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DEVELOPMENT OF A MODEL FOR OPTIMUM SATURATION EFFICIENCY OF AN EVAPORATIVE COOLING SYSTEM

Dzivama, A. U.[1] and J. C. Igbeka[2]

Abstract

The performance efficiency of an evaporative cooling system (fan and pad) under varied levels of parameters (water flow rate, pad thickness and air velocity) was evaluated using a 3-factor statistical design. A response equation was developed and was used to obtain the optimum levels of the parameters required for optimal operation of the evaporative cooling system. Simulation result of the response equation indicated that for optimum operation of the evaporative cooling system, a water flow rate of 4.4L/min, pad thickness of 47mm and air velocity of 1.6m/s was required. Simulated saturation efficiency of 70.4 % was obtained with these values while the measured was 84.6 % at water flow rate of 4.5L/min, pad thickness of 60mm and air velocity of 2.3m/s .

1. Introduction

An evaporative cooling system (fan and pad) essentially consists of a storage chamber (where the produce is stored), pad-end (where evaporation of water and consequently humidification and cooling of the air take place simultaneously), exhaust fan which draws the humidified and cooled air into the storage chamber and water circulation components (pump) which circulates the water on to the pad and keep the pad continuously moist.

The performance efficiency of an evaporative cooling system in terms of its saturation efficiency is dependent among other things, the water flow rate required to keep the pad moist, the pad thickness through which the air has to travel before entering the storage chamber and the velocity of air passing through the pad. Various research works have been carried out on the effects of these parameters on the saturation efficiency of an evaporative cooling system. The saturation efficiency under these parameters generally increases initially with increase in the levels of the parameters and then either remains constant or decline slightly at higher levels of the parameters (Wiersma, 1983; Thakur and Dhingra, 1983; FAO/SIDA, 1986; Dzivama, 2000; and Dzivama and Igbeka, 2001).

In order to set standards for the operation of the evaporative cooling system, this work was carried out to develop a model equation for the selection of the combination levels of the parameters for optimal performance of an evaporative cooler. This would enable the calculation of saturation efficiency of the cooler within the ranges tested.

2. Materials and methods

An active evaporative cooler earlier constructed and tested under varied levels of water flow rate (W_R), pad thickness (P_T) and air velocity (A_V) (Dzivama, 2000) was used for this study. The cooler consists of a pad-end of dimensions 1000 X 15000mm made of local sponge, a storage cabin of dimensions 1000 x 1300 x 15000 mm made of plywood and internally insulated with 50mm polystyrene, a suction fan of 20W power rating and water pump with a discharge capacity of 7.5l/min and power rating of 150 W. Figure 1 shows the schematic diagram of the cooler

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[1] Department of Agricultural & Environmental Resources Engineering, University of Maiduguri, Nigeria (email: audzivama@yahoo.com)
[2] Department of Agricultural Enginerring, University of Ibadan, Nigeria

