Theoretical Performance Analysis Of Direct Evaporative Cooler In Hot And Dry Climates

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Abstract: This paper is an attempt to theoretically analyse the performance of direct evaporative cooler in hot and dry climate with Kano being the study area. The performance of the cooler was determined at different air velocities at a saturation effectiveness of 50% to 90%. The determined parameters are the leaving air temperature, relative humidity, cooling capacity and the water consumption rates. The result shows that leaving air temperature of 21.9^{0}C and relative humidity of 82% were obtained with pad material of 90% saturation effectiveness. The cooling capacity and the water consumption rates are found to vary linearly with the saturation effectiveness. It is therefore axiomatic that direct evaporative coolers have high potential of providing thermal comfort for people in occupied spaces when moderate air velocities are used with pad materials of relatively higher saturation effectiveness.

Index terms: Evaporative cooler, Leaving air temperature, Relative humidity, Performance

Introduction

In direct evaporative cooling, the air to be conditioned comes in direct contact with the wetted surface, and gets cooled and humidified. Figure 1.0 shows an elementary direct evaporative cooling system. As shown in figure 1.0, hot and dry outdoor air is first filtered and then brought in contact with the wetted surface. The cooled and humidified air is supplied to the conditioned space, where it extracts the sensible and latent heat from the conditioned space. Finally, the air is exhausted into the atmosphere via windows, doors, exhaust fans, etc. In an ideal case when the evaporative cooler is perfectly insulated and an infinite amount of contact area is available between air and the wetted surface, then the cooling and humidification process follows the constant wet bulb temperature line and the leaving air temperature is equal to the wet bulb temperature of the outdoor air, i.e the process becomes an adiabatic saturation process [1]. However, in an actual system the leaving air temperature will be higher than the inlet wet bulb temperature due to heat leaks from the surroundings and also due to finite contact area. This paper is therefore an attempt to theoretically analyze the performance of direct evaporative cooler in Kano, Nigeria, under different saturation effectiveness of the cooling pad and different air velocities through the cooling pad.

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Description of the system

In direct evaporative coolers, non-saturated outside air is blown through a water saturated pad and evaporation occurs. The necessary latent heat is provided by the air which cools down. Therefore, the leaving air temperature reduces while the relative humidity increases. A typical direct evaporative cooler is shown in figure 1.0.

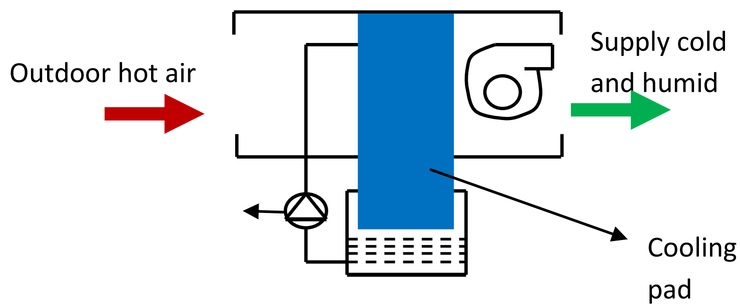

Figure 1.0 Direct Evaporative Cooler

Methodology

Assumptions

The following assumptions were made in the analysis of the direct evaporative cooler:

- The conditions are at steady state
- The cooler will be placed in a shaded region and radiation effects are negligible
- The heat of vaporization of water is constant and 2270kJ/kg
- The entire system operates at atmospheric pressure (101.325kPa)
- The cooling pad is kept continually saturated with water
- The direct evaporative cooler is perfectly insulated (no heat transfer)
- The frontal area of the opening of the cooler and density of the outdoor air remain constant throughout the analysis

Ambient Conditions

The weather data of Kano on the basis of usually prevalent conditions in the months of March, April and May were classified into five groups of average maximum dry bulb temperature(T_1), relative humidity(RH_o), wet bulb temperature (T_3) and humidity ratio (ω_1) as shown in Table 1.0. The most frequent occurring conditions of $T_1 = 39.4^0$C, $RH_o = 8.1\%$, $T_3 = 17.4^0$C and $\omega_1 = 0.0032$ kg/kg dry air, are selected for the analysis.

