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Heat and mass transfer analysis and optimization of direct evaporative cooling system

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Abstract
The phenomenon of evaporative cooling is a common process in nature, whose applications for cooling air are being used since the ancient years. In fact, it meets this objective with low energy consumption, being compared to the primary energy consumption of other alternatives for cooling, as it is simply based in the phenomenon of reducing the air temperature by evaporating water on it. The fundamental governing process of evaporative cooling is heat and mass transfer due to the evaporation of water. This process is based on the conversion of sensible heat into latent heat. While changes in sensible heat affect temperature, it does not change the physical state of water. Conversely, latent heat transfer only changes the physical state of a substance by evaporation or condensation. This change of phase requires latent heat to be absorbed from the surrounding air and the remaining liquid water. As a result, the air temperature decreases and the relative humidity of the air increase. The maximum cooling that can be achieved is a reduction in air temperature to the wet-bulb temperature (WBT) at which point the air would be completely saturated. Accordingly, the proposed research envisages the design of evaporative cooling system, to find cooling capacity, to find cooling efficiency/saturation efficiency, optimization of influence parameter such as air flow rate, No. of cooling pads, water flow rate etc.

Keywords: Evaporative cooling, Design, Heat and mass transfer, Analysis.

1. Introduction

World energy consumption pattern showed that fossil fuels including oil, coal and gas are being consumed significantly higher than the environmentally friendly renewable energy sources. This will result in increased CO_2 emission to the environment and subsequent climate change. Similarly the historical and projected share of primary world energy consumption indicated continuous dominance on oil, gas and coal [1]. However, renewable energies which represent very small amount of the world energy consumption are receiving attention because of the falling trend in their costs and are also friendlier to the environment [2]. Majority of the energy consumption in building for cooling or heating is derived from fossil fuels. It is therefore very vital to provide a less energy intensive system for space cooling which will replace or minimize dependency on the conventional vapour compression air conditioning systems. Evaporative cooling is one method of simulating natural cooling effects.

1.1 Theory and basic principle of evaporative cooling system

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. When considering water evaporating into air, the wet-bulb temperature, as compared to the air's dry-bulb temperature, is a measure of the potential for evaporative cooling. The greater the difference between the two temperatures, the greater the evaporative cooling effect. Evaporation of water produces a considerable cooling effect and the faster the evaporation the greater is the cooling. When the temperatures are the same, no net evaporation of water in air occurs, thus there is no cooling effect. The principle of working of this system is 'when a particular space is conditioned and maintained at a temperature lower than the ambient temperature surrounding the space, there should be release of some moisture from outside the body'. This maintains low temperature and elevated humidity in the space compared to the surrounding [3]. Evaporative coolers provide cool air by forcing hot dry air over a wetted pad. The water in the pad evaporates, removing heat from the air while adding moisture. When water evaporates it draws energy from its surroundings which produce a considerable cooling effect. Evaporative cooling occurs when air, that is not too humid, passes over a wet surface; the faster the rate of evaporation the greater the cooling. The efficiency of an evaporative cooler depends on the humidity of the surrounding air. Very dry air can absorb a lot of moisture so greater cooling occurs. In the extreme case of air that is totally saturated with water, no evaporation can take place and no cooling occurs. The

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evaporatively cooled storage structures work on the principle of adiabatic cooling caused by evaporation of water, made to drip over the bricks or cooler pads. Generally, an evaporative cooler is made of a porous material that is fed with water. Hot dry air is drawn over the material. The water evaporates into the air raising its humidity and at the same time reducing the temperature of the air. Cooling is provided by the evaporative heat exchange which takes advantage of the principles of the latent heat of evaporation where tremendous heat is exchanged when water evaporates. It makes use of the free latent energy in the atmosphere [4].

