Experimental investigation of air cooler using local palm tree waste

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ABSTRACT

Middle Saudi Arabia has weather conditions where the temperature is high in summer with low humidity. Conventional air conditioning systems operated by a vapor compression cycle are not economical because of the high electrical power consumption. Therefore, evaporative cooling through evaporative coolers is one of the best and most economical solutions. This study experimentally investigates the factors affecting the performance of evaporative coolers. Pad materials and airflow rate are the main variables to investigate the evaporative cooler's performance in terms of saturation effectiveness, pressure drop across the pads, and coefficient of performance (COP). Pads material are the local palm tree “Nakheel” waste that are leaflet, leaf base, bulb, and roots. The maximum COP of the cooling system in the case of bulb pad material is 80% more than that of leaflet pad material. The saturation effectiveness of the bulb pad was a maximum which is 61.93% at an air flow rate of 2.25 m/s, which is more than two times that of the saturation effectiveness of the leaflet pad. The pressure drop across the bulb pad is almost 2.5 times to 9.5 times than that of leaflet pad. Results show that bulb pad performance best, whereas the leaflet pad material has the lowest performance in terms of pressure drop, saturation effectiveness, and COP.

1. Introduction

The worldwide demand for electrical energy for industrial and commercial purposes increases electrical power prices. Especially in Saudi Arabia, a major section of the production of electrical energy is consumed to operate refrigerating devices [1, 2, 3, 4]. Evaporative cooling (EC) is the best and cheapest solution to overcome the high electrical energy consumption for space cooling through a vapor-compression refrigerating (VCR) system. Compared to the VCR system, the EC system requires less electrical power because of the small water pump and blower. Also, the initial cost, maintenance cost, and operational cost of the EC system are much less than that of the VCR system [5, 6, 7]. In evaporative cooling, when air at ambient temperature passes through the cooling pads, its temperature decrease because water absorbs heat from the air. This means that as the dry bulb temperature increase and humidity decreases, the cooling effectiveness of the EC system also increases. Several investigations have been carried out by different researchers to improve the performance of the EC system. The major factors that significantly affect the performance of the EC system are air flow rate, condition of ambient air like dry bulb temperature, humidity, etc., the water flow rate through the cooling pads, thickness, density, and material of cooling pads [8, 9, 10, 11, 12, 13]. The selection of the wet media pad material depends on many factors such as safety, cost, availability, effectiveness, and application [14]. Ajiwiguna et al. [15] experimentally investigated the performance of the EC system for the air velocity 0.6 m/s to 3.4 m/s with the increment of 0.2 m/s at an angle of set 0° (parallel), 45° (inclined), and 90° (perpendicular) to the wet medium surface. The results show that the heat absorption rate increases with air velocity. Also, the Perpendicular direction of airflow results in the highest cooling capacity compared with other directions. Aziz et al. [16] experimentally investigated the effect of water temperature from 100°C to 500°C with the increment of 100 and airstream velocity for 2.9 m/s, 3.9 m/s, and 4.5 m/s on the performance of direct evaporative air cooler for thermal comfort. Results show that relative humidity increases with water temperature but is unaffected by the airstream velocity. The cooling effectiveness increases with an increase in air velocity and a decrease in water temperature. The effect of airflow velocity and water flow rate on the performance of direct and indirective evaporative cooling systems is also conducted by Franco et al. [14], Rodrigues et al. [17], and Antonellis et al. [18]. Overall it is noted that the performance is significantly affected by the water flow rate. Fouda and Melikyan [19] have used synthetic paper as a wet material on a direct evaporative cooling system.

