Performance enhancement of a counter flow induced draft cooling tower

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Abstract

An evaporative cooling tower is a direct contact heat exchanger that transfer heat from circulating water to the surrounding atmosphere. Warm water from the heat source is pumped to the top of the cooling tower and then it flows down through the plastic or wooden shells also known as packing material or fills. As it falls downward across the fills, water is broken into small droplets. Simultaneously, air is drawn in through the air inlet louvers at the base of the cooling tower which travels upward through the wet deck fill opposite to the water flow. Hence evaporation of hot water occurs and the water is cooled down until it reaches to the below placed cold water basin. In present study, Taguchi method of optimization is used to optimize various cooling tower performance parameters such as mass flow rate of water, mass flow rate of air and different pitch sized packing material. The main aim of the study is to optimize these performance factors in order to achieve maximum cooling effect in the counter flow induced draft cooling tower. The experiments were planned based on Taguchi's L9 orthogonal array .The trail was performed under different inlet conditions of flow rate of water, air and fill pitch size. Signal-to-noise ratio (S/N) analysis, analysis of variance (ANOVA) 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 test was carried out to verify the reliability of Taguchi method for optimization of counter flow induced draft cooling tower performance with sufficient accuracy.

Keywords: *Counter flow induced draft cooling tower, Taguchi method, optimization, performance parameters, maximum cooling effect*

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1. Introduction

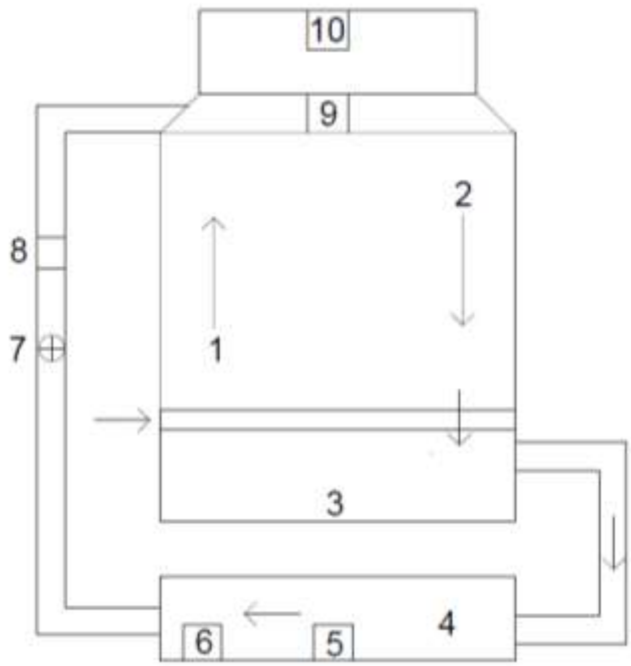
Cooling towers are widely and extensively used in various industries such as process industries, pharmaceutical companies, plastic manufacturing industries, etc. where cold water is required in large amount. As it is not economical to circulate new cold water everytime into the industrial plants, cooling tower is used to circulate hot water by cooling it in the cooling tower.

An evaporative cooling tower is a direct contact type of semi-enclosed heat exchanger that transfers heat from circulating water to the atmosphere. It is a wooden, steel or concrete structure and is provided with corrugated surfaces, troughs, baffles, fills or perforated trays within the cooling tower for uniform distribution and better distribution of water.

The hot water coming out from the condenser is fed to the tower on the top and is allowed to tickle in form of thin sheets or drops. The air flows from bottom of the tower or perpendicular to the direction of water flow and then exhausts to the atmosphere after effective cooling. To prevent the escape of water particles with air, drift eliminators are provided at the top of the tower. A cooling tower ordinarily reduces the fresh cooling water requirement by about 98% although there is some mutual contamination caused by the saturation of the air with water vapor.

2. Experimental setup

The experimental setup for the thermal performance analysis of a counter flow induced draft cooling tower of size 24 x 24 x 60 inches consists of a water circulation loop, air circulation loop and cooling tower sections. Figure 1 illustrates the layout of experimental setup. The layout shows the direction of water circulation as well as air circulation in the cooling tower. The experimental results obtained are useful to understand the role of operating variables such as range, flow rate of water, flow rate of water, capacity of cooling tower, etc. The experimental results are used to plot graphs to understand the variation of cooling tower performance with respect to the performance variables.