1.2 Direct Evaporative Cooling (DEC)

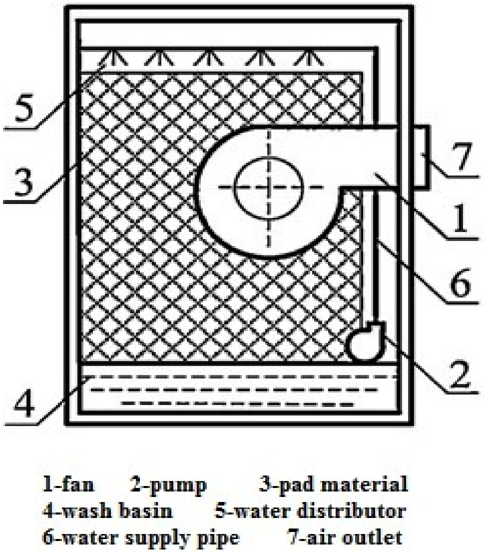

Fig 1: Schematics of a drip-type DEC [5]

This system is the oldest and the simplest type of evaporative cooling in which the outdoor air is brought into direct contact with water, i.e. cooling the air by converting sensible heat to latent heat. Ingenious techniques were used thousands of years ago by ancient civilizations in variety of configurations, some of it by using earthenware jar water contained, wetted pads/canvas located in the passages of the air [6].

The most commonly used direct evaporative coolers are essentially metal cubes or plastic boxes with large flat vertical air filters, called "pads", in their walls. Consisting of wettable porous material, the pads are kept moist by the water dripped continuously onto their upper edges. The process air is drawn by motorized fans within the coolers. After being cooled and humidified in the channels between the pads, the air leaves the cooler as "washed air" for cooling use. Many coolers use two-speed or three-speed fans, so the users can modulate the leaving air states as needed [7]. Fig. 1 is the schematic diagram of a drip-type DEC. Water is sprayed at the top edges of the pads and distributed further by gravity and capillarity. The falling water is recirculated from the water basin by the water pump. In DEC, the process air contacts directly with the sprayed water and hence is cooled and humidified simultaneously by the evaporation of water [5].

The fundamental governing process of evaporative cooling is heat and mass transfer due to the evaporation of water. This process is based on the conversion of sensible heat into latent heat. Sensible heat is heat associated with a change in temperature. While changes in sensible heat affect temperature, it does not change the physical state of water. Conversely, latent heat transfer only changes the physical state of a substance by evaporation or condensation [15]. As water evaporates, it changes from liquid to vapor. This change of phase requires latent heat to be absorbed from the surrounding air and the remaining liquid water. As a result, the air temperature decreases and the relative humidity of the air increases. The maximum cooling that can be achieved is a reduction in air temperature to the wet-bulb temperature (WBT) at which point the air would be completely saturated [8]. Accordingly, this paper envisages objectives such as design of Evaporative cooling system, to find cooling capacity, to find cooling efficiency/saturation efficiency, Optimization of influence parameter such as air flow rate, No. of cooling pads, water flow rate etc.

1.

2. Experimental setup

Construction of evaporative cooler was designed as per following parts:

1] Cabinet of the evaporative cooler

The direct evaporative cooling unit that is used for this study is made of mild steel sheet and fabricated in cylindrical shape. Two half cylindrical moulded sheets are flanged and joined together using bolt arrangement. There is one hole in centre for connecting the blower from the cabinet. Height of the column is 1.21 m, internal diameter of the column is 0.30 m and Flange length is 2.54 cm.

2] Coil set up

Copper pipe is molded in a spiral shape for making the coil used for circulation of hot water. Ten numbers of turns are made of coil to increase the retention time of hot water.

Diameter of copper pipe is 1.5 cm, Length of copper pipe is 7.92 m.

3] Shower set up

Shower is made up of rubber pipe used for spraying the cold water over the pads. It is molded in ring shape and small holes are made in the pipe for spraying cold water.

4] Blower

Blower is attached to the cooler cabinet using duct. It is attached below the coil so that the cold water and air comes in contact counter currently. The power of blower is 600 watt.

5] Pad

The aspen wood pad is used as the packing material with a diameter of 25 cm, and thickness of 1 cm. The pad considered in this study is assumed positioned in such a way that air traverses vertically across the pad entering on one side and leaving the other. The lower sides of the cooler are assumed to be closed. This means that there is one dimensional flow of air across the pad.

3.

4. Experimental Procedure for Methodology Assessment 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 entire system operates at atmospheric pressure (101.325kPa).
- The cooling pad is kept continually saturated with water.
- The frontal area of the opening of the cooler and density of the outdoor air remain constant throughout the analysis.