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Based on the experimental data and computed results he proposed the mathematical model between the heat and mass transfer between the air and water flow rate in the direct evaporative cooler. Wu et al. [20] also proposed the mathematical model between the heat and moisture transfer between the air and water flow rate. Velasco et al. [21] provided the comparative performance of direct and semi-indirect evaporative cooling system. Results show that overall, direct evaporative cooling system perform better as compared to semi-indirect evaporative cooling system. Zhao [22] has done an investigation on different types of materials like ceramics, metals, carbon, fibers, and zeolite. Results show that cost, durability, and shape formation/holding ability are the major criteria for pad material selection. Ndukwu et al. [23] studied some local materials as a wet material cooling pad in their area in Nigeria. The study was at constant speeds and made on 4 different types of materials: Charcoal, Palm Fruit Fibre, Shredded latex Foam, and Jute Fiber. Harris [24] found out that the main reason for air to be cooled in the evaporative cooling system depends on the pad material used. Ibrahim et al. [25] studied the porosity of ceramic material and its effect on the performance of the evaporative cooling system. And as expected he found the higher the porosity the higher the cooling capacities. Jain and Hindoliya [24] experimentally investigated the evaporative cooling performance for the pad material coconut fibers and Palash fibers along with aspen and khus fibers. The effectiveness of pad with Palash fibers was found to be 13.2% and 26.31% more than that of aspen and khus pads respectively. Whereas the effectiveness of coconut fibers was found to be 8.15% more than that of khus and comparable with that of aspen pad. Rawangkul, Khedari, Hirunlabh, and Zeghmati [26] conducted an experimental investigation in the Thailand region for coconut coil cooling pads. Results show that the tested cooling pad has a cooling efficiency is 50% which is close to the commercial pad cooling efficiency. Zhao, Liu, and Riffat [22] experimentally investigated heat transfer characteristics and cooling efficiency for five different types of cooling pad materials which are carbon, ceramics, metals, zeolite, and fibers. Thought that investigation best suitable cooling pad material were identified. Shrivastava, Deshmukh, and Rawlani [27] investigated coconut fiber pads for evaporative cooling and compared with them with Aspen wood pads. Results show that both pads have similar effectiveness but the relative drop was observed in Aspen wood pads in the range of 80–85% whereas in coconut fiber pads in the range of 50–60%. Also, the water consumption in coconut fiber pads is less as compared to Aspen wood pads. Salins, Reddy, and Kumar [28] experimentally investigated the performance of evaporative cooling in the case of coconut coil and wood-shaving by varying the air-flow rate and compared with celdek packing pads. Results show that wood shaving performed better as compared to coconut pads. Daeho and strand [29] numerically investigated the performance of PDEC towers with a spray system based on the parameters of wind speed, tower height, and wet-bulb depression. Based on the study, the regression equations were proposed between the studied parameters and the performance of the air conditioning system. Liao and Chiù [30] developed a compact wind tunnel to simulate evaporative cooling pad-fan systems for direct measurement of system performance. Two alternative materials of coarse and fine fabric PVC spongy mesh were tested as pads in the wind tunnel experiment. The effect of air velocity, water flow rate, static pressure drop across the pad, and pad thickness was experimentally examined. The results show that the cooling capacities of coarse PVC spongy in between 81.75% to 84.48% whereas in the case of fine fabric PVC spongy, it is in between 76.68% to 91.64%. Camargo, Ebinuma, and Silveira [31] experimentally determined the convective heat transfer coefficients studies for the direct evaporator cooler. Rong et al. [32] investigated the performance of evaporative cooling pads for the parameters like water supply duration, control time cycle, etc. for cellulose pads. Results show that a larger variation in air temperature difference occurred between inlet and outlet of evaporative cooling pad occurred if the control time cycle was longer and face airspeed was bigger. Also, resistance to airflow through the pad increases with an increase in the supply of water to the pad.

It is concluded above literature survey that scientists are trying to develop the most effective and sustainable material for cooling pads which should be very efficient to enhance the performance of the cooling devices. The present work is aiming to study evaporative coolers which use palm tree waste as cooling pads. The pads material for the evaporative cooler is Leaflet, Leaf-base, roots, and bulb. Inlet and outlet temperature difference, relative humidity, water flow rate, and pressure drop across the pads are the major factors to evaluate the overall performance of the evaporative cooler.