1: Air flow direction

2: Water flow direction

3: Cold water storage basin

4: Hot water basin

5: Immersion Heater and Thermostat

6: Submersible Pump

7: Flow control valve

8: Rotameter

9: Temperature sensor

10: Aluminum fan

Figure 1: Experimental setup

3. Optimization using Taguchi method for design of experiment

First proposed by Taguchi in 1960s, the quality design is widely applied because of its proven success in improving industrial product quality greatly. The Taguchi approach is used to optimize parameters and to enhance the system performance. In addition to this, obtaining the effect of process parameters on quality characteristics and their optimum levels have easily increased its popularity.

Various steps involved in Taguchi methodology are mentioned below:

- Decide the important input process parameters and their levels (by pilot experimentation and literature survey), response parameters and its characteristics.
- Select the appropriate orthogonal array and assign the parameters to its various columns
- Conduct experiments for the levels given in each row randomly and note down the values of response parameter.
- Study factor effects and find out the optimum combination of the input parameters. Calculate the best value of the response characteristic.
- Calculate the range within which the experiment should lie and conduct confirmation experiment to verify the same.
- Perform analysis of variance (ANOVA) to find out the significance of various factors and their relative contribution.

In this study, the effect of process parameters viz. mass flow rate of water, mass flow rate of air and different sizes of packing material (fills) have been determined to obtain maximum cooling effect (ΔT) of the cooling tower. Also optimum factor levels have been obtained by applying the steps descried above. The specified factors and their levels are stated in table 1.

Table- 1: 3-level design of performance parameters

Parameter	**Water flow rate (lph)**	**Air flow rate(CFM)**	**Fills pitch size(mm)**
Level 1	2800	180	15
Level 2	2900	190	17
Level 3	3000	200	19

Taguchi recommends the use of the criterion he calls, "Signal to noise ratio "as performance statistic. The change in quality characteristic of a product under investigations in response to factor induced in the experimental design is the signal of the desired effect. The effect of external factors (Uncontrollable factors) on the outcome of the quality characteristic under test is termed the noise. From the quality point of view, there are three possible categories of quality characteristic. They are:

1. Smaller is better

2. Nominal is the best

3. Larger is better.

In our case, cooling effect is to be maximized. So, S/N ratio larger is better is selected.

For analysis of the results and optimization of different condition setting of the control factors, MINITAB-17 software is used. It is the window version software for automatic design and analysis of Taguchi experiments.

3.1 Selection of orthogonal array

The Taguchi design method applies fractional factorial test designs called OAs that serve to reduce the number of experiments. The selection of a suitable OA depends on the number of control factors and their levels. Using OA design can estimate multiple process variables which is simultaneously affecting on the performance characteristic, while minimizing the number of test runs. For example, for three parameters at three levels, the traditional full factorial design would require 27 experiments. In the Taguchi L9 OA, the required experiments are only 9. To accomplish such goal, Taguchi L9 OA design (3 factors with 3-level design) was used to determine and optimize the cooling tower performance parameters in the Minitab software. Table 2 indicates 9 different combinations of performance parameters that are used for conducting experiments.

Table 2: L9 orthogonal array

Sr. no.	**Mw**	**Ma**	**Fill pitch size**
1.	2800	180	19
2.	2800	190	17
3.	2800	200	15
4.	2900	180	17
5.	2900	190	15
6.	2900	200	19
7.	3000	180	15
8.	3000	190	19
9.	3000	200	17

For the above stated experimental combinations, experiments were carried out for different uncontrollable factors. Here uncontrollable factor is the surrounding wet bulb temperature. For different range of wet bulb temperatures, experiments were carried out to determine optimum combination of performance parameters. Table 3 indicates the experiments that were carried out for different range of wet bulb temperatures. S/N ratio and mean are calculated