Water enters from the top of the tower and is fed into pads from which it flows down and contacted with copper coil. Normal ambient air was passed through the Orifice meter unit from lower side of cooler. Under the action, air is driven upward through the wet pad. Location of the six temperature readings to be taken when using the system, dry bulb temperature of air entering base of column, Wet bulb temperature of air entering base of column, Dry bulb temperature of air at exit from column, Wet bulb temperature of air at exit from column, Hot water temperature entering the coil and water temperature on leaving the coil. Experimental tests are carried out to evaluate the performance of the direct evaporative cooling unit. To measure the air temperature at inlet and outlet points of the evaporative cooling unit thermometer was used. Orifice meter is installed at the air inlet point of the evaporative cooling unit to measure the mass flow of air. Proportional derivative controller was used for maintain the temperature of hot water at 60^{0}C. During experimentation, the inlet air flow rates were 0.00856, 0.01048, 0.0121, 0.0135, 0.01483 kg/sec.

3.1 Performance parameters

A direct evaporative cooler (DEC) is a simple air-conditioning system widely used in dry and hot regions. The air and water are in direct contact; the hot, dry air passes over a wet pad's surfaces; the air will lose its sensible heat, thereby reducing its temperature. The performance parameters of DEC are calculated based on the following relation:

Generally for the direct evaporative cooling process the system performance can be based on the saturation efficiency, defined in the expression given below:

$$\eta = T_{db\ in} - T_{db\ out} / T_{db\ in} - T_{wb\ in} \quad \text{…………….. (1)}$$

The cooling capacity Q of a direct evaporative cooler is determined from equation

$$Q_{hot\ water} = m_{hot\ water} * Cp * \Delta T_{hot\ water} \quad \text{…………. (2)}$$

$$Q_{Air} = m_{Air} * Cpa * \Delta T_{Air} \quad \text{……………………. (3)}$$

Log mean Temperaure difference is calculated from

$$\Delta T_{lm} = (Th_{out} - Tc_{in}) - (Th_{in} - Tc_{out}) / (\ln(Th_{out} - Tc_{in}) / (Th_{in} - Tc_{out}) \quad \text{…(4)}$$

Heat transfer rate of Air is calculated as:

$$Q_{Air} = UA\, \Delta T_{lm} \quad \text{……………… (5)}$$

Mass Transfer flux and Mass Transfer coefficient is calcualed as:

$$Na = (H_{out} - H_{in}) * \text{Mass of Air} / (18 * \text{Area}) \quad \text{…. (6)}$$

$$K_g = Na / (p_o - p_i) \quad \text{………….(7)}$$

Where, Tdb, in = The dry bulb temperature at inlet, ^{0}C; Tdb,out = The dry bulb temperature at outlet, ^{0}C; Twb, in = The wet bulb temperature at the inlet, ^{0}C;Q $_{hot\ water}$=Heat transfer rate of hot water, kJ/Sec; m $_{hot\ water}$=Mass flow rate of hot water, kg/sec; Cpa= Specific heat capacity of air, kJ/kg. ^{0}C; Cphw= Specific heat capacity of hot water, kJ/kg^{0}C ;Q $_{Air}$ = Heat transfer rate of Air, kJ/Sec; m $_{Air}$= Mass flow rate of hot water, kg/sec; ΔT_{lm} = Log mean Temperature difference; Th_{out}=Outlet hot water temperature, ^{0}C; Tc_{in} = Inlet cold water temperature, ^{0}C; Th_{in} = Inlet hot water temperature, ^{0}C; Tc_{out} = Outlet cold water temperature, ^{0}C; U=Overall heat transfer coefficient, W/m^{2}K; A=Heat transfer Area, m^2;Na=Mass transfer flux, Kmol/m^2.Sec; H_{out}=Humidity in outlet air, kg/kg; H $_{in}$= Humidity in inlet air, kg/kg; K_g=Mass transfer coefficient, kmol/m^2.Sec.kPa; p_o=partial pressure of outlet air, kPa; p_i=partial pressure of inlet air, kPa

5.