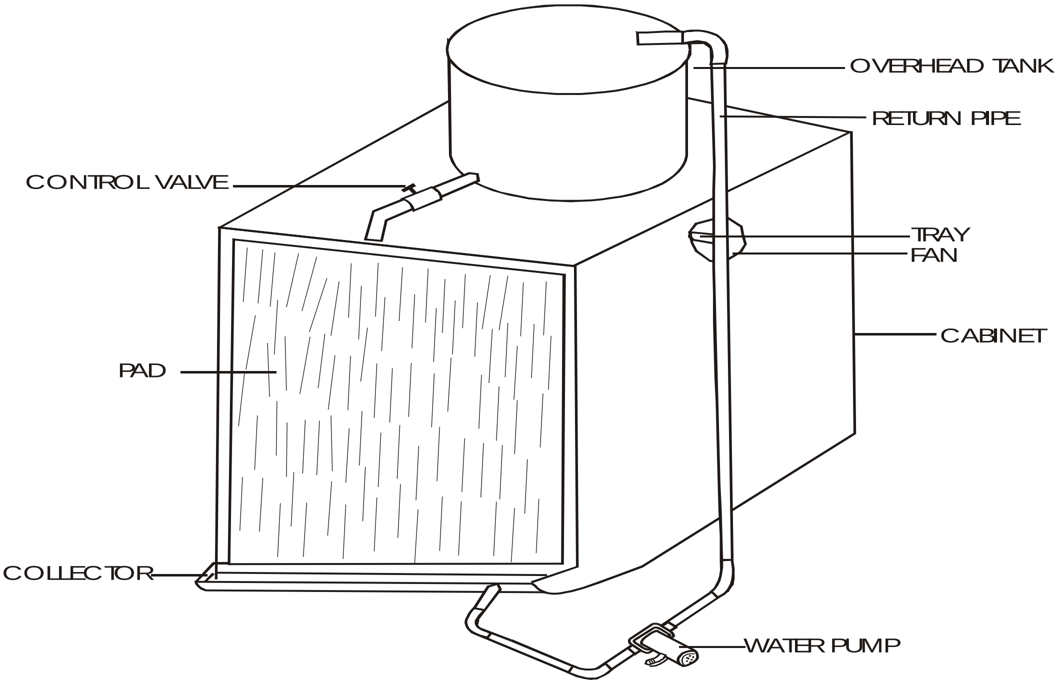

Figure 1: Schematic Diagram of the Evaporative Cooler

The Study involved interactive effects of water flow rate, pad thickness and air velocity on the saturation efficiency of the cooler. Three levels of W_R *(3.5, 4.5* and *5 L/min)*, three levels of P_T *(30, 60 and 90mm*) and five levels of A_V *(0.8, 1.3, 1.8, 2.3, and 2.8 m/s)* were used. The choice of these levels of parameters was based on available information (Thakur, 1983; FAO/SIDA, 1986, Walker and Hellickson, 1983; Brooker *et al.,* 1992) and factors related to the physical properties of the local sponge for use as pad (Dzivama *et al*. 1999).

The parameters were combined in a split-split plot design experiment, which is best suited for a three – factor experiment (Gomez and Gomez, 1983). The water flow rate was considered as the main plot, the pad thickness as the subplot and the air velocity as the sub-subplot. The design layout of the experiment is shown in Table 1. Each level of selected water flow rate was randomly assigned a level of pad thickness and air velocity. The evaporative cooler was then operated and the change in temperature and relative humidity inside the storage chamber was measured with a hygroskop GT-LHygrometer. Readings were taken at 10 minutes interval until steady state conditions were reached. Each test was conducted in three replicates and the average at the steady state conditions were calculated and recorded for each setting. The saturation efficiency of the cooler was calculated from Equation 1 as suggested by Harris (1987):

$$S_E = \frac{T_{o(db)} - T_{i(db)}}{T_{o(db)} - T_{(wb)}} x100 \qquad 1$$

Where:

S_E = Saturation Efficiency, %
$T_{O\,(db)}$ = Outdoor dry bulb temperature, ^{O}C
$Ti_{\,(db)}$ = Storage Chamber dry bulb temperature, ^{O}C
$T_{\,(wb)}$ = Outdoor wet bulb temperature of the region, ^{O}C;
for Maiduguri T = 18.5, ^{O}C (Maiduguri Meteorological Station, 1996)

Table 1: Experimental layout (split-split plot design)

W_R, L/min	P_T, mm	Air Velocity, m/s				
		A_{V1}	A_{V2}	A_{V3}	A_{V4}	A_{V5}
W_{R1}	P_{T1}	$W_{R1}P_{T1}A_{V1}$	$W_{R1}P_{T1}A_{V2}$	$W_{R1}P_{T1}A_{V3}$	$W_{R1}P_{T1}A_{V4}$	$W_{R1}P_{T1}A_{V5}$
	P_{T2}	$W_{R1}P_{T2}A_{V1}$	$W_{R1}P_{T2}A_{V2}$	$W_{R1}P_{T2}A_{V3}$	$W_{R1}P_{T2}A_{V4}$	$W_{R1}P_{T2}A_{V5}$
	P_{T3}	$W_{R1}P_{T3}A_{V1}$	$W_{R1}P_{T3}A_{V2}$	$W_{R1}P_{T3}A_{V3}$	$W_{R1}P_{T3}A_{V4}$	$W_{R1}P_{T3}A_{V5}$
W_{R2}	P_{T1}	$W_{R2}P_{T1}A_{V1}$	$W_{R2}P_{T1}A_{V2}$	$W_{R2}P_{T1}A_{V3}$	$W_{R2}P_{T1}A_{V4}$	$W_{R2}P_{T1}A_{V5}$
	P_{T2}	$W_{R2}P_{T2}A_{V1}$	$W_{R2}P_{T2}A_{V2}$	$W_{R2}P_{T2}A_{V3}$	$W_{R2}P_{T2}A_{V4}$	$W_{R2}P_{T2}A_{V5}$
	P_{T3}	$W_{R2}P_{T3}A_{V1}$	$W_{R2}P_{T3}A_{V2}$	$W_{R2}P_{T3}A_{V3}$	$W_{R2}P_{T3}A_{V4}$	$W_{R2}P_{T3}A_{V5}$
W_{R3}	P_{T1}	$W_{R3}P_{T1}A_{V1}$	$W_{R3}P_{T1}A_{V2}$	$W_{R3}P_{T1}A_{V3}$	$W_{R3}P_{T1}A_{V4}$	$W_{R3}P_{T1}A_{V5}$
	P_{T2}	$W_{R3}P_{T2}A_{V1}$	$W_{R3}P_{T2}A_{V2}$	$W_{R3}P_{T2}A_{V3}$	$W_{R3}P_{T2}A_{V4}$	$W_{R3}P_{T2}A_{V5}$
	P_{T3}	$W_{R3}P_{T3}A_{V1}$	$W_{R3}P_{T3}A_{V2}$	$W_{R3}P_{T3}A_{V3}$	$W_{R3}P_{T3}A_{V4}$	$W_{R3}P_{T3}A_{V5}$

