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Application of Response Surface Methodology (RSM) for Optimization of Operating Parameters and Performance Evaluation of Cooling Tower Cold Water Temperature

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Abstract. The performance of a cooling tower was analyzed with various operating parameters to find the minimum cold water temperature. In this study, optimization of operating parameters was investigated. An experimental design was carried out based on central composite design (CCD) with response surface methodology (RSM). This paper presents optimum operating parameters and the minimum cold water temperature using the RSM method. The RSM was used to evaluate the effects of operating variables and their interaction towards the attainment of their optimum conditions. Based on the analysis, air flow, hot water temperature and packing height were high significant effect on cold water temperature. The optimum operating parameters were predicted using the RSM method and confirmed through experiment.

Keywords: Cooling tower, Optimization, Response surface methodology, Cold water
AMS Classification: 62K20

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1. 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 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 towers was first suggested by Walker [1]. Simpson and Sherwood studied the performance of forced draft cooling towers with a 1.05 m packing height consisting of wood slats [2].

Kelly and Swenson studied the heat transfer and pressure drop characteristics of splash grid type cooling tower packing [3]. Barile et al studied the performances of a turbulent bed cooling tower. They correlated the tower characteristic with the water/air mass flow ratio [4]. Bedekar et al 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, L/G [5].

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Goshayshi and Missenden also studied experimentally the mass transfer and the pressure drop characteristics of many types of corrugated packing, including smooth and rough surface corrugated packing in atmospheric cooling towers [6]. Their experiments were conducted in a 0.15 m x 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 [6]. Kloppers and Kroger 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 1.5m x 1.5m [7]. Lemouari and Lemouari and Boumaza used this packing in an evaporative cooling system to study its thermal and hydraulic performances [8-10]. Lemourai et al. experimentally investigated the thermal performance of a counter flow wet cooling tower filled with a vertical grid apparatus type packing [11, 12]. The Response Surface Mehtdology (RSM) is a combination of statistical and opimization methods that can be used to model and optimize designs [18, 19, 21]. It has many applications in design improvement of products and process operation.

So far, no work has been carried out on optimization of cooling tower performance using the RSM method. In this study, an experimental investigation of the performance analysis of a cooling tower with the Response Method has been analyzed. From the RSM study, the optimum cooling tower cold water sink temperature is obtained from the cooling tower operating parameters.

2. Experimental Setup

A schematic diagram of the experimental apparatus is shown in Figure 1. The main part of the installation is the cooling tower, 1.5m in height and 0.3m x 0.3m in cross section. The tower structure is transparent and is made of acrylic plate of 5mm thickness. The front plate of the tower is removable to allow access for packing replacement as well as to various measuring probes. Water is transported by pump through a flow regulated valve. The water flow rate is measured by a flow meter and distributed through spray nozzles. Water is distributed in the form of falling films over the expanded wire mesh (EWM) packing using spray nozzles. The size of the spray nozzle is 2mm diameter. By using this system, water is directly distributed over the EWM packing, and the films of falling water are uniform across the whole surface of packing. The pressure drop at the fill zone is measured by U-tube manometer. Chromel-alumel thermocouples are used to measure water inlet and outlet temperature and measure the water temperature in fill zone area. All thermocouples are 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 is used to provide air flow to the tower. The air enters into the tower, passes through the rain zone, fill zone, spray zone and leaves the tower. In our experiment, many parameters affecting the performance of counter flow wet cooling towers are investigated. The operating parameters and their corresponding ranges are given in Table 1.

Table 1. Cooling tower operating parameters and their corresponding range

Parameter	Range
Water flow(kg/hr)	100-200
Air flow(kg/hr)	100-200
Inlet water temp (^{o}C)	40-48
Packing height(m)	0-1.25

3. Expanded Wire Mesh (EWM)

In the experimental study, expanded wire mesh was used as tower packing material. This type of wire mesh is considered to be unique for film packing.