Table- 3: Experimental response values for designed experiments

Experiment no.	mw	Ma	Fill	20.5-21	21-21.5	21.5-22	22-22.5	22.5-23	23-23.5	S/N ratio	Mean
1	2800	180	19	5	5	4.9	4.9	4.9	4.7	13.7983	4.9
2	2800	190	17	5.9	5.8	5.8	5.6	5.4	5.4	15.0248	5.6
3	2800	200	15	6.2	5.8	5.6	5.4	5.4	5.4	14.9823	5.6
4	2900	180	17	6.9	6.3	6.2	6.0	5.9	5.7	15.7540	6.2
5	2900	190	15	6.9	6.9	6.8	6.7	6.7	6.5	16.5805	6.8
6	2900	200	19	5.4	5.4	5.3	5.3	5.2	5.0	14.4215	5.3
7	3000	180	15	5.8	5.8	5.8	5.8	5.7	5.3	15.1031	5.7
8	3000	190	19	5.1	5.0	4.9	4.9	4.9	4.7	13.8254	4.9
9	3000	200	17	6.4	6.2	6.2	6.2	6.1	5.9	15.7933	6.1

3.2 S/N ratio analysis:

Taguchi method employs a signal to noise(S/N) to measure the present variation. 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 present study involves maximization of cooling effect, LB is chosen. S/N ratio of LB is formulated as follows:

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

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 table 11111. As WBT cannot be kept at a particular level during experimentation, it is taken as uncontrolled or noise parameter in the experimentation.

3.3 Determination of optimum performance parameters:

When Taguchi design is analyzed in minitab-17 software, we obtain the following graph showing S/N ratio: larger is better.

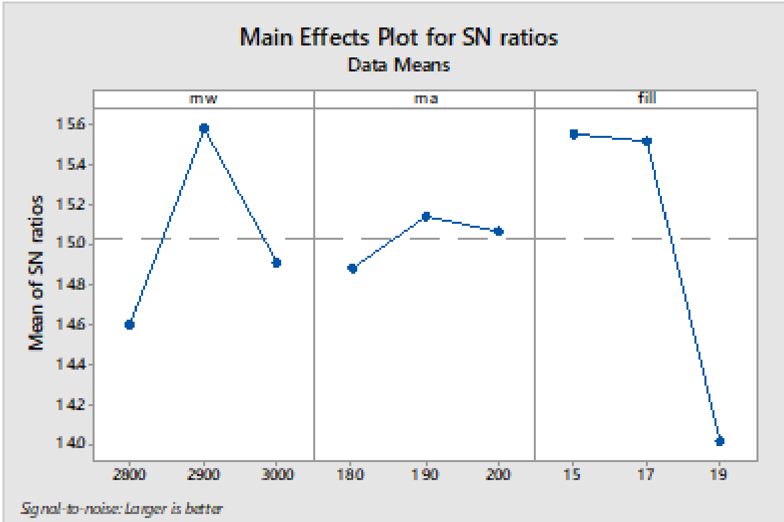


Figure- 2: Determination of optimum performance parameters

It can be observed that the peak points are obtained in the above analyzed graph. These peak points have the highest signal to noise ratio. The peak points having highest S/N ratio are the optimum performance parameters that give maximum cooling effect according to the Taguchi analysis. The optimum performance parameters which give maximum cooling effect are stated in the below table 4.

Table- 4: Optimum performance parameters

m_w (lph)	m_a (CFM)	Fill pitch size (mm)
2900	190	15

3.4 Analysis of variance (ANOVA)

Performance analysis of variance (ANVOA) is a method most widely used for determining the significance of various performance parameters on the response and their relative contribution. The ANVOA results for S/N ratio and mean are illustrated in table 1111. 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 or not. This process is carried out by comparing the F-test value of the parameter with the standard value at the 5% significance level. If F-test value is greater than 5%, the process parameter is considered significant. Depending on it, it can be seen that all factors and their interactions on the cooling effect are significant. The last column of tab.1111 indicates the percentage contribution (significance rate) of each process parameter to the total variation, indicating their degree of influence on the results. It is observed that all the 3 performance parameters are significant and need to be taken into consideration while optimizing cooling tower performance (see table 5). Fill pith size has the most dominant effect on total variation with a percentage contribution of 60.6%, followed by mass flow rate of water having 26.7% contribution and mass flow rate of air having 11.5% contribution.