6. Results and Discussion

Table 1 to 3 shows the experimental data and the performance parameters for three, two and one pad with optimum air flow rate as 0.0135kg/sec. The values of the experimental test; dry-bulb temperature of the inlet and outlet air, temperature of inlet and outlet hot water, saturation efficiency, and cooling capacity, heat transfer coefficient and mass transfer coefficient are shown in tables. During experimentation, the inlet air conditions were as follows: the dry bulb temperature were 31.5 °C to 35.5 °C, Hot water flow rate was 0.018kg/sec, Cold water flow rate was 0.0667 kg/sec. Hot water inlet temperature was kept constant at 60 °C, minimum hot water outlet temperature is 43 °C.

Table 1: Experimental data and the performance parameters for three pads, Air flow rate=0.0135 kg/sec

Sr. No.	Time (Min)	Air in DBT (^{0}C)	Air in WBT (^{0}C)	Hot water out (^{0}C)	Air out DBT (^{0}C)	Air out WBT (^{0}C)	Effic-iency (%)	U (W/m^{2}K)	H_{out} (Kg/Kg)	H $_{in}$ (Kg/Kg)	Na (Kmol/m^2. Sec)	Kg (Kmol/m^2. Sec. kPa)
	10	35	24	46	26	22	81.81	0.0020	0.0152	0.0144	$2.07893*10^{-7}$	$2.64116*10^{-6}$
	20	35	23.5	45	26	21.5	78.26	0.0021	0.0145	0.0136	$2.3388*10^{-7}$	$2.63725*10^{-6}$
	30	35	23.5	45	25.5	21.5	82.60	0.0022	0.0144	0.0136	$2.07893*10^{-7}$	$2.63699*10^{-6}$
	40	35	23	44	25.5	21	79.16	0.0023	0.0138	0.0126	$3.1184*10^{-7}$	$2.63283*10^{-6}$
	50	35	23	43	25.5	21	79.16	0.0024	0.0138	0.0124	$3.63813*10^{-7}$	$2.63231*10^{-6}$
	60	35	22.5	45	25.5	20.5	76.00	0.0022	0.0131	0.012	$2.85853*10^{-7}$	$2.62946*10^{-6}$
	70	35	21.5	43	25.5	20	70.37	0.0024	0.0126	0.0108	$4.67759*10^{-7}$	$2.62504*10^{-6}$

Table 2: Experimental data and the performance parameters for two pads, Air flow rate = 0.0135 kg/sec

Sr. No.	Time (Min)	Air in DBT (^{0}C)	Air in WBT (^{0}C)	Hot water out (^{0}C)	Air out DBT (^{0}C)	Air out WBT (^{0}C)	Effici-ency (%)	U (W/m^{2}K)	H_{out} (Kg/Kg)	H $_{in}$ (Kg/Kg)	Na (Kmol/m^2.Sec)	Kg (Kmol/m^2.Sec. kPa)
	10	32.5	26.5	50	29.5	26	50.00	0.0011	0.02	0.0198	$7.49026*10^{-8}$	$3.84473*10^{-6}$
	20	32.5	26.5	49	29.5	26	50.00	0.0013	0.02	0.0198	$7.49026*10^{-8}$	$3.84473*10^{-6}$
	30	32.5	26.5	49	29	26.5	58.33	0.0013	0.0202	0.0198	$1.49805*10^{-7}$	$3.84548*10^{-6}$
	40	32.5	26.5	48	28	26	75.00	0.0016	0.0206	0.0198	$2.99611*10^{-7}$	$3.84699*10^{-6}$
	50	33	26.5	48	28	25.5	76.92	0.0019	0.0199	0.0195	$1.49805*10^{-7}$	$3.84322*10^{-6}$
	60	33	26	47	28	25.5	71.42	0.0020	0.0199	0.0185	$5.24318*10^{-7}$	$3.83945*10^{-6}$
	70	33	25.5	47	27.5	24.5	73.33	0.0009	0.0184	0.0178	$2.24708*10^{-7}$	$3.83117*10^{-6}$

Table 3: Experimental data and the performance parameters for one pad, Air flow rate = 0.0135 kg/sec

