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Research paper

Performance evaluation of a developed evaporative air cooler with solar irradiance effect

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Abstract

Direct evaporative air cooler has been developed to enhance the cooling effectiveness in hot and low relative humidity region. The evaporation area of the conventional evaporator was increased and tested in Baghdad city (N33.3, E44.4). The present study aims to evaluate the developed evaporative air cooler under the direct effect of the solar irradiance and dry-bulb temperatures variation. For test conditions with low relative humidity range 10 to 15 percent, it is found that inlet dry-bulb temperature of the air could be cooled lower than wet-bulb temperature. The cooling effectiveness tends to rise when inlet dry-bulb temperatures increase between 26.3°C to 44.7°C. Inversely, the cooling effectiveness tends to reduce when the solar irradiance affects between 268 W/m2 to 636 W/m2. Moreover, the cooling effectiveness of the developed evaporative air cooler in shade is higher than that in sunny places of Baghdad by 10%. The energy savings by using the developed evaporative air cooler are 80% and 84% in sunny and shade places, respectively, when compared to an identical vapor compression air conditioning unit. In conclusion, it was found that increasing the area of evaporation is an efficient method to increase cooling effectiveness, while solar irradiance has the opposite effect.

Keywords: *Direct Evaporative Air Cooler; Solar Irradiance; Evaporation Area; Cooling Effectiveness.*

1. Introduction

Water liquid changing to water vapor, especially near the surface, when the molecules have adequate kinetic energy to escape represents an evaporation phenomenon. The kinetic energy is proportional to the temperature of the molecules. Hence, the evaporation increases when the temperature increases. Therefore, the rate of water vapor added to the air depends on the molecules temperature rises [1].

Accordingly, direct evaporative cooling, DEC, uses a wetted pad to cool the air. In the extremely dry air, the evaporative air cooler can be significantly dropped temperatures through the phase change of water to water vapor, which cools air by less energy consumption than the compression refrigeration system. Low consumption of energy is obtained when the DEC process operates at a constant wet-bulb temperature (approximately constant enthalpy). The underlying principle of DEC is ambient air heat extraction, which converts to latent heat associated with the evaporation of water. Thence, supply air leaves at low air temperature with high humidity.

A novel coupled system for decreasing temperature of air conditioning below the wet-bulb temperature of surrounding has been developed by Heidarinejad et al. [2]. A ground piping circuit provides pre-dropping of air temperature; subsequently, air temperature cools below its wet-bulb by applying DEC unit. Assisted simulation results revealed comfort conditions of a hybrid system up to higher than 100%. Jain [3] developed and tested two-stage evaporative cooling storage of vegetables. The developed cooler could provide necessary comfort conditions even though outside humidity is higher. The two-stage cooler was found to provide 20 % better cooling than a single stage cooler. Sodha et al. [4] evolved DEC unit for space cooling in various climates in the condition of the floor area. Obtained results show a reduction in the discomfort of space cooling by 90%. Lin et al. [5] modeled mathematically and experimentally the DEC system under different conditions. The evaporative air cooler utilized a pre-dehumidifier to improve effectiveness with the condition of ambient humidity. The dehumidification improvement ranged from 70–135 % whereas the effectiveness reaches to 1.25. Camargoa et al. [6] investigated the cooling performance of the DEC system and determined the convection heat transfer coefficient.

Performance of evaporative air cooler increased when using porous ceramic materials as wetted pads for air conditioning units. Boukhanouf et al. [7] presented a computational model validated by measurements for wetted ceramic cooler; while Ibrahim et al. [8] and Gómez et al. [9] investigated the performance of porous ceramic evaporators experimentally. Obtained results show that the evaporative cooler with porous ceramic has high thermal performance in terms of low temperatures of supplying air. Ndukwu and Manuwa [10] reviewed the DEC systems by means of; designs of an evaporative cooler, technologies utilize in DEC systems that improve the performance, and analyses of parameters of evaporative cooler such as air flow, a thickness of pads, and the effectiveness.

The DEC system revealed by Elmetenani et al. [11], Whaley et al. [12], and El-Awad [13] benefited from solar radiation. Performance of the evaporative air cooler for different operating months has simulated by using TRNSYS environment [11]. Integrated evaporative cooling systems with a heating process that utilizes the solar energy were studied [12], [13]. The integration systems have used for heating/cooling processes.