Table 5: Analysis of variance

Factor/source	Sum of squares	DOF	Variance	F-ratio	% contribution	Remarks

Mass flow rate of water(mw)	1.78337	2	0.89168	2.31	26.7	Significant
Mass flow rate of air(ma)	0.77097	2	0.03448	0.09	11.5	Significant
Fill pitch size	4.03977	2	2.01989	5.24	60.6	Significant
Error	0.06896	2	0.38548	-	1.2	-
Total	**6.66307**	**8**	**-**	**-**	**100**	**-**

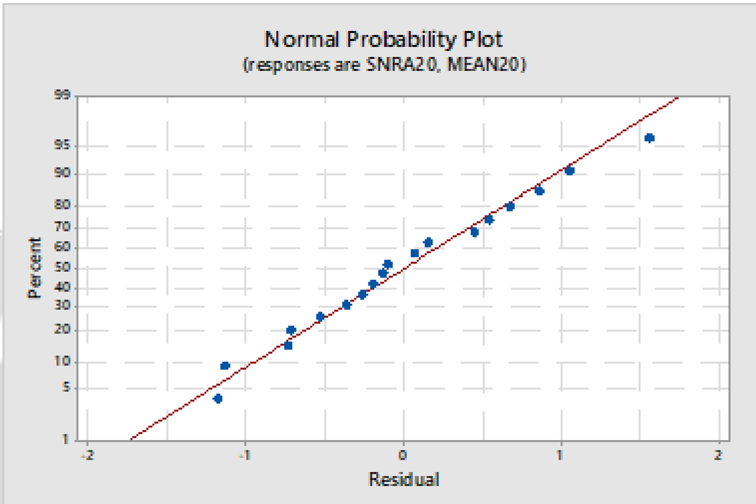


Figure 3: Normal probability plot

In this graph it is shown that the data is very closer to the normal distribution curve. Hence the error in the experiment is very less. It is shown that the graph follows normal distribution. The normality plot takes the standardized residual of each data point and plots it against its percentage ranked position within distribution. The diagonal reference line gives the expected values if the data were to be following an exact normal distribution. It can be observed from the above graph that the experimental data points are closely aligned to this reference line and it appears that the data is normally distributed.

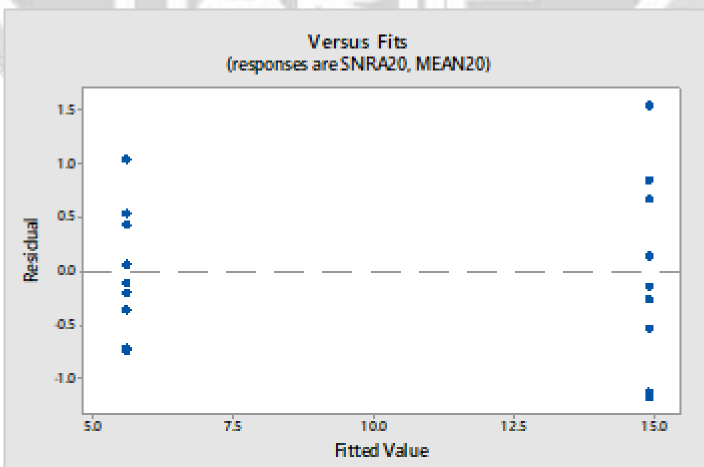


Figure 4: Residual plots

Here the residuals are plotted against the fitted value. It can be observed that the residuals have a constant variance.

3.5 Regression modelling:

Linear regression, also known as simple linear regression or bivariate linear regression, is used when we want to predict the value of a dependent variable based on the value of an independent variable. The dependent variable can also be referred to as the outcome, target or criterion variable, while the independent variable can also be referred to as the predictor, explanatory or regressor variable.

$\Delta T = 6.08 + 0.00100\ mw + 0.0050\ ma - 0.250\ fill$

Here the cooling effect (ΔT) is the dependent variable and mass flow rate of water (mw), mass flow rate of air (ma) and fill pitch size (fill) are the independent variables. This equation predicts the cooling effect with an accuracy of 95% depending upon the obtained correlation coefficients to best fit the regression model. The predicted values of cooling effect are shown in below table 6.