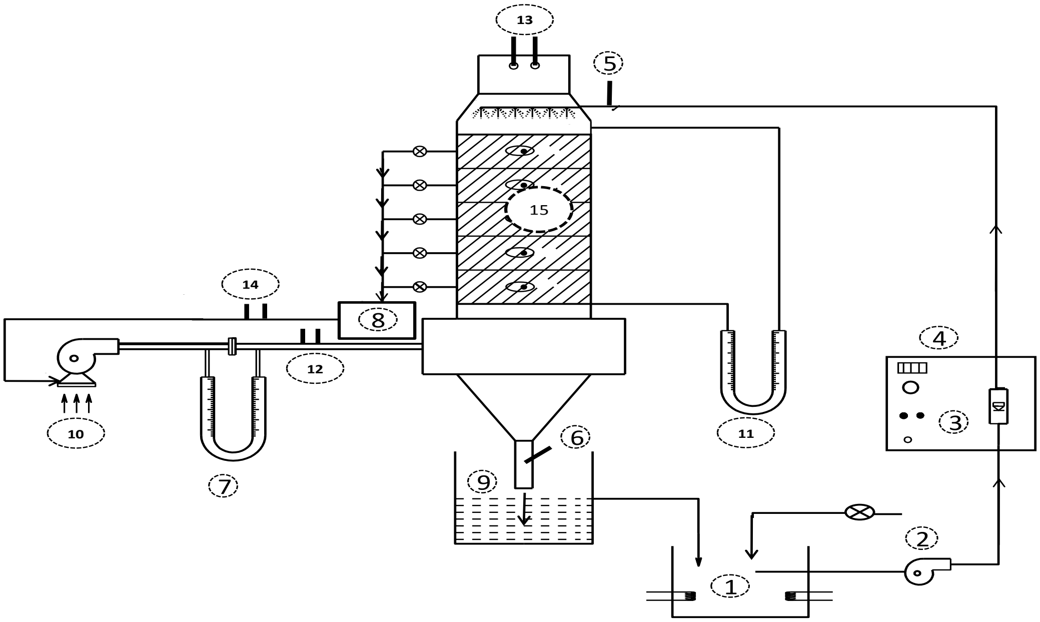


Figure 1 . Experimental Setup of Forced Draft cooling tower

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. Boiler.

Expanded wire mesh fill:

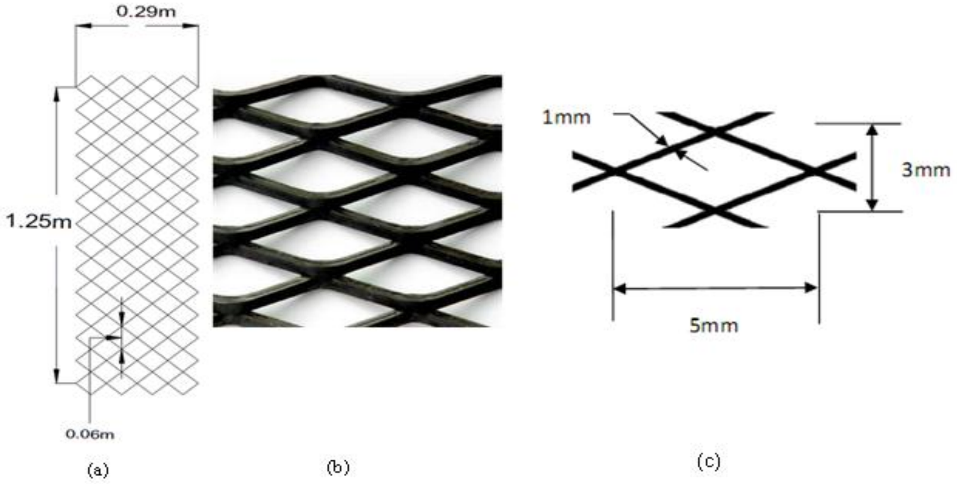


Figure 2. (a) Expanded Wire mesh packing in cooling tower, (b) Enlarged view of expanded wire mesh packing, (c) Wire mesh dimensions

The forming of wire meshes is done so that each little aperture acts as a directing vane for air, moving the bulk of air alternately from one side to the other. This action results in air travelling a distance of about 1.25m of total depth of the packing. Compare with different solid packings, wire mesh presents the minimum restriction to the passage of air. The schematic arrangement of the packing is shown in Figure 2 (a, b and c). In one sq. inch area 32 diamond shapes are present.