Sr. No.	Time (Min)	Air in DBT (^{0}C)	Air in WBT (^{0}C)	Hot water out (^{0}C)	Air out DBT (^{0}C)	Air out WBT (^{0}C)	Efficie-ncy (%)	U (W/ m^{2}K)	H_{out} (Kg/ Kg)	H_{in} (Kg/Kg)	Na (Kmol/ m^2. Sec)	Kg (Kmol/m^2. Sec. kPa)
	10	33.5	27	53.5	30.5	27.5	46.15	0.00198	0.0222	0.0202	$1.33785*10^{-6}$	$6.88466*10^{-6}$
	20	33.5	27	53.5	30	27	53.84	0.0022	0.0216	0.0202	$9.36497*10^{-7}$	$6.88062*10^{-6}$
	30	33.5	26.5	53	30	27	50.00	0.0022	0.0216	0.0192	$1.60542*10^{-6}$	$6.87388*10^{-6}$
	40	33.5	26.5	52.5	29.5	26.5	57.14	0.0027	0.0207	0.0192	$1.00339*10^{-6}$	$6.86782*10^{-6}$
	50	34	26.5	51	29.5	26.5	60.00	0.0028	0.0207	0.0192	$1.00339*10^{-6}$	$6.86782*10^{-6}$
	60	34	26.5	50	29.5	26.5	60.00	0.0029	0.0207	0.0192	$1.00339*10^{-6}$	$6.86782*10^{-6}$
	70	34	26.5	49	29.5	26.5	60.00	0.0016	0.0207	0.0192	$1.00339*10^{-6}$	$6.86782*10^{-6}$

Fig. 2, 3, 4 shows variation of outlet air temperature at the effect of the number of pads on the outlet air temperature with respect to time respectively. When the pad numbers are increased, outlet air temperature is decreased. The effect of the mass flow rate of air on the outlet air temperature from humidifier is shown, which proves that in case of growing of air flow rate, the outlet air temperature is decreased, and steady state condition is achieved.

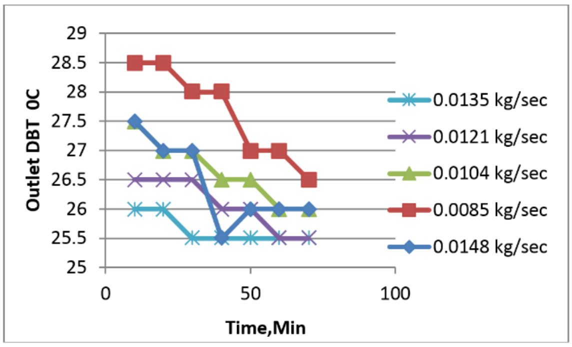

Fig 2: Variation of outlet air temperature at different of values of air flow rate for three pads.

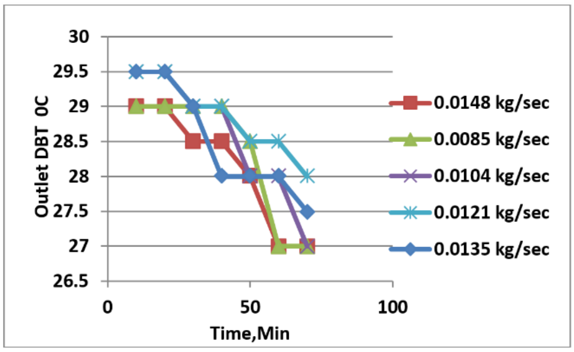

Fig 3: Variation of outlet air temperature at different of values of air flow rate for two pads.

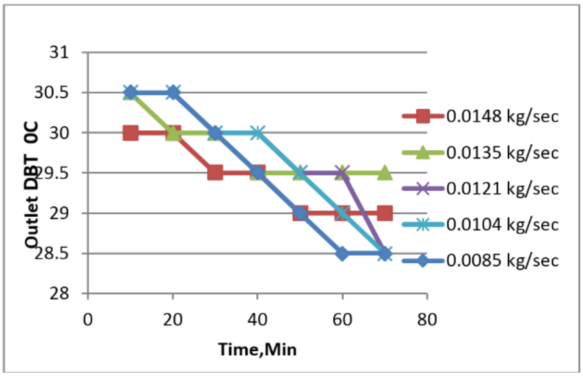

Fig 4: Variation of outlet air temperature at different of values of air flow rate for one pad.