Table 1.0 Average Weather Data of Kano, Nigeria

Ambient Condition	$DBT_{max}(^0C)$	Total days	$T_1(^0C)$	RH_o (%)	$T_3(^0C)$	ω_1(kg/kg)
A	Less than 34	3	32.4	9.4	13.7	0.0028
B	$34 \leq DBT < 37$	7	36.1	6.8	14.2	0.0020
C	$38 \leq DBT < 40$	23	39.4	8.1	17.4	0.0032
D	$41 \leq DBT < 42$	12	41.4	12.2	19.8	0.0058
E	43 & Above	–	–	–	–	–

Air Velocity through the Cooling Media

In an experiment conducted by [2] to determine the effects of air velocity on the performance of pads of evaporative cooling systems, the air velocities through the pads were kept at 0.5, 0.75, 1.0, 1.25 and 1.75m/s. These velocities are therefore considered in this study.

Air Flow Rates

The mass flow rate of air through the evaporative cooler is a function of the air velocity and is calculated on the basis of frontal area of the cooler, the density and velocity of air at the entry. The mass flow rate of air , m_a, is determined from equation 1 [3].

$$m_a = \rho * A * V_a \quad (1)$$

Where
ρ = density of air at the entry of the cooler, kg/m^3
A = frontal area of the cooler's opening, m^2
V_a = air velocity at the entry of the cooler, m/s

The computed mass flow rate of air at different air velocities are presented in Table 2.0.

Table 2.0: Mass flow of Air at different selected Air Velocities

V_a m/s 0.5 0.75 1.0 1.25 1.75	
m_a kg/s 0.031 0.046 0.062 0.078 0.108	

Saturation Effectiveness

Saturation effectiveness, ε_{sat}, is the index used to assess the performance of a direct evaporative cooler. It is defined as [1]:

$$\varepsilon_{sat} = \frac{T_1 - T_2}{T_1 - T_3} \quad (2)$$

Saturation effectiveness to a very large extent is a function of the pad material used, the structural arrangement and the configuration of the pad. The pad materials commonly used as cooling media are Aspen pad, CEL-dek pad, Jute fiber, Cotton fiber, Coconut coir, Stainless steel wire mesh, etc [1]. Experiment conducted by some researchers showed that the saturation effectiveness of commonly used cooling pad materials is in the range 50% to 90% [1].

Leaving Air Condition

The humidified and cooled leaving air leaves the evaporative cooler to the space to be conditioned. The leaving air temperature, T_2, is determined from equation 3. From equation 2, the leaving air temperature can be expressed as:

$$T_2 = T_1 - \varepsilon_{sat}(T_1 - T_3) \quad (3)$$

The corresponding relative humidity (RH_i) and humidity ratio (ω_2) of the leaving air are determined from psychrometric chart. The leaving air temperature, relative humidity and humidity ratio for the saturation effectiveness considered within the range 50% and 90% are presented in Table 3.

Table 3: Conditions of Leaving Air at different Saturation Effectiveness

ε_{sat}(%)	T_2 (0C)	RH_i (%)	ω_2 (kg/kg dry air)
50	28.4	32.5	0.0078
60	26.2	37.0	0.0080
70	24.0	52.0	0.0097
80	21.8	67.0	0.0108
90	19.6	82.0	0.0117

Cooling Capacity
The cooling capacity (Q_c) of a direct evaporative cooler is determined from equation 4 [4].

$$Q_c = m_a C_p (T_1 - T_2) * 3.6 \text{ kJ/h} \quad (4)$$

Where C_p is the specific heat capacity of air The cooling capacities at different air mass flow rates for the given saturation effectiveness are presented in Table 4.

Water Consumption

The water consumption is essential because it indicates the amount of water (in weight quantity) needed to operate the system. The water consumption of the evaporative cooler, Q_{co}, can be determined from equation 5 [5].

$$Q_{co} = m_a(\omega_2 - \omega_1) \quad (5)$$

As stated earlier, ω_1 and ω_2 are determined from the psychrometric chart. The water consumption at different air mass flow rates for the given saturation effectiveness are presented in Table 4.