Analysis of variance (*ANOVA*)

Analysis of variance was used to examine the variation in the results of the performance efficiency of the cooler obtained under the experimental variables and their interactions. Microstat statistical software with split-split plot program was used for the analysis Table 2 shows an outline for the.

Table 2: Outline of the ANOVA

Source of Variation	DF	SS	MS	F – factor	P – factor
Main plot analysis					
Replication	2				
Main plot factor (A)	2				
Errors (a)	4				
Sub-Plot analysis					
Sub-plot factor (B)	2				
A X B	4				
Error (b)	12				
Sub-Subplot analysis					
Sub-subplot factor (C)	4				
A X C	8				
B X C	8				
A X B X C	16				
Total	134				

Optimization technique

Regression analysis was used to describe the relationship between the independent variables (water flow rate, pad thickness and air velocity) and the saturation efficiency of the cooler (dependent variable). According to Gomez and Gomez (1983), the relationship between independent variables is multi non-linear when:

1. At least one of the independent variables exhibits a non-linear relationship with the dependent variable;
2. At least two independent variables interact with each other; and
3. Both 1 and 2 cases occur simultaneously.

It was found out earlier (Dzivama, 2000) that the relationship is non-linear. As a result a method of multiple non-linear regression as described by Ott (1977) and Babatunde (1997), was used to derive the response equation given by Equation 2.

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_1^2 + b_4X_2^2 + b_5X_1X_2 + b_6X_2^2X_1 + b_7X_1^2X_2 + b_8X_1^2X_2^2 \qquad 2$$

Where b_o, $b_1 \ldots b_8$ are constants.

Equation 2 was adopted and modified to take care of the 3 – factor factorial design experiment in this study. The possible response equation based on the modified form of Equation 2 of a multiple regression is expressed as:

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_1^2 + b_5X_2^2 + b_6X_3^2 + b_7X_1X_2 + b_8X_1X_3 + b_9X_2^2X_3 + b_{10}X_1X_2X \qquad 3$$

Where:

Y = The saturation efficiency (S_E) of the cooler, %

X_1 = Water flow rate (W_R), *L/min*

X_2 = Pad thickness (P_T), *mm*

X_3 = Air velocity (A_V), *m/s*

The response equation was determined by the inverse of the 135 X 9 matrix, Y = bx as presented below:

$Y_1 = X_{11}\ X_{21}\ X_{31}\ X_{11}^2\ X_{21}^2\ X_{31}^2\ X_{11}X_{21}\ X_{11}X_{31}\ X_{21}X_{31}\ldots\ldots\ldots\ b_0$

$Y_2 = X_{12}\ X_{22}\ X_{32}\ X_{12}^2\ X_{22}^2\ X_{32}^2\ X_{12}X_{22}\ X_{12}X_{32}\ X_{22}X_{32}\ldots\ldots\ldots b_1$

...

...

