), smaller is better (SB), and larger is better (LB). As the objective of this study is the maximization of cooling tower effectiveness, LB is chosen. S/N ratio of LB is formulated as:

$$\frac{S}{N} = -100\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \tag{6}$$

where n is the number of measurements and y_i – the parameters being measured through the experiments. The experimental results and corresponding S/N ratios are given in tab. 6 .The uncontrolled or the noise parameters are the outside air drybulb temperature (DBT) and wetbulb temperature (WBT). As these can not be kept at a particular level during experimentation, experiments are conducted at each experimental setting from 7.00 a. m. to 9.00 a. m. Data measured at two hour interval are used at noise parameters (N_1 to N_8).

Table 6. Experimental/predicted results and S/N ratios

Expt. no	Output response Cooling tower effectiveness								Cooling tower effectiveness (ε)		S/N
	N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8	Mean	Predicted	
1	63	63	63	64	64	65	64	63	63.6	61.4	36.0710
2	64	64	64	64	65	65	64	64	64.2	62.6	36.1569
3	65	65	65	65	66	66	65	64	65.1	63.8	36.2738
4	69	69	69	69	70	70	69	68	69.1	67.5	36.7917
5	70	70	70	70	71	71	70	69	70.1	68.7	36.9165
6	71	71	71	71	72	72	71	70	71.1	69.9	37.0395
7	72	73	73	73	74	74	73	72	73.0	73.7	37.2652
8	73	74	74	74	75	75	74	73	74.0	74.9	37.3834
9	74	75	75	75	74	75	74	73	74.4	75.1	37.5143
10	50	50	50	50	51	51	51	49	50.2	53.2	34.0205
11	51	51	51	51	52	52	51	50	51.1	54.4	34.1709
12	52	52	52	52	53	53	52	51	52.1	55.6	34.3392
13	60	60	60	60	61	61	60	59	60.1	59.3	35.5798
14	61	61	61	61	62	62	61	60	61.1	60.5	35.7231
15	62	62	62	62	62	63	62	61	62.0	61.7	35.8470
16	66	66	66	66	67	66	66	65	66.0	65.5	36.3901
17	67	67	67	67	68	68	67	66	67.1	66.7	36.5366
18	68	68	68	68	69	68	68	67	68.0	67.9	36.6495
19	44	44	44	44	45	44	44	43	44.0	45.0	32.8674
20	47	47	47	47	48	48	47	46	47.1	46.2	33.4629
21	49	49	49	49	50	50	49	48	49.1	47.4	33.8241
22	53	53	53	53	54	54	53	52	53.1	51.1	34.5043
23	54	54	54	54	55	54	54	53	54.0	52.3	34.6468
24	56	56	56	56	57	57	56	55	56.1	53.5	34.9816
25	57	57	57	57	58	58	57	56	57.1	57.3	35.1351
26	58	58	58	58	59	59	58	57	58.1	58.5	35.2859
27	59	59	59	59	60	60	59	58	59.1	59.7	35.4341

Analysis of variance

ANVOA is a method most widely used for determining significant parameters on response and measuring their effects. In the cooling tower performance, the major factor of the non-reproducibility is the controls the test facility and the cooling tower operating condition. In order to reduce those factors, the test procedure was standardized and inter -tester group proficiency test has been conducted regularly. In the inter-tester groups (A&B) conducted four tests for each experimental run at the defined test condition and the results were analyzed by two way ANOVA in order to ensure the repeatability tests [19]. The ANVOA results for S/N ratio and mean are illustrated in tabs. 7 and 8. In ANOVA, the ratio between the variance of the process parameter and the error variance is called as F-test. It determines whether the parameter has significant effect on the quality characteristics. This process is carried out by comparing the F-test value of the parameter with the standard value ($F_{0.05}$) at the 5% significance level. If F-test value is greater than $F_{0.05}$, the process parameter is considered significant. Depending on it, it can be seen that all factors and their interactions on temperature gradient are significant. The last column of tabs. 5 and 6 indicates the percentage contribution (significance rate) of each process parameter to the total variation, indicating their degree of influence on the results. According to tab. 5, inlet water flow (WF = 59.33%) has the most dominant effect on total variation and it is followed by inlet air flow (AF = 36.27%), Inlet water temperature (WT = 1.40%), water flow -air flow (WF·AF = 2.43) and interactions.