4. Experimental Design and Analysis

The optimum cold water (CW) temperature form the mechanical draft cooling tower was carried out with desing of experiments (DoE) using the RSM method. The RSM is a collection of mathematical and statistical technique . It is useful for the optimization of the industrial process and is commonly used for experimental designs [13–17]. In this study, RSM was used to assess the relationship between response cold water temperature (°C) and independent variables, as well as to optimize the relevant conditions of variables in order to predict the best value of responses. In this study, experiments were designed on the basis of the experimental design technique that has been proposed by Central Composite Design (CCD). CCD the most widely used approach in RSM, was employed to determine the effect of operational variables on coldwater temperature in a cooling tower. According to Guven et al. [16], CCD is an effective design that is ideal for sequential experimentation, as it allows a reasonable amount of information to test lack of fit when a sufficient number of experimental values exist. CCD and RSM were established with the help of the Desing Expert 8.0.6. The four significant independent variables considered in this study were water flow (WF), air flow (AF), water temperature (WT), and packing height (PH), which are presented in Table 2. Each independent variable was varied over five levels between −2 and +2 at the determined ranges based on some preliminary experiments. The total number of experiments for the four factors were obtained as 30 (=2^k+2k+6), where k is the number of factors (k=4). As there are only five levels for each factor, the appropriate model is the quadratic model Eq. (1).

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \tag{1}$$

In our model, Y is the response; X_i and X_j are the variables; β_0 is a constant coefficient; β_j, β_{jj}, and β_{ij} are the interaction coefficients of linear, quadratic and second-order terms, respectively; k is the number of studied factors; and e_i is the error. The quality of the fit of the polynomial model was expressed by the value of the correlation coefficient (R^2). The main indicators demonstrating the significance and adequacy of the used model include the model F-value (Fisher variation ratio), probability value (Prob>F), and Adequate Precision [13,18]. Instantaneous consideration of multiple responses involved the initial creation of a suitable response surface model, and subsequently, identifying a set of operational conditions that maximize targeted response, or at the minimum, maintains such in the most desired ranges [17,19].

Table 2. Coding of process parameters

Level	Water flow (WF) kg/hr	Air flow (AF) kg/hr	Hot water (HW) °C	Packing height (PH) m
-2	100	100	40	0.00
-1	125	125	42	0.31
0	150	150	44	0.62
1	175	175	46	0.94
2	200	200	48	1.25

5. Result and Discussion

5.1. Response Surface Modeling

During the experimental study, the cold water temperature was varied between 28 and 36°C. Table 3 shows the analysis of variance (ANOVA) of regression parameters of the predicted response surface quadratic model for cold water temperature.

The experiment was conducted based on the experimental desing technique and the experimental run is shown in Table 4. As can be seen from Table 3, the model F-value of 75.71 and a low probability value (Pr >F<0.0001) indicate that the model was significant for cold water temperature. Values of P>F less than 0.0500 indicate that model terms are significant, while values greater than 0.1000 indicate that the model terms are not significant.

The adequate precision measurements of signal to noise ratios were computed by dividing the difference between the maximum predicted response and the minimum predicted response by the average standard deviation of all predicted responses. Ratio greater than 4 are desirable [18]. The “Adequate Precision” ratio of the model was 25.906 (Adequate Precision>4), which is an adequate signal for the model [15]. PRESS stands for ‘Prediction Error Sum of Square’ and it is a measure of how well the model for the experiment is likely to predict the responses in a new experiments. Small values of PRESS are desirable. In this case the value was 14.71.

The lack of fit F-statistic was statistically significant as the P values were less than 0.05. A significant lack of fit suggests that there may be some systematic variation unaccounted for in the hypothesized model [21]. This may be due to the exact replicate values of the independent variable in the model that provide an estimate of pure error. The value of the correlation coefficient (R^2=99.11%) obtained in the present study for cold water temperature was higher than (R^2adj=98.33%). A high R^2 value illustrates good agreement between the calculated and observed results within the range of the experiment. The R^2(pre) of 94.47% is in reasonable agreement with the R^2(adj) of 98.33%. In this case A, B, C, D, AB, BD, A^2, B^2, C^2, D^2 are significant model terms. Insignificant model terms, which have limited influence, such as AC, AD, BC and CD, were excluded from the study to improve the model. Based on the results, the response surface model constructed in this study for predicting cold water temperature was considered reasonable.