$Y_n = X_{1n}\ X_{2n}\ X_{3n}\ X_{1n}^2\ X_{2n}^2\ \mathrm{X3n2}\ X_{1n}X_{2n}\ X_{1n}X_{3n}\ X_{2n}X_{3n}\ldots\ldots\ldots b_n$

X'X was computed and the vector of the totals given by *X'Y.* Then the inverse of the design matrix $(X'X)^{-1}$ was computed and multiplied by the vector of the totals $(X'X)X^{-1}Y$ to get the coefficient $b_0, b_1 \ldots b_n$

However, it was not possible to obtain an inverse of the matrix 135 X 9 and therefore the factors which were not significant in the result of the analysis of variance were identified and dropped in the calculations. The combinations W_R x P_T X A_V was not significant in the result of the analysis of variance and it was not used. The extreme values of the co-ordinates, S_E (W_R, P_T, and A_V) were obtained by solving the partial differential equation (Equations 4 - 6) as in Stephenson (1975).

$$dS_E/dW_R \quad = \quad b_1 + b_4W_R + b_7P_T + b_8A_v \quad = \quad 0 \qquad 4$$

$$dS_E/dP_T \quad = \quad b_2 + b_5P_T + b_7W_R + b_9A_v \quad = \quad 0 \qquad 5$$

$$dS_E/dA_V \quad = \quad b_3 + b_6A_V + b_8W_R + b_9P_T \quad = \quad 0 \qquad 6$$

Thus, we have three simultaneous equations which were solved to obtain the extreme values of the co-ordinates S_E (W_R, P_T, and A_V). The nature of the extreme values is given by the signs of the second differentials of S_E (W_R), SE (P_T) and S_E (A_V). The function is maximum when the second differential is negative and minimum when it is positive at the values; W_R, P_T, and A_V given by the solutions of the simultaneous equations. Minitab software was used in analyzing the matrix.

3. Results and discussions

3.1. Saturation efficiency of the cooler

The results of the saturation efficiency calculated from the measurements using equation 1 is presented in Table 3.

Table 3: Saturation efficiency, % (calculated from the cooler temperature)

W_R, *L/min*	P_T, *mm*	**Air velocity, *m/s***				
		0.8	1.3	1.8	2.3	2.8
3.5	30	48.7	56.4	57.4	55.4	54.9
	60	61.5	66.7	69.2	68.7	68.7
	90	56.4	61.5	65.6	66.7	66.7
4.5	30	64.1	70.8	74.4	74.4	76.9
	60	76.9	82.1	84.6	84.6	84.6
	90	69.2	79.5	82.1	84.1	83.1
5	30	53.3	62.6	64.1	65.1	66.7
	60	66.7	72.8	79.5	82.1	84.6
	90	64.7	69.2	76.9	80.1	82.6

The result in Table 3 shows that the saturation efficiency of the evaporative cooling system increased initially with the levels of the parameters and then either remained constant or slightly declined. This could be attributed to the fact that, at low water flow rate, pad thickness and air velocity, the water could only partially wet the pad and therefore, less available water to be evaporated and thus less cooling. With less pad thickness, the distance of travel for the air inside the pad is less and thus the contact time between the air and water is less and this means less amount of water is evaporated. At low air velocity, the air moves in a streamline and therefore only evaporates the water within its path. At high levels of the parameters, the saturation efficiency increased and this could be due to the fact that:

(i) the water flow rate was enough to sufficiently moisten the pad;

(ii) (ii) the pad was thick enough so that the distance of air travel within the pad was long enough for the air-water time to effect good evaporation; and

(iii) (iii) at high air velocity, turbulence could have been developed within the pad to evaporate more water from the pad.

However, at much higher levels of the parameters, the saturation efficiency either remained constant or slightly declined. This could be due to excess water blocking the pore spaces within the pad and thus impeding air flow through the pad. Also, air moving at higher velocity might push out the water from the pad in droplets instead of evaporating the water as evidenced by the presence of water droplets inside the cooler during the experiment at these levels of the parameters.

From Table 3, the optimum operating condition of the cooler was observed to be at water flow rate of 4.5 *L/min*, pad thickness of 60 *mm* and air velocity of 2.3 *m/s*, with a performance efficiency of 84.6 %. This could be explained by the fact that at P_{T2} (60 *mm*) and W_{R2} (4.5 *L/min*), the pad was sufficiently moist to allow more evaporation, but without excessive flow of water to block the pore spaces within the pad for the air movement. Furthermore, at A_V of 2.3 *m/s*, the velocity was fairly high but because of the fairly large pad thickness of 60 *mm*, the air – water contact time was increased. This allowed for an increase in heat and mass transfer, thus an increase in efficiency. For a region with very low outdoor relative humidity and high temperature, it is possible to obtain saturation efficiency in the cooler approaching 85 % (Rusten, 1985). Thus, the 84.6 % performance efficiency obtained in the cooler in Maiduguri with an average ambient condition of 38 ^{O}C and 15 % temperature and relative humidity respectively, and a wet bulb depression of 18.5 ^{O}C compared to 21.5^{O}C of the evaporative cooler, is considered efficient.