2. Description of cooling pads

The pads of the evaporative cooler were taken from local palm trees known as “Nakheel” in the kingdom of Saudi Arabia. The cooling pads of four different types were prepared. The cooling pad of Type 1 prepared from the leaflet of the palm tree as shown in Figure 1(a), Type 2 cooling pad prepared from the leaf base which supports the leaflet weight shown in Figure 1(b), Type 3 cooling pad prepared from roots which are usually on the top of soil shown in Figure 1(c), and Type 4 cooling pad prepared from the bulb which is highly compact fibrous and at near the outer part of the trunk shown in Figure 1(d). The selection of pad materials is based on a growing of palm trees with a height between 5 to 8 m. The pad material is evenly distributed in the wire mesh frame of dimension 35 cm × 35 cm × 5 cm. The weight of pad material including wire mess frame is the same in all four different cases.

3. Experimental procedure and theoretical analysis

3.1. Experimental setup

Figure 2 shows the diagram of the experimental setup and Figure 3 shows the schematic arrangement of cooling pads of the present study. The major components of the experimental setup are a submersible water pump (MY-333D) having a flow rate in the range of 1500 LPH to 2000 LPH, a 55-watt axial centrifugal air fan (DVN-121) having a speed in the range of 1250 RPM to 1450 RPM, air duct having the dimension of the

![Figure 1. Types of cooling pad material.](image)
height of 35 cm, a width of 35 cm, and a length of 80 cm, and a thickness of 1 cm, test section of dimension height of 35 cm, a width of 35 cm, and a thickness of 5 cm, data logger, UIY6-D digital pressure meter having an accuracy of 0.5%FS, K-type thermocouples having the accuracy of 0.1 °C were used to measure the temperature of the air before and after the pad, and Relative humidity meter (RH101) having the range of 10%–95% with an accuracy of ±3%.

Before experimenting with taking experimental data, the flow rate of the water pump that circulates water through the pad is set by the controller to the required value. The present study investigated three different speeds that are 1.75 m/s, 2.25 m/s, and 2.75 m/s. Once the flow rate of air in the duct across the pad and the flow rate of water through the pad come in the steady-state, the temperature, pressure, and humidity of air before and after the pad was recorded.

### 3.2. Data reduction

The difference in the temperature of the air before and after flow through the duct is given by

$$\Delta T = T_1 - T_2$$  \hfill (1)

The cooling pads saturation effectiveness is calculated by equation 2 in terms of temperatures [33] and is given by

$$\eta_s = \frac{T_d - T_w}{T_d - T_{sat}} \times 100$$  \hfill (2)

The mass flow rate of air through the cooling pad is calculated by Eq. (3) [34] and is given by

$$\dot{m}_a = \rho A V_a$$  \hfill (3)

In case of performance analysis, one of the important parameter is the sensible cooling capacity [35] and is given by

$$Q_c = \dot{m}_a \times c_p \times (T_{d1} - T_{d2})$$  \hfill (4)

The relative humidity ($H_r$) of air is defined as the amount of water vapor present in the air and is calculated by

$$H_r = \frac{e_w - A \times P_{am}}{e_d} \times (T_d - T_w) \times 100$$  \hfill (5)

Where.

The saturation vapor pressure ($e_w$) in the wet-bulb temperature is given by [36]

### Table 1. List of instruments with uncertainty.

| S. No. | Instrument                  | uncertainty | Range        |
|-------|----------------------------|-------------|--------------|
| 1     | Temperature (Type-K Thermocouple) | ±0.1 °C     | −5 to +200 °C |
|       | Relative humidity (RH101)   | ±3.5%       | 10% to 95%   |
| 2     | Axial centrifugal air fan (DVN-121) | ±5 RPM     | 1250 RPM to 1450 RPM |
| 3     | UIY6-D digital pressure meter | 0.5%FS     | 0.1 bar to 35 bar |
The saturation vapor pressure \((e_d)\) in the dry bulb temperature is given by [36]

\[
e_d = 6.112 \times \text{Exp}\left(\frac{17.502 \times T_d}{240.97 + T_d}\right)
\]