Table 6: Comparison of experimental values with regression model

Experiment no.	Factors			Cooling effect	
	mw	Ma	Fill	Mean	Predicted using regression model
1	2800	180	19	4.9	5.0
2	2800	190	17	5.6	5.4
3	2800	200	15	5.6	5.2
4	2900	180	17	6.2	6.4
5	2900	190	15	6.8	6.6
6	2900	200	19	5.3	5.1
7	3000	180	15	5.7	5.9
8	3000	190	19	4.9	5.0
9	3000	200	17	6.1	5.8

3.6 Confirmation test:

The final step in Taguchi analysis is to verify the results based on Taguchi experimental design using the experimental confirmation test. Table 7 shows the experimental condition including optimal factors settings. Hence experiment is performed at the optimum performance parameters obtained using Taguchi design of experiment.

Table 7: Confirmation test

Optimum Performance parameters			Cooling effect (ΔT)		Error
m_w	m_a	Fill	Experimental result	Result as per developed regression model	
2900	190	15	6.9	6.6	4.1%

4. Conclusion

- More the approach, more amount of water can be evaporated as the difference between cold water temperature and wet bulb temperature increases. When more amount of hot water evaporates, more cooling effect is obtained. As a result we obtain further lower temperature of the cold water.
- Based on the ANOVA results, all control factors and their two-way interactions have significant effect on the quality characteristics statistically.
- The optimum combination of performance parameter that gives maximum cooling effect is achieved at 2900 lph water flow rate, 190 CFM air flow rate and 15mm fill pitch size.
- Regression model was prepared for the obtained data with 95% confidence level. Confirmation experiment was carried out and the experimental result and the result obtained as per developed regression model were in good coordination with around 95.9% accuracy.

5. References

1. pdhengineers.com {pdh} (2001), course No. M-7002
2. Wanchai Asvapoositkul, Supawat Treeutok (2012). A simplified method on thermal performance capacity evaluation of counter flow cooling tower. Applied Thermal Engineering 38 (2012) 160-167.
3. Farhad Gharagheizi, Reza Hayati, Shohreh Fatemi (2006). Experimental study on the performance of mechanical cooling tower with two types of film packing. Energy Conversion and Management 48 (2007) 277–280.
4. H.R. Goshayshi, J.F. Missenden (1999). The investigation of cooling tower packing in various arrangements. Applied Thermal Engineering 20 (2000) 69-80.
5. Jameel-ur-Rehman Khan and Syed M. Zubair (2001). An Improved Design and Rating Analysis of Counter Flow Wet Cooling Towers. Journal of Heat Transfer AUGUST 2001, Vol. 123.
6. M. Lemouari, M. Boumaza, A. Kaabi (2009). Experimental analysis of heat and mass transfer phenomena in a direct contact evaporative cooling tower. Energy Conversion and Management 50 (2009) 1610–1617.
7. Si Y. Lee, James S. Bollinger, Alfred J. Garrett and Larry D. Koffman (2008). CFD modeling analysis of mechanical draft cooling tower. Proceedings of 2008 ASME Summer Heat Transfer Conference HT2008 August 10-14, 2008, Jacksonville, Florida USA.
8. Nenad Milosevljevic, Pertti Heikkila (2000). A comprehensive approach to cooling tower design. Applied Thermal Engineering 21 (2001) 899-915.
9. J.C. Kloppers, D.G. Kroger (2004). A critical investigation into the heat and mass transfer analysis of counterflow wet-cooling towers. International Journal of Heat and Mass Transfer 48 (2005) 765–777.
10. Stephen A. Leeper (1981), Wet cooling Towers: 'Rule of Thumb' design and simulation. EGG-GTH-5775.
11. Calculation for CFM of cooling tower fan available online (CFM) http://www.eng-tips.com/faqs.cfm?fid=1152
12. Cooling tower thermal design manual [cooling tower technical site of Daeil Aqua Co., Ltd. for cooling tower engineers, operators and purchasers]
13. Cooling tower theory available on https://en.wikipedia.org/wiki/Cooling_tower
14. Details of latest inventions in cooling tower available online at http://www.hamon.com/en/cooling-systems/wet-cooling-systems/plume-abated-cooling
15. J.L. Hermon and association, 1996. Cooling tower selection, volume 1
16. M. Lemouari, M. Boumaza (2010). Experimental investigation of the performance characteristics of a counterflow wet cooling tower. International Journal of Thermal Sciences 49 (2010) 2049-2056.
17. Zoran, K. Morvay, Dusan, D. Gvozdenac, and John Wiley (1977).Toolbox 12 Cooling towers, Applied industrial energy and environmental management.