Table 7. Analysis of variance for S/N ratios

Source	Degree of freedom (DF)	Seq. sum of squares (SS)	Adj. sum of squares (SS)	Adj. mean of squares (MS)	F ratio	[%] of contribution
WF	2	25.3060	25.3060	12.6530	1132.05	59.33
AF	2	15.4723	15.4723	7.7362	692.15	36.27
WT	2	0.5970	0.5970	0.2985	26.71	1.40
WF·AF	4	1.0400	1.0400	0.2600	23.26	2.43
WF·WT	4	0.1045	0.1045	0.0261	2.34	0.25
AF·WT	4	0.0436	0.0436	0.0109	0.97	0.10
Residual error	8	0.0894	0.0894	0.0112		0.21
Total	26	42.6529				100

Table 8. Analysis of variance for means

Source	Degree of freedom (DF)	Seq. sum of squares (SS)	Adj. sum of squares (SS)	Adj. mean of squares (MS)	F ratio	[%] of contribution
WF	2	1224.86	1224.86	612.431	1916.31	61.65
AF	2	698.94	698.94	349.469	1093.50	35.20
WT	2	25.68	25.68	12.841	40.18	1.30
WF·AF	4	31.97	31.97	7.994	25.01	1.61
WF·WT	4	2.20	2.20	0.550	1.72	0.11
AF·WT	4	0.59	0.59	0.148	0.46	0.03
Residual error	8	2.56	2.56	0.320		0.13
Total	26	1986.81				100

Regression analysis

By mean of regression and correlation analysis, the effect of process parameter on the quality characteristics of cooling tower effectiveness (ε) was obtained as follows.

$$\varepsilon(\text{predicted}) = 53.8 - 0.164\ \text{WF} + 0.123\ \text{AF} + 0.299\ \text{WT} \tag{7}$$

Here ε is dependent variable and WF, AT, and WT are independent variables. Corresponding coded levels are given in tab. 7. It is clear that statistical model can predict the cooling tower effectiveness with sufficient accuracy depending on the obtained correlation coefficients ($R^2 = 96.6\%$). Predicted results obtained by eq. (7) are shown in tab. 6.

Determination of optimal factor levels

Main effects plots of *S/N* ratios and means and interactions effect plots for *S/N* ratios are given in figs. 4, 5, and 6, respectively. From fig. 4, it is obvious that the inlet *WF* and inlet *AF* are 100 kg/h and 200 kg/h in obtaining the maximum cooling tower effectiveness. It is difficult to determine the optimum level of *WT* from this graphic. According to fig. 6, *WF-AF* and *WF-WT* interactions are considered, the optimum parameter settings are *WF* = 100 kg/h, *AF* = 200 kg/h, and

