Performance Evaluation Of Evaporative Cooler Using The Predictive Mean Vote (Pmv) Model

Ibrahim, U.H., D.A. Aremu

Abstract: Most of the developing nations like Nigeria intend to develop in a sustainable manner. This development cannot be realized if refrigerated-based air conditioning systems that are characterized by high power requirement, high cost and with a negative influence on the environment are used as a means of achieving thermal comfort in living spaces. Evaporative coolers are viable options of achieving thermal comfort especially in hot and dry climates. These systems apart from their low power requirement, they are relatively cheap and have no negative impact on the environment. This paper therefore attempts to evaluate the performance of direct evaporative coolers using the Predicted Mean Vote (PMV) model. Further Predicted Percentage Dissatisfied (PPD) was used to estimate the thermal comfort satisfaction of people in the study area. The study reveals that the computed PMV for the months of January through December range from -0.92 to -0.86 on the ASHRAE scale of thermal sensations. The computed PPD for the respective months ranges from 10.2% to 15%. These values of both the PMV and the PPD show the high potential of using evaporative coolers in Kano and in areas with similar climate characteristics.

Index terms: Thermal comfort, Predicted mean vote, Predicted percentage dissatisfied, Evaporative cooler

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1 Introduction

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment. Although thermal comfort is difficult to define because of the range of environmental and personal factors that need to be taking into account when deciding what will make people feel comfortable. These factors make up what is known as human thermal environment. The best one realistically hopes to achieve is a thermal environment that satisfies the majority of people in an occupied space. Studies have shown that 80% of occupants is a reasonable limit for the minimum number of people who should be thermally comfortable in an environment (Ismail et al, 2009). There are multifarious ways of achieving thermal comfort. Some of these ways of achieving thermal comfort are active, passive or hybrid. The passive methods of achieving thermal comfort such as the use of shading devices, natural ventilation, nocturnal thermal radiation etc, to a reasonable degree can only provide relief comfort for the occupants of a space. During harsh weather conditions, especially in hot and dry climates, active systems such as refrigerated based air conditioning systems are used to condition the air suitable for human thermal comfort. But the use of the conventional air conditioning systems is associated with problems such as:

They are relatively expensive for the common man

They are not fully utilized in areas where the power supply is epileptic and constantly interrupted

They are characterized by poor indoor air quality because of the use of recirculated air

Their maintenance require the service of a skilled personnel

They are detrimental to the ozone layer because of the release of CFC and HCFC

The high electric power consumption translates to high operational cost

Evaporative coolers can be a suitable alternative to the refrigerated based air conditioning systems. Evaporative cooling is a physical process that occurs when water evaporates within a stream of ambient air without a supply of external heat, resulting in the drop of the dry bulb temperature (DBT), increase of the relative humidity (RH) while the wet bulb temperature (WBT) remains approximately constant (Ana et al, 2006). Evaporative coolers could make full use of the local climatic potential and can easily be integrated into modern construction. The systems are relatively cheap, requiring relatively less power supply, easier to maintain and operate, and the working fluid which is water has no negative impact on the environment. Nevertheless, the performance of evaporative coolers to a very large extent is a function of climatic parameters such the ambient dry bulb temperature, wet bulb temperature, relative humidity and wind speed. This paper is an attempt to evaluate the performance of evaporative coolers using the Predictive Mean Vote (PMV) model and to estimate the thermal satisfaction of people in the study area using Predicted Percentage Dissatisfied (PPD) index.

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1.1 Description of the Evaporative Cooler

In direct evaporative coolers, non-saturated air comes into contact with water-saturated cooling pad, and evaporation occurs. The necessary latent heat is provided by the air, which cools down. In addition, the moisture content of the air rises. Direct evaporative cooling is represented on the psychrometric chart in figure 1 by a displacement along a constant wet-bulb temperature line AB.

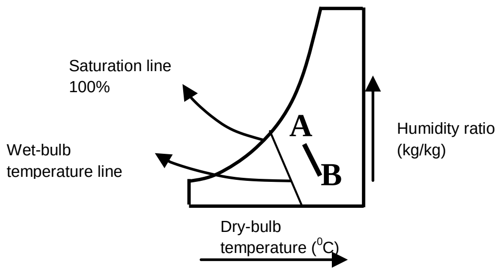

Figure 1 Direct Evaporative Cooler

1.2 Predicted Mean Vote

The Predicted Mean Vote (PMV) is a parameter for assessing thermal comfort in occupied zone based on the conditions of metabolic rate, clothing, air speed besides temperature and relative humidity (Ismail et al, 2009). The PMV model is expressed on the 7-point ASHRAE scale of thermal sensation. The scale ranges from -3 to +3 as presented in Table 1.