Table 3. ANOVA for analysis of variance and adequacy of the quadratic model

Source	Sum of squares	Degree of freedom	Mean square	F-value	Prob >F
Model	176.67	14	12.62	75.71	< 0.0001
A-WF	13.50	1	13.50	*81.00*	< 0.0001
B-AF	16.67	1	16.67	*100.00*	< 0.0001
C-WT	2.67	1	2.67	*16.00*	0.0012
D-PH	54.00	1	54.00	*324.00*	< 0.0001
AB	2.25	1	2.25	*13.50*	0.0023
AC	0.063	1	0.063	*0.37*	0.5495
AD	0.063	1	0.063	*0.37*	0.5495
BC	0.063	1	0.063	*0.37*	0.5495
BD	10.56	1	10.56	*63.37*	< 0.0001
CD	0.000	1	0.00	0.00	1.0000
A^2	19.05	1	19.05	*114.29*	< 0.0001
B^2	25.19	1	25.19	*151.14*	< 0.0001
C^2	28.58	1	28.58	*171.50*	< 0.0001
D^2	36.01	1	36.01	*216.07*	
Residual	2.50	15	0.17	R^2	= 99.11%
				R^2(pred)	= 94.87%
Lack of Fit	2.50	10	0.25		
Pure Error	0.00	5	0.000	R^2 (adj)	= 98.33%
Cor Total	179.17	29		Adeq	
				Precision	= 25.906
				PRESS	= 14.71
				Std Dev.	= 0.41

Table 4. Response values for different experimental conditions

Run	Factor				Response Cold water(CW) Temperature	
	WF kg/hr	AF Kg/hr	WT °C	PH m	Experimental	RSM
1	150	150	44	0.62	28.0	28.00
2	175	125	42	0.31	34.5	34.88
3	150	150	48	0.62	31.0	31.42
4	125	125	46	0.94	31.0	30.71
5	175	125	42	0.94	33.5	33.63
6	150	150	44	0.62	28.0	28.00
7	100	150	44	0.62	29.5	29.83
8	125	125	42	0.31	33.0	32.63
9	150	150	40	0.62	33.0	32.75
10	150	150	44	0.00	36.0	35.58
11	175	175	46	0.94	28.5	28.79
12	125	125	42	0.94	31.0	31.13
13	150	150	44	0.62	28.0	28.00
14	125	175	42	0.94	29.0	28.71
15	125	125	46	0.31	32.0	32.21
16	150	150	44	0.62	28.0	28.00
17	175	175	42	0.94	30.0	29.71
18	175	125	46	0.31	34.0	34.21
19	125	175	46	0.94	28.5	28.04
20	150	100	44	0.62	33.5	33.50
21	125	175	42	0.31	33.0	33.46
22	200	150	44	0.62	33.0	32.83
23	150	200	44	0.62	30.0	30.17
24	150	150	44	0.62	28.0	28.00
25	125	175	46	0.31	33.0	32.79
26	150	150	44	0.62	28.0	28.00
27	175	125	46	0.94	33.5	32.96
28	175	175	46	0.31	33.5	33.29
29	150	150	44	1.25	29.0	29.58
30	175	175	42	0.31	34.0	34.21

$$\begin{aligned} \mathrm{CW} &= 28.00 + 0.75\,A - 0.83\,B - 0.33\,C - 1.50\,D - 0.37AB - 0.062\,A\,C + 0.063\,A\,D \\ &\quad -0.062\,B\,C - 0.81\,B\,D + 0.000\,C\,D + 0.83\,A^2 + 0.96\,B^2 + 1.02\,C^2 + 1.15\,D^2 \end{aligned} \tag{2}$$

$$\begin{aligned} \mathrm{CW} &= +563.00000 - 0.23000\,WF - 0.28333\,AF - 22.25000\,WT - 6.33333\,PH - \\ &\quad 6.00000E - 04\,WF\,AF - 1.25000E - 003\,WF\,WT + 1.00000E - 002\,WF\,PH - \\ &\quad 1.25000E - 003\,AF\,WT - 0.13000\,AF\,PH - 6.82787E - 015\,WT\,PH + 1.33333E - \\ &\quad 003\,WF^2 + 1.53333E - 003\,AF^2 + 0.25521\,WT^2 + 18.33333\,PH^2 \end{aligned} \tag{3}$$

The final regression model, in terms of its coded and uncoded factors is expressed by the second-order polynomial form Eq. (2) and (3).