Previous studies comprised the developments and incorporated processes that carried out on DEC systems. The developments were implemented to increase the cooling performance by using various wetted pads and hybrid systems, while incorporated pro-

cesses with the solar energy were carried out by heat exchangers. However, it is evident that the literature has a lack of experimental verifies of solar radiation effect on evaporative air cooler effectiveness and evaporation area changing.
Therefore, the present study aims to evaluate the evaporative air cooler under new investigation with/without increasing the evaporation area and with/without the direct effect of the solar irradiance.

2. Experimental work

An experimental development was carried out on a conventional evaporative air cooler to enhance thermal process has. Experiments are relying on measurements of the thermal process. Hence, cooling effectiveness for the evaporative air cooler has evaluated. Measurements implemented during the months of March, April and May / 2017 in Baghdad city (latitude N33.3, longitude E44.4 and altitude 34 m). Parameters observed during the tests are inlet dry-bulb temperature $T_{db,i}$ and relative humidity RH_i, outlet dry-bulb temperature $T_{db,o}$ and relative humidity RH_o, outlet airspeed V_o and the solar irradiance I.
Fig. 1 depicts schematic of the conventional evaporative air cooler with main parts. The centrifugal fan pulls air through wetted pads located on three aspects of the unit. The conventional evaporative air cooler adopted in present work has external dimensions of (67 × 67 × 80) cm^3, and each evaporative pad has the dimensions of (58 × 43) cm^2 with wooden fiber padding, Fig. 2.

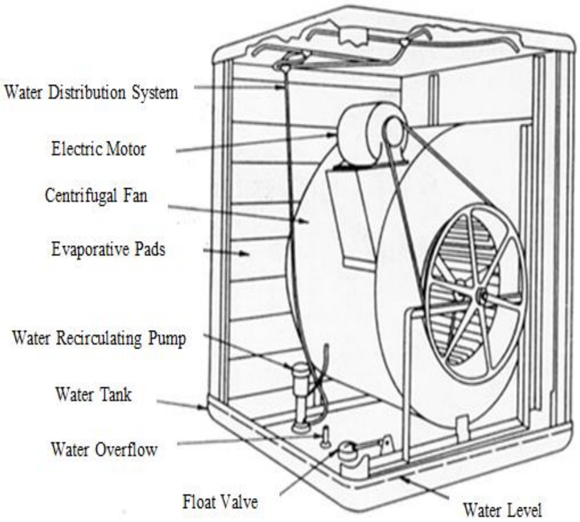

Fig. 1: Schematic of Conventional Evaporative Air Cooler [14].

In order to analyze the effectiveness of the evaporative air cooler, development has implemented to the conventional air cooler. Increasing area of evaporation is the main development in the present study. Instead of the side of the centrifugal fan; fourth evaporative pad was used. When the developed air cooler tested as a conventional cooler, this fourth pad changed by an alternative plate. Moreover, a propeller fan was installed at the top of the new unit to supply cold air through a hole of 40 cm in diameter, as shown in Fig. 2. In low humidity areas, such as present study, adding water vapor to the air will produce a realistic cooling. Therefore, two water recirculating pumps have used to dripping enough water for four evaporative pads.

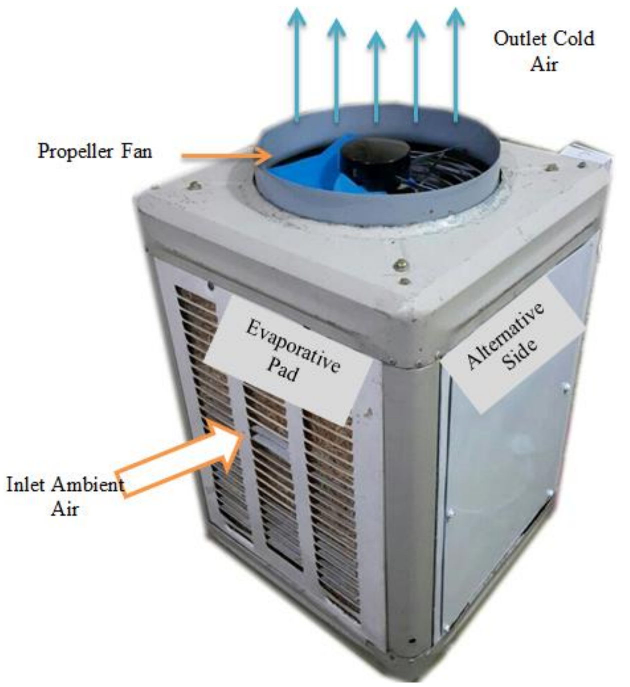

Fig. 2: Developed Evaporative Air Cooler.