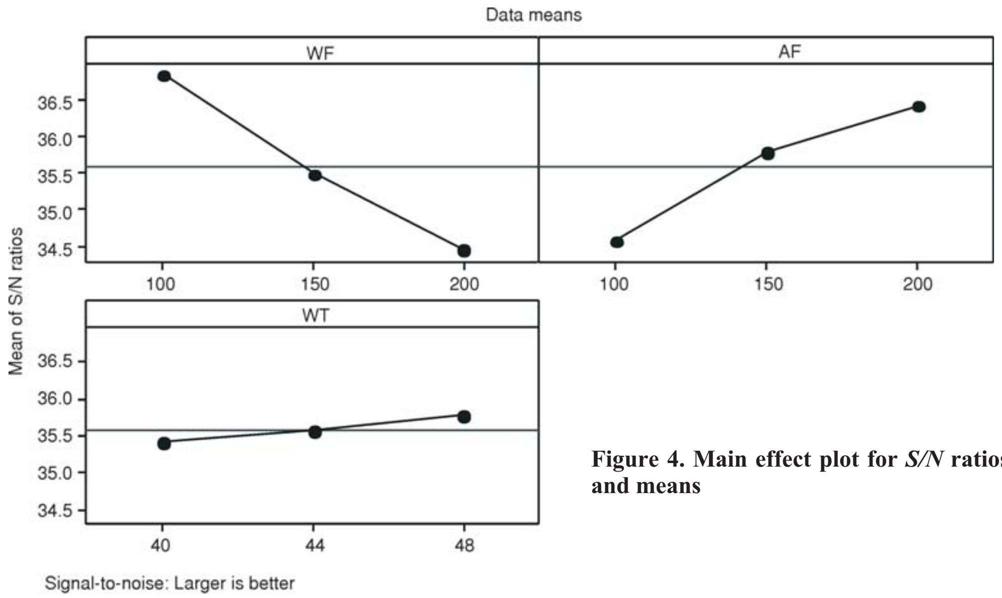

Figure 4. Main effect plot for *S/N* ratios and means

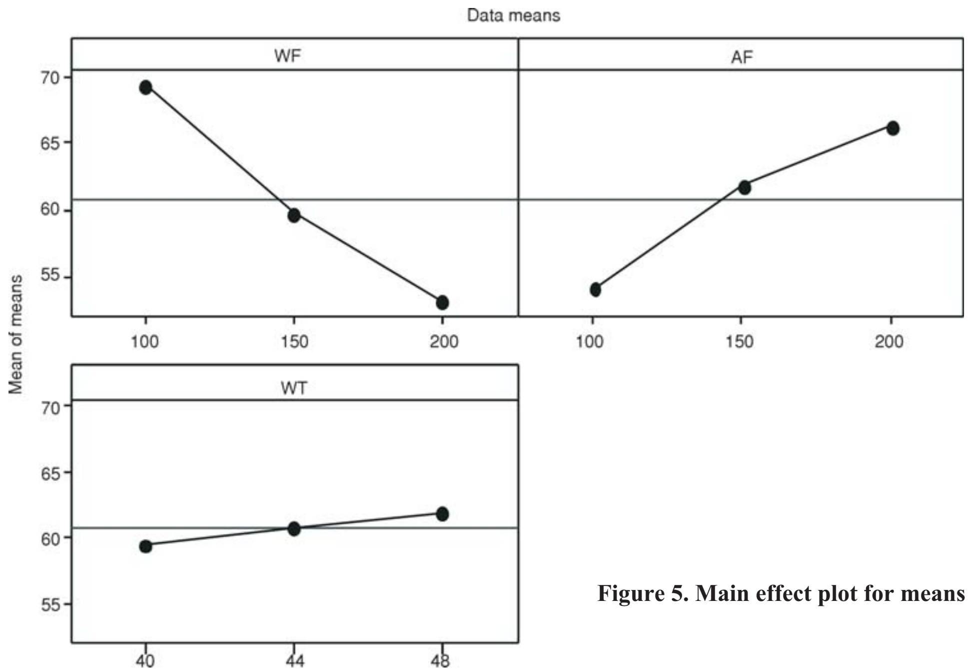

Figure 5. Main effect plot for means

WF = 100 kg/h, *WT* = 48 °C, respectively. As a result, the optimum setting of control factors maximizing the cooling tower effectiveness are *WF* = 100 kg/h, *AF* = 200 kg/h, and *WT* = 48 °C.