5.2. Model Adequacy Checking

Usually, it is necessary to check the fitted model to ensure that it provides an adequate approximation to the real system. Unless the model shows an adequate fit, proceeding with the investigation and optimization of the fitted response surface likely gives poor or misleading results. The residuals from the least squares fit, which is defined by $e_i = y_i - \hat{y}_i$, i = 1, 2, . . ., n, play an important role in judging model adequacy. By applying the diagnostic plots provided by Design Expert 8.0.6 software, such as normal probability plots of the studentized residuals, as well as the predicted versus actual value plots, the model adequacy can be judged. Figure 3 shows the normal probability plots of the studentized residuals for cold water temperature. A normal probability plot indicates if the residuals follow a normal distribution, in which case the points will follow a straight line [19]. The data is normally distributed, since some scattering is expected even with the normal data, as shown in Figure 3.

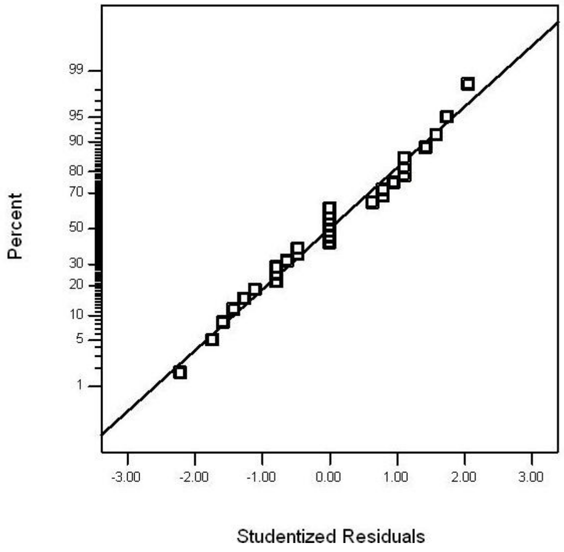


Figure 3. Normal probability plot of the studentized residual for cold water temperature

As shown in Figure 4, the predicted values of cold water temperature obtained from the model and the actual experimental data were in good agreement [19]. The Perturbation plot in Figure 5 shows the comparative effects of all independent variables on cold water temperature. In Figure 5, a sharp curvature in water flow (A), air flow (B) and Packing height (D) shows that the response cold water temperature was very sensitive to these three process variables. The comparative water temperature (C) curve shows the lesser sensitivity of the cold water temperature. In other words, the water temperature has less effect in the cold water temperature when comparing it with the other three factors.