The devices utilized in gathering measurements are (1) digital thermo-hygrometer to measure dry-bulb temperature and relative humidity of air, (2) anemometer to measure speed of air, (3) solar meter to measure the solar irradiance. The tests procedure of the evaporative air cooler includes four cases; developed / conventional evaporator in shade palace and developed / conventional evaporator under direct effect of the solar irradiance. For each case, inlet parameters to air cooler were measured before outlet parameters when steady state conditions approach. The evaporative padding was kept continuously saturated to obtain the steady conditions over test time. The systematic method for measurements included, experimental test start in shade place, and then the evaporative air cooler test under direct effect of the solar radiation. The solar radiation falling on two aspects (pads) in each test. The same procedure repeated for the conventional air cooler. The solar meter utilizes to measure the solar irradiance by setting it perpendicularly to the aspect that facing the sun. Therefore, the intensity of received irradiance is depending on the solar altitude angle at the hour and date of measurement. During the tests months, the cases of the evaporative air cooler with different ambient air temperatures have measured in the period of 12 pm to 1 pm, peak time, where ambient air temperatures range between 26.3°C to 44.7°C. Furthermore, the tests cases with different solar irradiance have measured in the period of 7 am to 1 pm, where the solar irradiance ranges between 268 W/m^2 to 636 W/m^2. The obtained measurements will be analyzed to compare the cooling efficiency for the conventional and the developed evaporators.

3. Performance analysis

Air conditioning process for an occupied space is relying on occupants comfort. The thermal comfort zone for the human being is a consequence of surrounding air temperature and water vapor that saturated the air. Wherefore, a computational program of psychrometric processes was utilized to analyze experimental outcomes. A psychrometric program has thermodynamic properties of moist air at steady pressure. The basic measured parameters are dry-bulb temperature T_{db} and relative humidity RH. Therefore, wet-bulb temperature T_{wb}, specific enthalpy h, specific volume v, and absolute humidity W can be determined. Wherefore, when dry and wet air temperatures identify, the cooling effectiveness ϵ can be estimated. The cooling effectiveness (or saturation efficiency) is the difference of dry air temperatures between inlet and outlet to the difference between dry and wet air temperatures of inlet air flow. The effectiveness of evaporative air cooler describes in equation (1).

$$\epsilon = \frac{T_{db,i} - T_{db,o}}{T_{db,i} - T_{wb,i}} \quad (1)$$

Where:
ϵ = cooling effectiveness (%)
$T_{db,i}$ = entering dry-bulb air temperature (°C)
$T_{db,o}$ = leaving dry-bulb air temperature (°C)
$T_{wb,i}$ = entering wet-bulb air temperature (°C)
Most DEC systems can lower the dry air temperature to the wet-bulb temperature. Others DEC systems can reduce the dry air temperature less than the wet-bulb temperature. The cooling effectiveness drops very little over time because of changes in surrounding air temperature and humidity ratio. The cooling effectiveness is the index used to assess the performance of DEC systems. In order to determine the evaporative cooler effectiveness; mean outlet air velocity utilizes is 4.3 m/s, which equates volumetric flow of outlet air of 0.54 m^3/s (32 CMM), and operational atmospheric pressure is 100.917 kPa (elevation 34m), which represents Baghdad location. Furthermore, the psychrometric program can be used to compute sensible and latent energy, which transfers during the cooling process. The current study focused on latent energy computed by the program. The latent energy of moisture added to air can be determined by equation (2) [15]. The latent energy is the index used to estimate the vaporization process within the evaporative air cooler. When the volumetric air flow is constant, latent energy depends on rising in absolute humidity.

$$\text{Latent Energy} = \dot{V} \times \rho \times h_{fg} \times (W_o - W_i) \quad (2)$$