3.2 Analysis of variance

The result for the analysis of variance is presented in Table 4. The result showed that all the main factors (W_R, P_T, A_V) and their interactions (W_R x P_T, W_R X A_V, and P_T x A_V) were significant at 5 %. However, the combined effect of W_R x P_T x A_v was not significant at 5 %. This result confirmed the observations earlier discussed that the performance efficiency was found to increase with increase in all the levels of the parameters up to a certain level and then it either remained constant or declined slightly.

Table 4: Results of the analysis of variance

Source of variation	*SS*	*DF*	*MS*	*F*	Sig. of F
Main effects	3864.80	8	1733.10	435.21	0.00
W_R	6649.17	2	3324.59	834.86	0.00
P_T	4317.89	2	2158.95	542.15	0.00
A_V	2897.74	4	724.44	181.92	0.00
2 - way interactions	708.85	20	35.44	8.90	0.00
W_R x P_T	338.12	4	84.53	21.23	0.00
W_R x A_V	249.30	8	31.16	7.83	0.00
P_T x A_V	121.44	8	15.18	3.81	0.00
3 – way interactions	97.86	16	6.12	1.54	0.00
W_R x P_T x A_V	97.86	16	6.12	1.54	0.00
Explained	14671.51	44	333.44	83.73	0.00

3.3 The response equation

The resulting equation obtained from Equation 3 is given as:

$$S_E = 7.9 - 0.013W_R + 22.2A_V + 0.27 W_R^2 - 0.008P_T^2 - 6.2_A V^2 + 0.067W_R P_T + 1.07W_R A_V - 0.029P_T A_V, (R^2 = 0.95) \qquad 7$$

The critical values and the nature of the coordinates of the parameters obtained by solving the simultaneous Equations 4, 5, and 6 for the optimum operation of the cooler are presented in Table 5.

Table 5: Critical values of the parameters for optimum performance efficiency

Parameter	**Values**	**Nature of coordinates**
Water flow rate	4.4 *L/min*	Maximum
Pad thickness	47 *mm*	Minimum
Air velocity	1.6 *m/s*	Maximum

The saturation efficiency obtained by substituting the optimum measured values in Table 3 and the critical values in Table 5 are presented in Table 6.

Table 6: Saturation efficiency, % (obtained by the predicted and measured values

Parameter	**Values**	
	Predicted optimum level	**Measured optimum level**
Water flow rate (*L/min)*	4.4	4.5
Pad thickness *(mm)*	47	60
Air velocity *(m/s)*	1.6	2.3
Saturation efficiency (%)	**70.42**	**84.6**

The saturation efficiency obtained by using the predicted values was slightly less than the one obtained by the measured values. This could be due to the fact that some combination levels of $W_R \times P_T \times A_V$ that were found insignificant and difficult to substitute in the solution of the 135 x 9 matrix were dropped. This equation gave the optimal values of the parameters for efficient operation of the evaporative cooler, which could not have been measured experimentally. It also enabled the calculation of the saturation efficiency given some independent variables within the range tested and not necessarily those tested.

3.4 Contribution of the parameters and their interactions

The contributions of the variables and their interactions are summarized and presented in Table 7. The result showed that the water flow rate contributed the most to the saturation efficiency of the cooler, followed by the pad thickness and then the air velocity. This could be explained from the fact that water is required for evaporation to take place and there must be a medium (pad) to provide the water for the evaporation. Air velocity is required to blow away the saturated air from the vicinity to allow more evaporation to take place.

Table 7: **Contribution of the parameters and their interactions**

Source	DF	SEQSS
WR	1	4097.9
PT	1	2406.4
AV	1	2322.9
WR2	1	2237.9
PT2	1	1599.3
AV2	1	566.3
WR x PT	1	203.8
WR x AV	1	141.4
PT x AV	1	45.2
WR x PT x AV	1	35.1

4. Conclusion

The results of the experiment and the analysis showed the interactive effect of the parameters and their levels on the saturation efficiency of evaporative cooling system. Optimum combination levels of W_R, P_T and A_V of 4.4 *L/min*, 47 *mm* and 1.6 *m/s* respectively were obtained by the analysis compared to W_R, P_T and A_V of 4.5 *L/min*, 60 *mm* and 2.3 *m/s* respectively obtained experimentally. The model allows for the calculation of the saturation efficiency of the cooler at levels not necessarily measured.

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