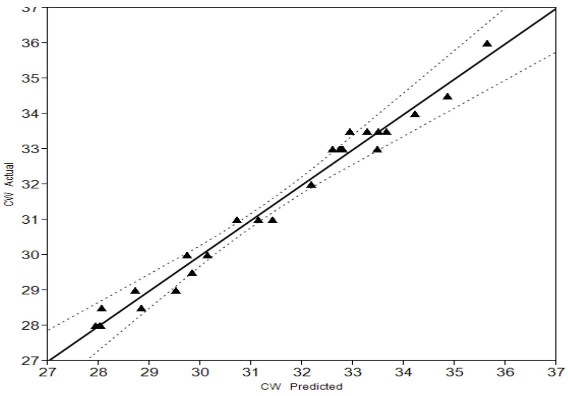


Figure 4. Predicted vs. Actual value plot for cold water temperature

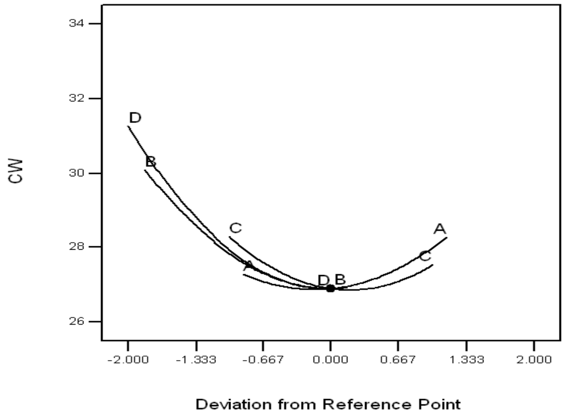


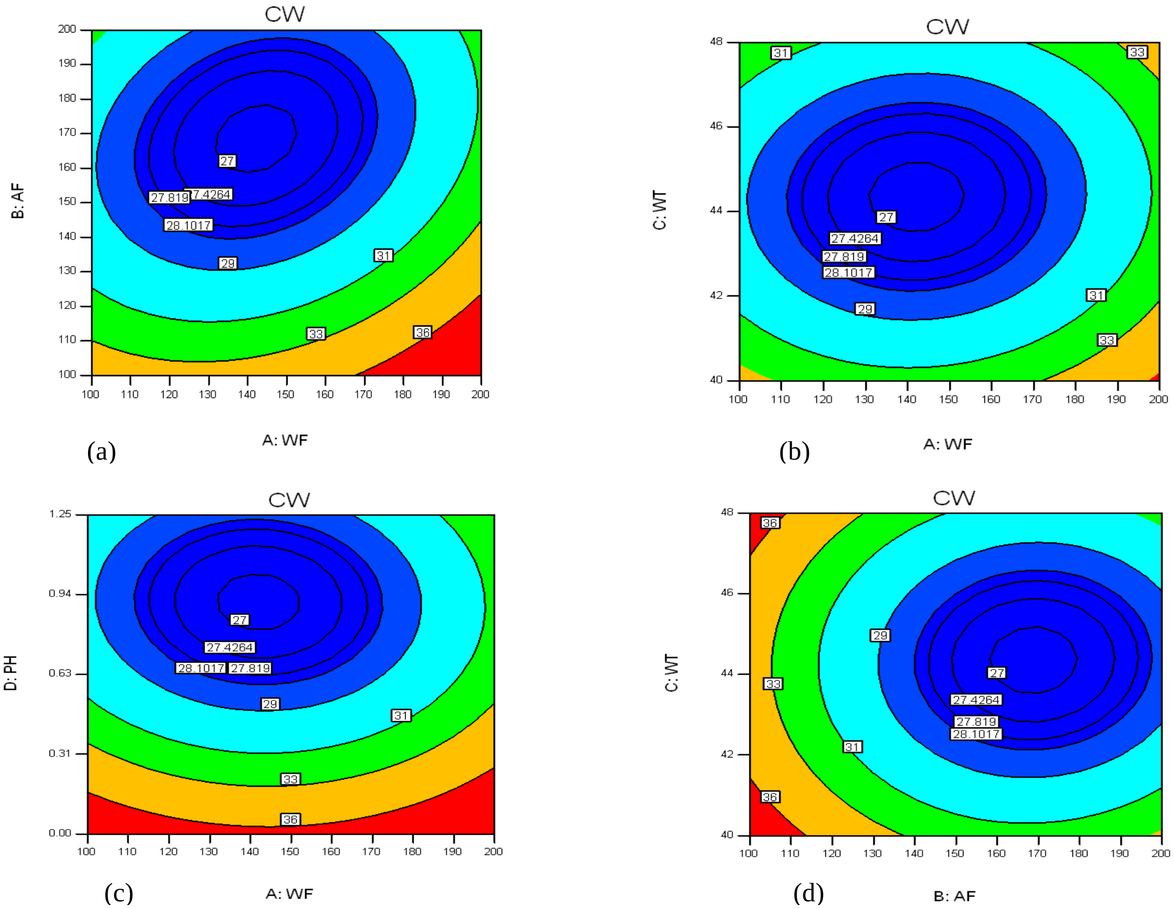
Figure 5. Perturbation plot for cold water temperature