Where:
$\dot{V}$ = volumetric flow of outlet air (m^3/s)
ρ = density of air at $T_{db,i}$ (kg/m^3)
h_{fg} = latent heat of vaporization at $T_{db,i}$ (kJ/kg)
W_o = absolute humidity at $T_{db,o}$ (g/kg dry air)
W_i = absolute humidity at $T_{db,i}$ (g/kg dry air)
Evaporative air coolers have valued for their reduced energy consumption in comparison to compression refrigeration systems. The cooling capacity of the direct evaporative air cooler has determined by equation (3). Discussions of the cooling effectiveness, latent energy and the energy savings for the developed evaporative air cooler are elaborate in the next section.

$$\dot{Q} = \dot{V} \times \rho \times C_p \times (T_{db,i} - T_{db,o}) \quad (3)$$

Where: $\dot{Q}$ = the cooling capacity (kW)
C_p = specific heat capacity of air at $T_{db,i}$ (kJ/kg.K)

4. Results and discussions

In this study, measurements and data analyzing were utilized to deduce outcomes. Measured dry-bulb and wet-bulb temperatures have examined at inlet and outlet air flow of the evaporative cooler. It is to highlight the cooling effectiveness that changes with dry-bulb temperatures and the solar irradiance. The change in latent energy with different dry-bulb temperatures and the solar irradiance have revealed. Furthermore, the uncertainty of measurements was achieved to improve the experiment.

4.1. Results of temperatures

Measurements of dry-bulb and wet-bulb temperatures at inlet/outlet air flow to/from the evaporative air cooler have shown in Figs. 3 and 4. Air temperatures elaborated for the cases of developed/conventional evaporative air cooler in sunny/shaded places. Figure 3 shows outlet dry-bulb temperatures behavior for different inlet dry-bulb temperatures. Figure 4 shows outlet wet-bulb temperatures behavior for different inlet wet-bulb temperatures. Outlet dry and wet air temperatures tend to rise for all cases when inlet dry-bulb and wet-bulb temperatures increase. Results of outlet dry and wet air temperatures of the evaporative air cooler in shade are lower than that in sunny places, as well temperatures of the developed air cooler are lower than that the conventional air cooler. High temperatures date back to the solar irradiance effect on inlet air. Results were demonstrated dry-bulb temperature drops by the range of 6-12°C, 3-11°C, 4.1-10.8°C, and 4-10°C for the cases of shaded developed, sunny developed, shaded conventional, and sunny conventional respectively. Simultaneously, wet-bulb temperature drops by 1-4°C, 0-3°C, 0.6-3.7°C, and 0.5-2.5°C for the same respectively cases. Consequently, outlet wet air temperatures drop less than the inlet, which means more cooling occurs when water evaporates.

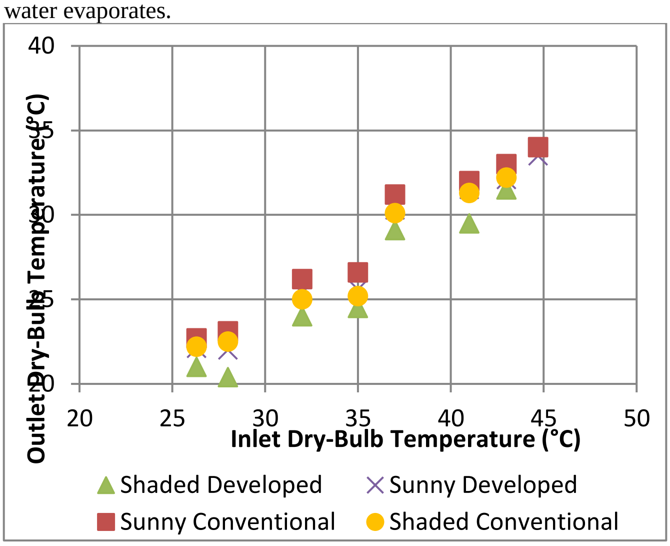

Fig. 3: Measured Dry-Bulb Air Temperatures for Outlet versus Inlet.