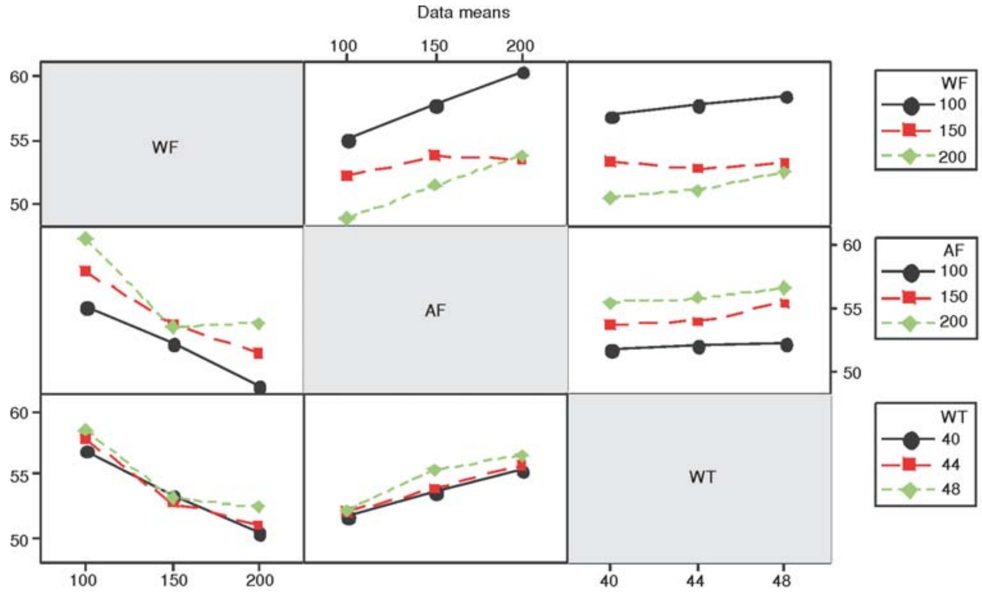

Figure 6. Interaction plot for S/N ratios

Confirmation tests

The final step is verifying the results based on Taguchi experimental design is the experimental confirmation test. Table 9 shows the experimental condition including optimal factors settings. Table 10 indicates the comparative test results for cooling tower effectiveness.

Table 9. Experimental condition including optimal factors setting

Experimental condition for confirmation test			
Test	Water flow [kgh^{-1}] (Factor-*WF*)	Air flow [kgh^{-1}] (Factor-*AF*)	Water temperature [°C] (Factor-*WT*)
1	100	200	48
2	150	150	44
3	200	100	40

Table 10. Comparative test results for cooling tower effectiveness

Confirmation results for confirmation tests			
Test	Experimental results	Results as per developed model eq. (5)	Error [%]
1	76.5	75.1	1.83
2	62.9	60.5	3.82
3	44.2	45.0	1.81
		Average error [%]	2.49

From the confirmation test results, average 2.49 % error was obtained between predicted values by regression model and confirmation test results. It can be concluded that Taguchi method achieves the statistical assessment of maximum cooling tower effectiveness in the counter flow cooling tower with sufficient accuracy. Experimental runs were compared with predicted value and error analyses of the experiments were compared with standard deviation (SD), *S/N* ratios, and mean. It is shown in fig. 7.