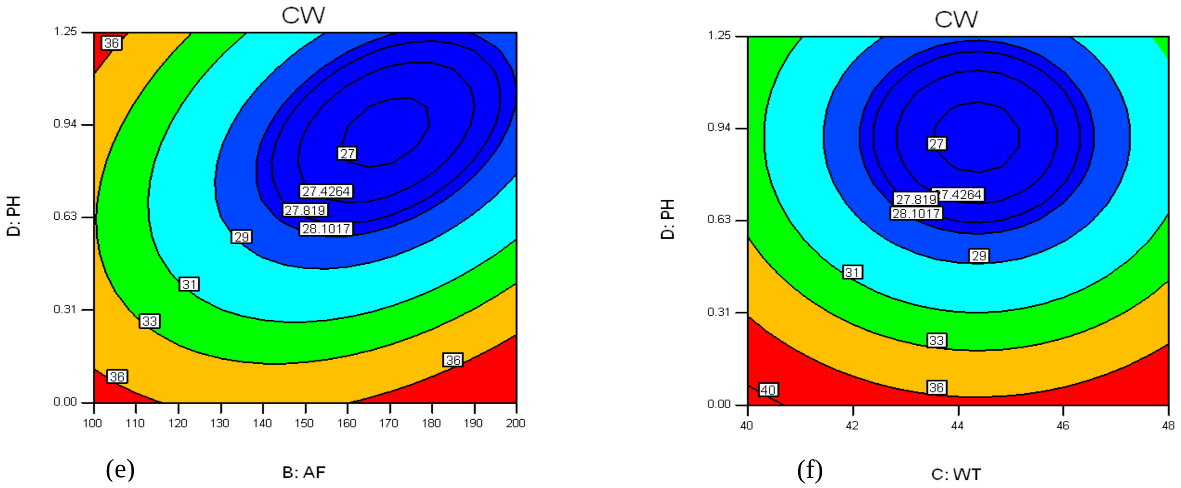
5.3. Optimising Parameters for Cold Water (CW) Temperature

RSM is used to find the optimal set of operating parameters that produce a maximum or minimum value of the response [20].

In the present investigation the operating parameters corresponding to the minimum cold water temperature are gotten by analysing the contour graphs and by solving Eq. (3). Hence, when these optimized process parameters are used, then it will be possible to attain the minimum cold water temperature. Figure 6 (a,b,c,d,e and f) presents two dimensional contour plots for the response cold water temperature obtained from the regression model. The optimum cold water temperature is exhibited by the apex of the response surface. It exhibits almost a circular contour, which suggests independence of factor effect, namely WF, AF, WT and PH. From Figure 6 (a) the minimum cold water (CW) temperature was achieved at the maximum AF and minimum WF.

A better heat transfer rate occurred and the optimum cold water temperature was obtained at the WF to AR ratio of 0.8 to 0.95. The interaction of WF and WT with respect to cold water temperature is shown in Figure 6 (b,d). At the higher and lower end of WT, there is no impact in CW. A WT of 45°C obtained the minimum CW. A better heat transfer rate between water and air was achieved only by the packing . If the PH is 0, it means there is no packing inside the cooling tower. In Figure 6 (c) CW is at a higher level at the 0 to 0.2m PH. It signifies that the heat transfer is very poor at lower PH. If the PH is increased to 0.92m, the CW lowers to 27°C. With further increases in the PH there is no effect in CW. From this Figure 6 (c,e,f), it can be seen that the optimum PH was achieved at between 0.85 to 0.95m.





(e) (f)

Figure 6. Contour diagram of cold water temperature as a function of (a) WF and AF, (b) WF and WT, (c) WF and PH, (d) AF and WT, (e) AF and PH and (f) WT and PH

5.4. Desirability Function Approach

The desirability function approach is one of the most popular methods used in the optimization of multiple-response surfaces [22]. Assume that there are *p* output requirements. In the desirability function approach, each transfer function is as $y_i(\mathbf{x})= f_i(x1,x2,\ldots,xk)$, $i = 1,\ldots,p$. The desirability function $d_{i=}$ $d_i(y_i)= d_i\ (y_i(\mathbf{x}))$ will assign values between 0 and 1. The possible values of y_i, with respect to $d_i(y_i) = 0$ and $d_i(y_i) = 1$ are the most undesirable and desirable.values of *yi*. Where $d_i(y_i)$ is the individual desirability for requirement y_i. The following geometric mean of all individual desirability *D* is used to represent the overall desirability for the whole multiple-response problem [23]:

$$D = \left(d_1(y_1)d_2(y_2)\cdots d_p(y_p)\right)^{\frac{1}{p}} \tag{4}$$

higher overall desirability *D* should indicate a higher overall satisfaction for all responses .

Each individual desirability function $d_i(y_i)$, depends on the optimality criterion for a particular y_i. There are four types of individual desirability functions: a) the larger the better, b) the smaller the better, c) nominal , and d) constraint.

In this study, the desirability function was selected as the smaller the better because minimum cold water temperature was achieved with optimization of process parameters.