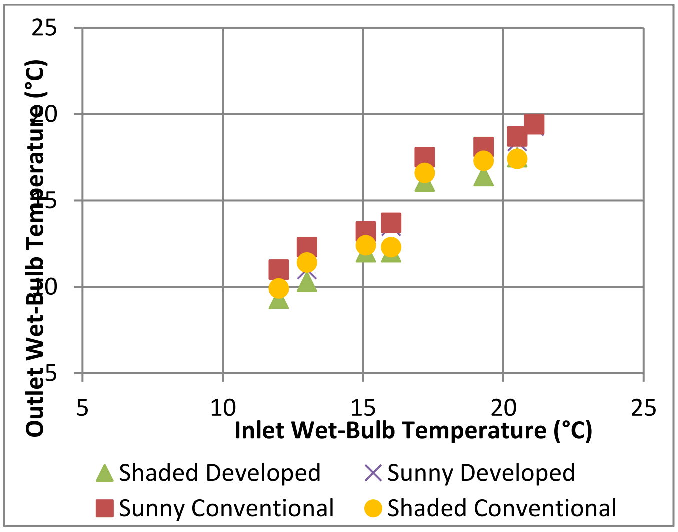

Fig. 4: Measured Wet-Bulb Air Temperatures for Outlet versus Inlet.

For the developed evaporative air cooler, average dry-bulb temperatures drop is 8.1°C and 10.3°C for sunny and shade places, respectively. Consequently, estimated cooling capacity is 5.28 kW and 6.72 kW for the sunny/shaded cases, respectively. In order to compare, for a specific zone, the power consumption of the developed evaporative air cooler with the identical vapor compression air conditioning unit. The power consumption of the vapor compression air conditioning unit to produce these cooling capacities are 2.4 kW and 3.0 kW in sunny and shade places respectively, compared with only 0.48 kW for the developed evaporative air cooler. Therefore, the energy savings of the developed evaporative cooler are 80% and 84% in sunny and shade places, respectively.

4.2. Results of the cooling effectiveness

Results of the cooling effectiveness are shown in Figs. 5, 6, and 7. The cooling effectiveness has elaborated for the cases of developed/conventional evaporative air cooler in sunny/shaded places. Figure 5 shows the cooling effectiveness behavior for different inlet dry-bulb temperatures and the mean solar incidence is 320 W/m^2. The cooling effectiveness tends to rise for all cases when inlet dry-bulb temperatures increase between 26.3°C to 44.7°C. These results are corresponding to the results obtained by Camargo et al. [6], which comments on that "more cooling is necessary to propitiate thermal comfort when the temperatures are higher". Significant results of the effectiveness revealed in Fig. 5. The effectiveness of developed air cooler in shade is higher than in sunny places, and the effectiveness of the sunny developed is higher than the sunny conventional. The results tendency deduced for the cooling effectiveness distribution shown in Fig. 5 with the coefficient of correlation R^2=0.83, 0.84, and 0.81 for the cases shaded developed, shaded conventional, and sunny conventional, respectively. An experimental relationship predicts the performance behavior for the case of the developed evaporator with direct solar effect, R^2=0.86, was obtained. Hence, a polynomial equation of an experimental relationship can describe in equation (4), which is capable of predicting the cooling effectiveness at any dry-bulb temperature input the evaporative cooler under the tests conditions.

$$\epsilon = -0.0422\left(T_{db,i}\right)^2 + 3.892\left(T_{db,i}\right) - 41.229 \qquad \text{For } T_{db,i} = 26.3°C \text{ to } 44.7°C \qquad (4)$$

In order to compare the cooling effectiveness results for different inlet dry-bulb temperatures, an average cooling effectiveness for all cases are shown in Fig. 6. The effectiveness of the developed air cooler in shade is higher than the sunny developed air cooler by 10% due to the effect of the solar irradiance. While in shade, the effectiveness of the developed air cooler is higher than the conventional air cooler by 8% due to the development of increasing the evaporation area. For direct solar assays, the effectiveness of the developed air cooler is higher than the conventional by about 4% due to the reduction in the speed of drawn air through the pads, which increases the liaison time between the air and the wetted padding then decreases outlet dry-bulb temperature. Hence, reducing the cooling effectiveness, when air flow speed increases, is corresponding to the results obtained by Camargo et al. [6]. The evaporative air cooler has tested in low relative humidity site, Baghdad. Therefore, the results of the cooling effectiveness shown in Figs. 5 and 6 obtained via experiments with inlet relative humidity in the range of 10 to 15 percent.