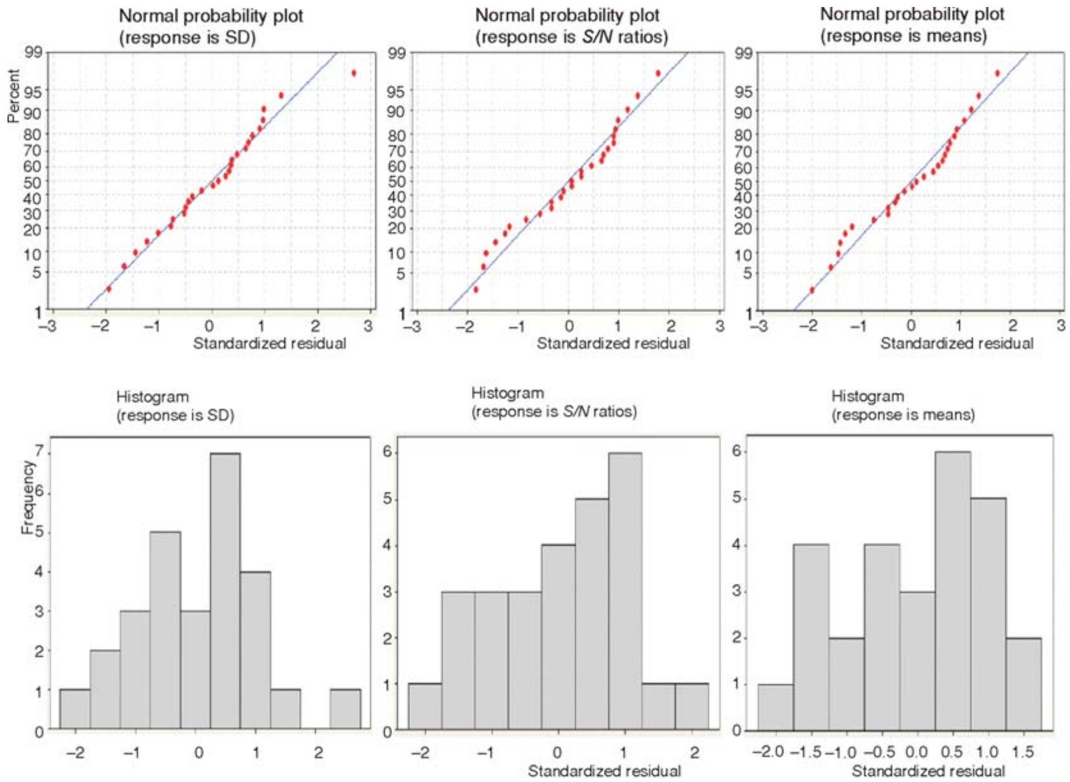

Figure 7. Normal probability plot and histogram for experimental runs

Conclusions

In this article, effect and optimization of process parameters in counter flow cooling tower on maximum cooling tower effectiveness were investigated through Taguchi methods. From the analysis on the results of cooling tower effectiveness of cooling tower, the following conclusions can be drawn from the study.

- Based on the ANOVA results, all control factors and their two-way interactions have significant effect on the quality characteristics statistically.
- Uncertainty analysis was conducted in the experimental runs. The cooling tower performance measurements were conducted in order to ensure the measurement reliability. Validation results agree with errors less than 0.1%.
- Water flow (*WF* = 59.33%) has the most dominant effect on total variation and it is followed by air flow (*AF* = 36.27%),water flow-air flow(*WF-AF* = 2.43%), and water temperature (*WT* = 1.4%).

- The effects of control factors and their two-way interactions on response were modeled via regression and correlation analysis with R^2-value of 96.6%.
- The optimum experiment condition which gives the maximum cooling tower effectiveness was obtained with *WF* kept at first level (100 kg/h), *AF* kept at third level (200 kg/h) and water temperature kept at third level (48 °C).
- Three confirmation experiments including one at optimum experiment condition were conducted and found that the error between predicted values and confirmation test results is only 2.49%. This result indicates that Taguchi method can be used in the optimization of counter flow cooling tower performance reliably.
- As seen from the optimum results, maximum cooling tower effectiveness was achieved at lower water flow rate, higher *AF* rate and higher *WT*.

Acknowledgment

The authors wish to thank the authorities of Annamalai University, Annamalai Nagar, Tamil Nadu, India, for use the steam laboratory in the Department of mechanical engineering to do the research work.

Nomenclature

AF – air flow, [kgh^{-1}]
DoF – degree for freedom
S/N – signal to noise ratio
T – temperature, [°C]
WF – water flow, [kgh^{-1}]
WT – water temperature, [°C]
ε – cooling tower effectiveness

Subscripts

i – inlet
o – outlet
w – water
wb – wet bulb

Acronyms

A – approach
R – range

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Paper submitted: May 28, 2011
Paper revised: December 11, 2011
Paper accepted: February 9, 2012