Results and Discussions

Table 4: Performance of DEC at different Air Mass Flow Rates and ε_{sat}

m_a	kg/s	0.50	0.75	1.00	1.25	1.75
$\varepsilon_{sat} = 50\%$						
Q_c	kJ/h	1233.7	1830.7	2407.4	3104.2	4298.2
Q_{co}	kg/h	0.514	0.763	1.026	1.292	1.789
$\varepsilon_{sat} = 60\%$						
Q_c	kJ/h	1480.4	2196.8	2960.9	3725.0	5157.8
Q_{co}	kg/h	0.536	0.796	1.073	1.346	1.864
$\varepsilon_{sat} = 70\%$						
Q_c	kJ/h	1727.2	2562.9	3454.4	4345.9	6017.4
Q_{co}	kg/h	0.727	1.076	1.451	1.825	2.527
$\varepsilon_{sat} = 80\%$						
Q_c	kJ/h	1973.9	2929.1	3948.0	4966.8	6877.0
Q_{co}	kg/h	0.849	1.260	1.696	2.134	2.956
$\varepsilon_{sat} = 90\%$						
Q_c	kJ/h	2220.7	3295.2	4441.4	5587.6	7736.7
Q_{co}	kg/h	0.950	1.408	1.897	2.386	3.304

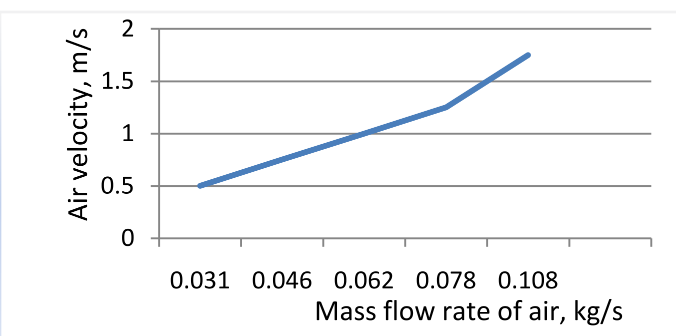

Figure 2.0 Air Velocity Vs Mass Flow Rate of Air

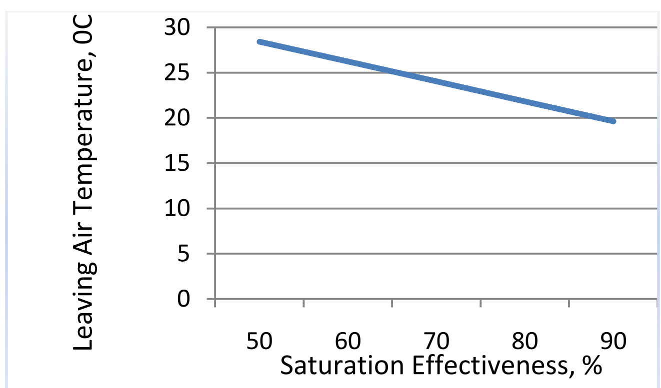

Figure 3.0 Leaving Air Temp. Vs Saturation Effectiveness

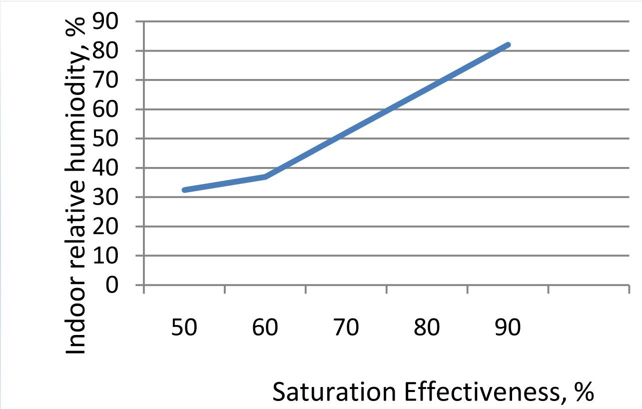

Figure 4.0 Indoor R. Humidity Vs Saturation Effectiveness

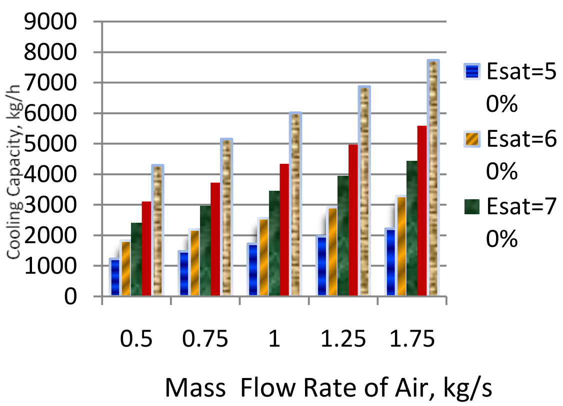

Figure 5.0 Cooling Capacity Vs Mass Flow Rate of Air

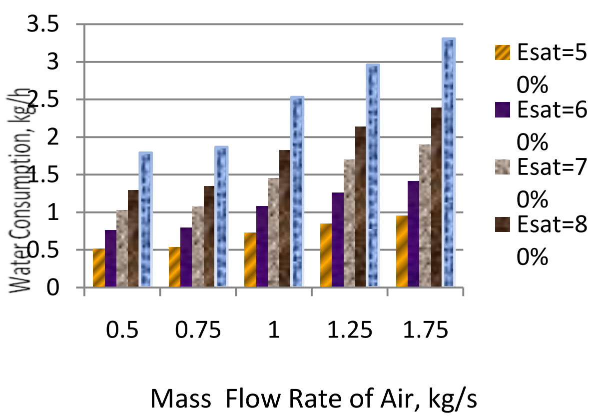

Figure 6.0 Water Consumption Vs Mass Flow Rate of Air

Saturation effectiveness varies inversely with the leaving air temperature as shown in figure 2.0. This means that evaporative pad materials with higher saturation effectiveness lower the air temperature more than materials with lower saturation effectiveness. The relative humidity of the leaving air varies linearly with saturation effectiveness as shown in figure 3.0. The higher the saturation effectiveness the more humid the leaving air temperature. This can be attributed to the fact that the higher the saturation effectiveness, the more the air stream gains moisture as it traverses the cooling pad. The mass flow rate of air passing through the DEC is a function of the air velocity. There is a linear relation between the