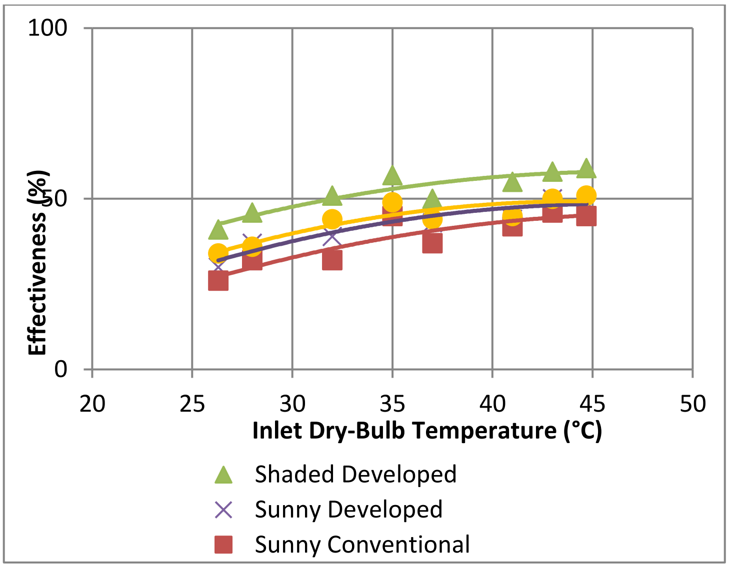

Fig. 5: The Cooling Effectiveness for Different Inlet Dry-Bulb Temperatures and Mean Solar Incidence I = 320 W/m^2.

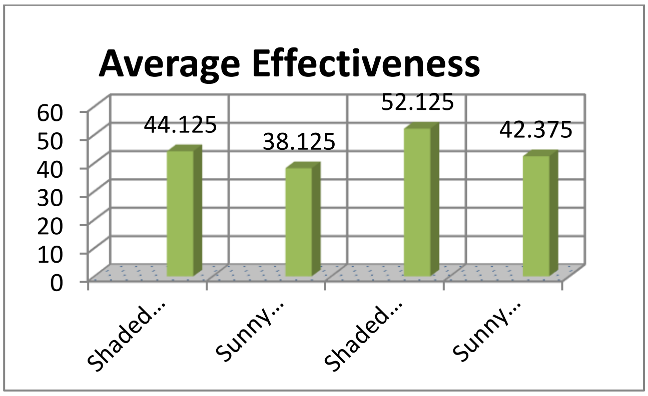

Fig. 6: Average Cooling Effectiveness.

Results of solar irradiance effect on the effectiveness of developed and conventional evaporative air cooler shown in Fig. 7. The results show the reduction in the cooling effectiveness when the solar irradiance increases between 268 W/m^2 to 636 W/m^2. The effectiveness of the developed air cooler is higher than the conventional due to lowering speed of the drawn air through the pads. Experimental relationships deduced for the cooling effectiveness behavior shown in Fig. 7 with R^2=0.83 and 0.89 for the developed and conventional air cooler, respectively. A polynomial equation for the developed evaporator can describe in equation (5), which is capable of predicting the cooling effectiveness for different solar irradiance incidence on the developed evaporator.

$$\epsilon = -[7 \times 10^{-5}(I)^2] + 0.0128(I) + 52.355 \qquad \text{For } I = 268 \text{ W/m}^2 \text{ to } 636 \text{ W/m}^2 \qquad (5)$$

The reason for reducing the cooling effectiveness dates back to lowering inlet dry-bulb and wet-bulb temperatures synchronized with the solar irradiance increases, as shown in Fig. 8. Measurements of the solar irradiance are depending on the solar altitude angle; subsequently, high irradiance has measured at the early time of the sunny day where the solar meter was adjusted perpendicularly to the evaporative pad surface. Hence, irradiance decreases when time increase due to the solar altitude angle increases. Simultaneously, surrounding dry-bulb and wet-bulb temperatures increase when time increases. Consequently, high cooling effectiveness obtained at low solar irradiance and vice versa.

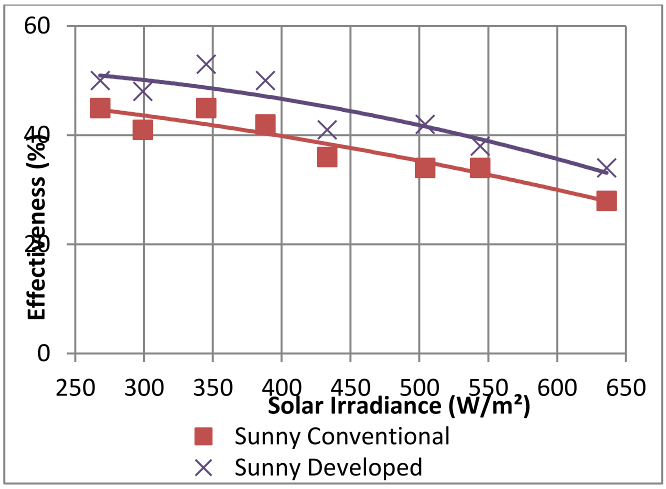

Fig. 7: Effect of the Solar Irradiance on the Cooling Effectiveness.