Table 1: Scale of Thermal Sensation

Thermal Sensation	Numerical Value
Much too warm	+3
Too warm	+2
Comfortably warm	+1
Comfortable	0
Comfortably cool	-1
Too cool	-2
Much too cool	-3

The general comfort equation developed by Fanger (1970) to describe the conditions under which a large group of people will feel in thermal neutrality is too complex and cannot be used in real time applications unless being simplified. Equations 1 – 3 show the comfort equation proposed by Fanger (Robert et al, 2008).

$$\begin{aligned} PMV = \left(0.028 + 0.3033e^{-0.036}\right)\{&(M-W) \\ &- 3.05[5.733 - 0.000699(M-W) - P_a] \\ &- 0.42[(M-W) - 58.15] \\ &- 0.0173M(5.867 - P_a) \\ &- 0.0014M(34 - T_a) - 3.96 \\ &\times 10^{-8} fcl\left[(T_{cl}+273)^4 - (T_{mrt}+273)^4\right] \\ &- fcl.h_c(T_{cl} - T_a)\} \qquad \ldots \quad (1) \end{aligned}$$

$$\begin{aligned} T_{cl} &= 35.7 - 0.028(M-W) \\ &- 0.155 I_{cl}\left[3.96 \times 10^{-3} fcl\left[(T_{cl}+273)^4 - (T_{mrt}+273)^4\right] - fcl.h_c(T_{cl} - T_a)\right] \qquad \ldots \quad (2) \end{aligned}$$

$$h_c = \begin{cases} 2.38(T_{cl}-T_a)^{0.25} & \text{for } 2.38(T_{cl}+T_a)^{0.25} \geq 12.1\sqrt{V_{air}} \\ 12.1\sqrt{V_{air}} & \text{for } 2.38(T_{cl}-T_a)^{0.25} \leq 12.1\sqrt{V_{air}} \end{cases} \qquad \ldots \quad (3)$$

1.3 Predicted Percentage Dissatisfied

The Predicted Percentage Dissatisfied (PPD) is used to estimate the thermal comfort satisfaction of an occupied zone. It is considered that satisfying 80% of occupants is good. That is, PPD less than 20% is good (Hamdi et al, 2009). Equation 4 is used to calculate PPD.

$$PPD = 100 - 95\exp\left(-0.03353PMV^4 + 0.2179PMV^2\right) \qquad \ldots \quad (4)$$

1.4 Saturation Effectiveness

Saturation effectiveness, ε_{sat}, is the index used to assess the performance of a direct evaporative cooler. It is defined as:

$$\varepsilon_{sat} = \frac{T_a - T_L}{T_a - T_3} \qquad \ldots \quad (5)$$

1.5 Description of the Study Area

2.0 Methodology

The performance of evaporative coolers for human thermal comfort using Kano State as case study was evaluated using Predicted Mean Vote Model and Predicted Percentage Dissatisfied was used to estimate the thermal satisfaction of people in a thermal environment provided by the evaporative cooler. In this study, the pertinent past weather data of the study area averaged over several years which will be a representative of a typical year in the future was considered. The outdoor data considered are presented in Table 2.

2.1 Leaving Air Temperature

Using equation 5, the leaving air temperature, T_L, that is the air supplied from the evaporative cooler to the leaving space for the months of January through December were determined from equations 5 and 6 and are presented in Table 2.

$$T_L = T_a - \varepsilon_{sat}(T_a - T_3) \qquad \ldots \quad (6)$$

The corresponding wet bulb temperature and the partial vapour pressure of the leaving air are determined from psychrometric chart and steam table and are presented in Table 2.