The measuring humidity coefficient \((A)\) is given by

\[
A = 0.00066 \times (1 + 0.00115 \times T_d)
\]

The ratio of the cooling capacity to total electrical power consumed is defined as the coefficient of performance and is given by

\[
\text{COP} = \frac{Q_c}{W_p + W_f}
\]

\[\text{ed} = 6.112 \times \text{Exp}\left(\frac{17.502 \times T_d}{240.97 + T_d}\right)\]

\[A = 0.00066 \times (1 + 0.00115 \times T_d)\]

\[\text{COP} = \frac{Q_c}{W_p + W_f}\]

3.3. Experimental uncertainty

During experimentations, it is always recommended to measure the experimental errors. By the use of the error formula, propagation of Uncertainty analysis is possible to calculate [37,38]. In the present study, the measurement of temperature difference, Pressure difference, and relative humidity are the main source of an error. Therefore, experimental uncertainty can be calculated by Eq. (11).

\[
\delta Y = \sqrt{\left(\frac{\partial Y}{\partial X_1}\delta X_1\right)^2 + \left(\frac{\partial Y}{\partial X_2}\delta X_2\right)^2 + \left(\frac{\partial Y}{\partial X_3}\delta X_3\right)^2 + \ldots + \left(\frac{\partial Y}{\partial X_n}\delta X_n\right)^2}
\]

where \(\delta Y\) is the overall uncertainty in the result, \((X_1, X_2, X_3, \ldots , X_n)\) are the set of measurements that are directly measurable parameters. \(\delta X_1, \delta X_2, \ldots , \delta X_n\) are the overall uncertainty of parameters. Each term represents the same calculation: The partial derivative of \(Y\) with respect to \(X_1\) is multiplied by the uncertainty value for that variable. The uncertainty range for each instrument shown in Table 1.

4. Results and discussion

The experimental data were collected in the month of March and April by conducting experiments for air velocities of 1.75 m/s, 2.25 m/s, and 2.75 m/s. One by one, tests were conducted on four different pad materials. The type 1 which is leaflet of palm tree present in the form of pinnate leaves in a green color mixed with gray tones which indicates the short cycle of its live. It has extended stalk covered with sharp spikes on the base. The type 2 which is leaf base that support the leaflet weight and withstand forced loud from the wind. Type 3 which is the roots that usually on the top of soil and do not puncture deep into the ground. And type 4 are the Bulb which is highly compact fibrous and cylindrical in shape. It is much thicken near the outer part of the trunk. For steady-state conditions, the experimental setup first runs for about 15–20 min. Then measured wet-bulb temperatures of air at the inlet and dry bulb temperature at the inlet and outlet using thermocouples and recorded through a data logger. Also recorded the water temperature of the collecting tank. The cooling pads saturation effectiveness was calculated using Eq. (2) and the coefficient of performance was calculated using Eq. (9). The pressure difference across the pad was recorded and plotted for each pad in Figure 4 for the velocity of air at 1.75 m/s, 2.25 m/s, and 2.75 m/s.

Overall, it is noted from Figure 4 that the pressure difference across the pad increases with the increase of air velocity. Also, the pressure difference across the pad of Type 1 is maximum and minimum in the case.
of Type 4. For every 0.5 m/s rise in air velocity, the pressure difference across the pad increases to 30%, 15.5%, 41.5%, and 137.5% in the case of Type 1, Type 2, Type 3, and Type 4 respectively. The variation of COP of four different pads with respect to the velocity of 1.75 m/s, 2.25 m/s, and 2.75 m/s are shown in Figure 5.