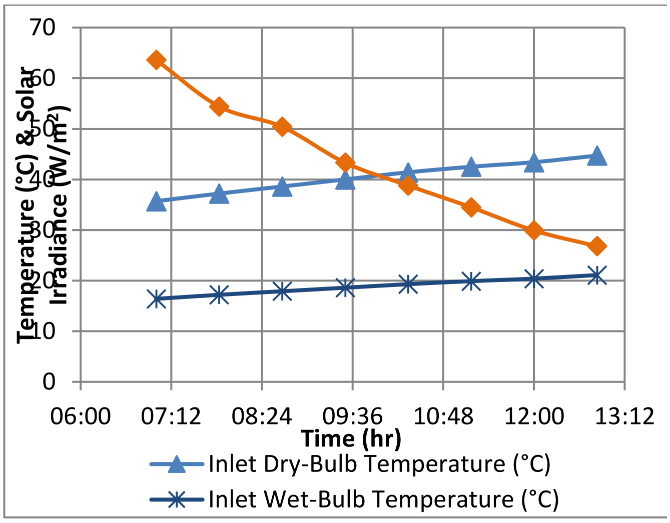

Fig. 8: Measurements of Air Temperature & Solar Irradiance versus Time.

4.3. Results of latent energy

Results of latent energy of evaporation process for different inlet dry-bulb temperature and solar irradiance are shown in Figs. 9 and 10. Results of latent energy elaborated for the cases of developed/conventional evaporative air cooler in sunny/shaded places. Figure 9 shows results of latent energy behavior for different inlet dry-bulb temperatures with the tendency of R^2=0.83, 0.71, 0.89, and 0.81 for the cases shaded developed, shaded conventional, sunny developed, and sunny conventional, respectively. The results tend to rise for all cases when inlet dry-bulb temperatures increase. Results of latent energy for the case of the developed evaporator are lower than the conventional evaporator, and for the case in shade place are lower than in a sunny place. Figure 10 shows the results of the solar irradiance effect on latent energy growing; the results of latent energy of the conventional evaporator, R^2=0.90, are higher than the developed evaporator, R^2=0.97. Volumetric air flow and absolute humidity difference, shown in equation (2), are the main parameters affecting the results of latent energy. To understand the latent energy tendency for different dry-bulb temperatures and solar irradiance; a steady volumetric air flow rate of 0.54 m^3/s is divided through three aspects for the conventional evaporator and four aspects for the developed evaporator. Therefore, the speed of drawn air through three evaporative pads is higher than that pulls through four pads, due to changing inlet area, which leads to transport more moisture; i.e. increasing humidity production carrying by air flow. Consequently, the cases of latent energy behave to matching the cases that shown in Fig. 3 due to temperature effect on the evaporation. For the results shown in Fig. 9, the solar irradiance received by two sides of the evaporator in the sunny case, which produces more humidity due to water evaporation by dry-bulb temperature and irradiance exposure. Hence, differences in absolute humidity of the sunny developed evaporator are higher than that in the shade, which reflects on the results of latent energy.

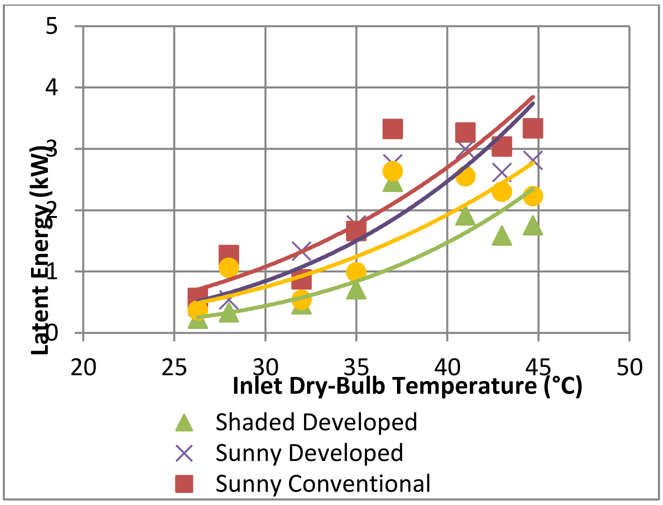

Fig. 9: Latent Energy for Different Inlet Dry-Bulb Temperatures and Mean Solar Incidence I = 320 W/m^2.