2.2 The Reduced Fanger's Comfort Equation

In reducing the Fanger's comfort equation suitable for the application in conditioned space provided by a direct evaporative cooler, the following assumptions were made:

Mean radiant temperature equal to the ambient air temperature ($T_{mrt} = T_a$)

Surface temperature of clothing equal to the mean radiant temperature ($T_{cl} = T_{mrt}$)

External work (metabolic free energy production) equal to zero

Based on the aforementioned assumptions, the reduced Fanger's comfort equation is then expressed as:

$$PMV = \left(0.028 + 0.3033e^{-0.036}\right)\{M - 3.05[5.733 - 0.0000699M - P_a] - [0.42M + 24.42] - 0.0173(5.867 - P_a) - 0.0014M(34 - T_a)\} \quad \ldots \ (7)$$

The pertinent parameters of the indoor conditioned space were then used as the input values for the determination of the Predicted Mean Vote using the reduced Fanger's equation (equation 7). The PMV values for January through December were then used to determine the PPD values using equation 4.0. The computed values of the PMV and PPD for the months under consideration are presented in Table 3.

3.0 Results and Discussion

The outdoor conditions and the determined indoor conditions are presented in Table 2 and the corresponding PMV and PPD values computed are presented in Table 3.

Table 2 Outdoor and Indoor Conditions of Jan – Dec

	Outdoor Condition			Indoor Condition	
Mon	T_3(^{0}C)	T_1(^{0}C)	RH(%)	T_L(^{0}C)	P_a(N/m^2)
Jan	13.6	27.4	15.0	15.7	0.0142
Feb	16.4	32.7	17.0	18.9	0.0166
Mar	18.1	36.1	14.0	20.8	0.0191
Apr	22.0	37.4	25.0	24.3	0.0248
May	23.2	36.9	30.0	25.3	0.0272
Jun	24.6	35.0	38.0	26.2	0.0296
Jul	24.2	30.4	60.0	24.1	0.0301
Aug	24.6	30.1	65.0	24.4	0.0307
Sep	24.6	31.0	58.0	24.6	0.0298
Oct	22.1	33.6	37.0	23.8	0.0230
Nov	18.9	32.3	28.0	20.9	0.0218
Dec	15.8	29.5	22.0	17.9	0.0165

Table 3 Monthly Computed Values of PMV and PPD

Mon	PMV	PPD (%)
Jan	-0.92	11.5
Feb	-0.90	10.8
Mar	-0.89	10.5
Apr	-0.88	10.2
May	-0.86	14.6
Jun	-0.86	14.9
Jul	-0.86	15.0
Aug	-0.86	15.0
Sep	-0.86	15.0
Oct	-0.88	10.2
Nov	-0.89	10.5
Dec	-0.92	11.5

The PMV is used to quantify the comfort achieved in a living space. From Table 3, it can be seen that the numerical values of the PMV of January through December falls in the range of -0.92 to –0.86. This means that the indoor conditions achieved by the use of the evaporative cooler in the months under consideration are suitable for human thermal comfort based on the PMV because, these values fall within the comfortable range on the ASHRAE scale of thermal sensations. This agrees with the work of Kulkarni et al (2010) and Camrago et al (2006) that evaporative coolers perform better in climates with relatively low wet bulb temperatures. The PPD of January through December shown in Table 3 shows that the range of PPD for these months is 10.2% to 15.0%. This means that about 85% to 89.8% space provided by the evaporative cooler will be satisfied with the thermal environment. This agrees with the work of Ismail et al (2009) that PPD less than 20% is good.

4.0 Conclusion

The performance of a direct evaporative cooler in the months of January through December was evaluated using the Predicted Mean Vote (PMV) model and the Predicted Percentage Dissatisfied (PPD) was employed to estimate the thermal comfort satisfaction of people in an occupied space. The results obtained from the application of these models on the pertinent parameters of the conditioned space provided by the direct evaporative cooler shows that direct evaporative coolers are viable option for achieving thermal comfort in Kano and in areas with similar climate characteristics.

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Nomenclature

PMV Predicted Mean Vote
PPD Predicted Percentage Dissatisfied
M Metabolism (W/m^2)
W External work (W/m^2)
I_{cl} Thermal resistant of clothing (clo)
f_{cl} Ratio of body’s surface area when fully clothed to body’s surface area when nude
V_{air} Relative air velocity (m/s)
P_a Partial water vapour pressure (N/m^2)
h_c Convectional heat transfer coefficient $(W\,m^{-2}\,K)$
T_a Ambient air temperature (^0C)
T_{mrt} Mean Radiant Temperature (^0C)
T_{cl} Surface temperature of clothing (^0C)
T_3 Outdoor and indoor wet bulb temperature (^0C)
T_L Leaving air temperature (^0C)
RH Relative humidity (%)
ε_{sat} Saturation effectiveness of the direct evaporative cooler (%)