It is noted from Figure 5 that the COP for a pad of Type 1, Type 2, and Type 4 increases with velocity whereas COP for a pad of Type 3 decreases with velocity. The COP for a pad of Type 4 is maximum and the minimum for a pad of Type 1 is minimum for the entire range of velocity considered. The COP of the pad of Type 1 increases to 23% in the first 0.5 m/s velocity of air increase in velocity and 32% increases in the next 0.5 m/s velocity of air. Similarly, COP of the pad of Type 2 and Type 4 increases to 15.7% and 36.8% for every increase of 0.5 m/s velocity of air. In the case of the pad of Type 3, in the first increment of the velocity of air of 0.5 m/s, the COP decreases by 12%, and in the next increment of air velocity of 0.5 m/s, the COP decreases by 24%. The saturation effectiveness of four different types of cooling pads at three different velocities is 1.75 m/s, 2.25 m/s, and 2.75 m/s shown in Figure 6. It is observed from that saturation effectiveness for pad of Type 1 increases with velocity whereas for pad of Type 2 and pad of Type 3 decreases with velocity.

And in case of pad of Type 4, mixed variation is noted, that is the saturation effectiveness first increases and then decreases. The saturation effectiveness of pad of Type 4 is maximum when velocity of air is 2.25 m/s out of all four cases under study for entire range of velocity of air considered. The average increment in saturation effectiveness for every 0.5 m/s rise in air velocity in case of Type 1 pad is 8.5%. The decrement in saturation effectiveness for first 0.5 m/s rise in air velocity in case of Type 2 and Type 3 is 9.3% and 31% respectively whereas in second 0.5 m/s rise in air velocity, the decrement in saturation effectiveness in case of Type 2 and Type 3 is 90% and 45% respectively.

Figure 7 shows the variation of saturation effectiveness of four different types of cooling pads with respect to uniform time at three different velocities. The dry bulb as well as wet bulb temperatures were measured on both sides of the pad using thermocouples recorded through data logger after steady state of air flow through the pads. Based on the recorded data, saturation effectiveness is calculated and plot in Figure 7. Figure 7(a), (b), (c), and (d) shows the variation of saturation effectiveness for pad of Type 1, Type 2, Type 3, and Type 4 respectively. In Figures 7(a) and (c), it is observed that the saturation effectiveness increases with velocity but for pad of Type 2, the saturation effectiveness decreases with velocity. In Figure 7(d), it is observed that the saturation effectiveness almost stable with time and highest when the velocity of air flow is 2.25 m/s.

5. Conclusion

The present study conducted the experimental study of pressure drop across the pad, saturation effectiveness, and COP for four different types of pads material at three different air flow velocities. Based on the above discussions, the following major conclusions are drawn.

1. The pressure drop across the pad increases with the air flow rate. It is minimum in the case of bulb material pad and maximum in the case of leaflet material pad. But for every 0.5 m/s velocity increment in air flowrate, the highest increment in pressure drop is observed in the case of bulb material pad and minimum in the case of leafmat material pad.
2. The COP of the system increases with an air flow rate in the case of leaflet material pad, leaf base material pad, and bulb material pad whereas, in the case of roots material pad, the COP of the system decreases with air flow rate. For the first 0.5 m/s velocity increment in air flowrate, the highest increment in COP observed in bulb material pad and for next 0.5 m/s velocity increment in air flowrate, the highest increment in COP observed in the case of leafmat material pad.
3. The saturation effectiveness increases with an air flow rate in leaflet material pad and decreases with an air flow rate in leaf base and root.
material pad. Out of four different selected pad materials, the maximum cooling effectiveness recorded in bulb material pad at the air flow rate of 2.25 m/s that is 63.7%.

4. The cooling efficiency of bulb material pad is most stable with time as compared to other types of pads under study.

Overall, it is concluded that all type of pad material under study increases the saturation effectiveness and COP of the cooling system. But out of four different pads material, it is recommended that bulb pad material is best for the entire range of velocity of air flow and to optimize it the performance of air flow should be 2.25 m/s.

Declarations

Author contribution statement

Abdulmajeed Almaneea: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Talal Awad Alshammari; Fahad Yousef Aldhafeeri; Muhammed Hamdan Aldhfeeri; Abdullah Abdulaziz Allaboun; Talal Syan Almutairi: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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