air mass flow rate and the air velocity as shown in Table 2.0. The cooling capacity is a function of the air mass flow rate. There is a direct relationship between the cooling capacity and the air mass flow rate as shown in Table 4.0. The higher the air mass flow rates the higher the cooling capacity. Table 4.0 also shows that the cooling capacity depends on the saturation effectiveness of the cooling pad material used as it tends to increase with increase in the saturation effectiveness as shown in figure 5.0. The higher the air mass flow rate the more the water consumption by the DEC as shown in Table 4.. However, studies have shown that when the air velocity passing through the cooling pad is high, the contact between the air stream and saturated pad will be less; hence less water will be evaporated into the air stream. This agreed with the work of [6] that the longer the incoming air remains in contact with the saturated cooling pad, the more will be the evaporation. But at moderate air velocities as considered in this study, increase in air mass flow rate and saturation effectiveness of the cooling pad material increase the water consumption rate as shown in Table 4.0 and figure 6.0.

Conclusion

Theoretical performance of direct evaporative cooler at different air velocities at a given saturation effectiveness of the cooling pad was evaluated for the climate of Kano, Nigeria. Leaving air temperature of 21.9^{0}C and relative humidity of 82% were obtained with pad material of 90% saturation effectiveness for ambient condition of 41^{0}C and 19.8% relative humidity. The cooling capacity and the water consumption rate are calculated and are found to increase with increase in the air mass flow rate. Therefore, the DEC can be beneficial in hot and dry climates when the cooling pad materials used have high saturation effectiveness and moderate air velocity is used.

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