In this case a minimization of y_i is the most desirable result. The function $d_i(y_i)$ is defined as follows

$$\begin{aligned} d_i(y_i) &= 1 && y_i =\leq L_i \\ d_i(y_i) &= \left(\frac{U_i-y_i}{U_i-L_i}\right)^{w_i} && L_i \leq y_i \leq U_i \\ d_i(y_i) &= 0 && y_i \geq U_i \end{aligned} \tag{5}$$

where L_i is the lower bound for y_i, U_i is the upper bound for y_i, and w_i is the weight, or importance factor for y_i. The following diagram shows the shape of *di*(*yi*) for the optimization of process parameters. In this study the desirability value was 0.989 for the RSM model as shown in Figure 7. Where also the desirability value can be seen as very close to 1. From this graph's water flow (WF), air flow (AF), water temperature (WT) and packing height (PH) value were the most desirable one. The minimum cold water temperature (26.85°C) was achieved using the RSM method and compared with the experimental run as shown in Table5.

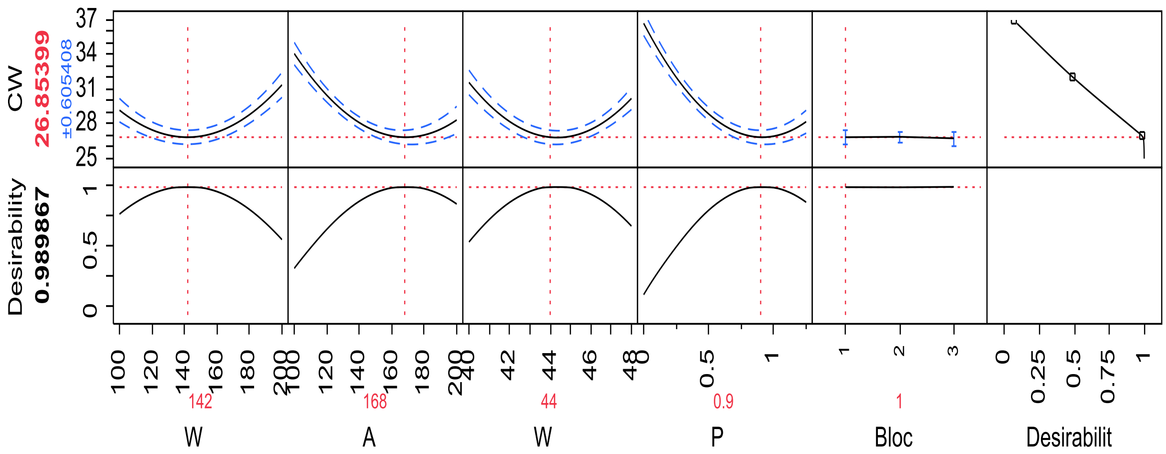


Figure 7. Optimization process variables for cold water temperature through desirability function approach

Table 5. Optimization process variables for cold water temperature – RSM Vs Experimental

	Water Flow (WF)	Air Flow (AF)	Water Temperature (WT)	Packing Height (PH)	Cold Water Temperature (CW)	
					Experimental	Predicted
	kg/hr	kg/hr	°C	m	°C	°C
RSM	142.0	168.00	44.00	0.90	27.50	26.87

6. Conclusion

In the present study, RSM has helped to precisely optimize the operating parameters like water flow (WF), air flow (AF), water temperature (WT) and packing height(PH) within the experimental zone for maximum and minimum values during cold water (CW) temperature. The perturbation plots indicate that the operating variables of packing height (PH) and air flow (AF) content have influenced the minimum cold water temperature, followed by water flow and water temperature. Response surface analysis indicates that a packing height (PH) of 0.7-1.0m, air flow (AF) of 160-180 kg/hr, water flow (WF) at 130-150kg/hr and a water temperature (WT) of 42-46°C resultes in a minimum cold water temperature, whereas variables with values beyond the limit result in a higher cold water temperature. RSM showed a better accuracy and capability of generalization with the DoE of experiments. The predictive accuracy of RSM was better and reduced the number of experiments, because RSM has a structured nature and provides useful insight on the interaction between different variables of the system. RSM has also shown higher accuracy in finding optimum conditions and predicting optimum value. In the desirability function approach, the value of desirability was 0.9898 for the RSM model very closed to 1. The predictive RSM model is found to be capable of better prediction of minimum cold water (CW) temperature within the range. The results of the RSM model indicate it is much more robust and accurate in estimating the values of minimum cold water (CW) temperature.

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