The cooling pad was found to be a significant parameter in predicting the cooling efficiency inside the column. Therefore, cooling is a 100% natural cooling process accomplished by the evaporation of water into air. Evaporation efficiency is as high as 82.6% with three numbers of pads, which allows for large drop in dry bulb temperature as the energy required to evaporate the water into the air is taken from the air. The drier the outside air, the better the cooling effect achieved and the higher the humidity of the outside air, the lower the resultant cooling effect. Fig.5 shows the effect of number of pads on the cooling efficiency. The cooling efficiency is increased with increasing of the pad numbers. This is because the contact surface between water and air is increased.

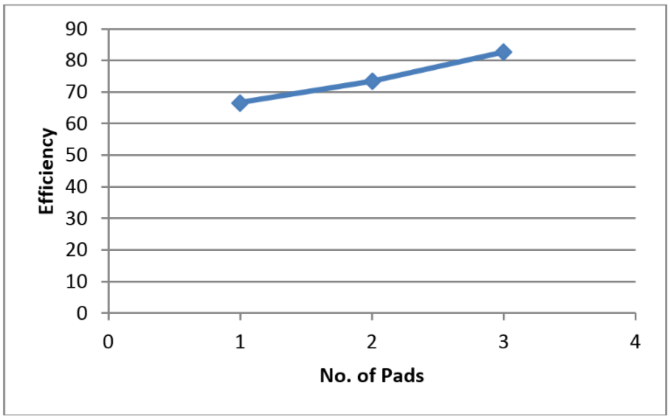

Fig 5: The effect of number of pads on the cooling efficiency

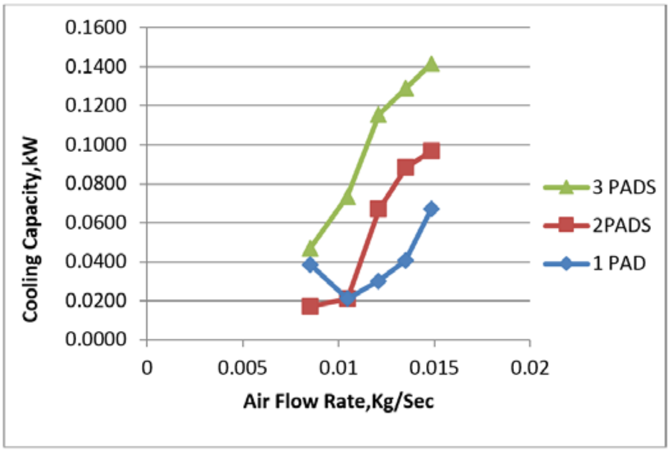

Fig 6: Cooling capacity Vs Air Flow Rate

Fig 6 shows Cooling capacity Vs Air Flow Rate. The cooling capacity of cooling pads in an evaporative cooling system is a function of the air flow rate through it. The higher the air mass flow rates the higher the cooling capacity. Cooling capacity depends on the saturation effectiveness of the cooling pad material used as it tends to increase with increase in the saturation efficiency. For three pads minimum temperature is achieved in direct evaporative cooling system, whereas for one and two pads temperature is higher for the effect of air flow rate on outlet dry bulb temperature. This is because the contact surface between water and air is increased for three pads. For three pads maximum efficiency was achieved. Analysis results indicated that the system performance could be improved by optimizing the mass flow rates of the feed water and processed air, as well as the number of the pads. The analysis showed that the air flow rate and the number of the pads are two key factors influencing the cooling efficiency of a direct evaporative cooler.

6. Conclusion

Analysis to the heat and mass transfer between air and water in a direct evaporative cooler with aspen wood pad modules is carried out in the present study. The analysis shows that the air flow rate and number of pads are two key influencing factors to the cooling efficiency of a direct evaporative cooler. Leaving air temperature of 25.5 ^{0}C and relative humidity of 75% was obtained with optimum number of pads was and 82.6% saturation effectiveness for ambient condition of 35 ^{0}C. The optimum air flow rate was 0.0135 kg/sec. The results may be helpful to the pre-design and engineering application of the direct evaporative cooler. Evaporative cooling is also important to the development of independent temperature and humidity control air conditioning systems. More R&D on potential applications of evaporative cooling systems would be advisable to promote environmentally friendly, energy-efficient, and comfortable air conditioning and, hence, a more sustainable world.

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