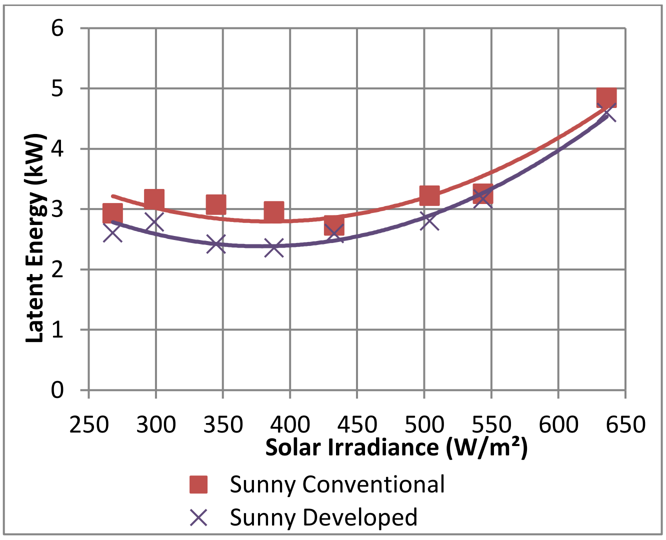

Fig. 10: Effect of the Solar Irradiance on Latent Energy.

4.4. Uncertainty in measurements

The purpose of uncertainty analysis for a set of measurements is to determine the errors and to improve the experiment. The most common way to describe the discrepancy between the measurement and the true value of the quantity shows in equation (6) [16].

$$\text{Measurement} = \text{true value} \pm \text{uncertainty} \quad (6)$$

Random and systematic errors are the common types associated with an uncertainty of measurements. Random errors can estimate through statistical analysis. Hence, statistical analysis achieved for parameters of air temperatures associated with the cooling effectiveness for the developed evaporative air cooler exposed to the sun. The outcome of error analysis for the selected parameters shows in Table 1, where x_i represents the individual measurement.

Table 1: Random Error Analysis in Measurements of Sunny Developed Evaporative Air Cooler

Statistical Expression	Equation	Air temperatures	Values (°C)
Measurements average,	$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$	Inlet dry-	35.875

$\bar{x}$		bulb	
		Outlet dry-bulb	27.813
		Inlet wet-bulb	16.775
The standard deviation, σ_{N-1}	$\sigma_{N-1} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$	Inlet dry-bulb	6.82
		Outlet dry-bulb	4.59
		Inlet wet-bulb	3.37
The standard error of the mean, S	$S = \frac{\sigma_{N-1}}{\sqrt{N}}$	Inlet dry-bulb	2.4
		Outlet dry-bulb	1.6
		Inlet wet-bulb	1.2

Air temperature and relative humidity are measured by digital thermo-hygrometer which has an accuracy of ±0.1°C and ±5% RH of readings, respectively. Air velocity and the solar irradiance measured by anemometers and solar meter which have an accuracy of ±5% and ±3% of readings, respectively. Therefore, the uncertainty of the instruments involved with experiments is determined. Relative uncertainty associated with measurements for sunny developed evaporative air cooler at $T_{db,i}$ = 37.2°C, RH_i = 10%, V = 4.3m/s, and I = 293W/m^2 are shown in Table 2.

Table 2: Uncertainty Values Associated with the Measured Values

Expression	Equation	Parameters	Uncertainty
Relative Uncertainty, RU	$RU = \left\lvert\frac{\text{Uncertainty}}{\text{Measured Quantity}}\right\rvert$	Air Temperature	0.27°C
		Relative Humidity	0.5%
		Air Velocity	1.2m/s
		Solar Irradiance	0.01W/m^2

5. Conclusions

An experimental study related to direct evaporative air cooler affected by the solar irradiance was carried out in Baghdad city. Increasing area of the evaporation implemented to the conventional air cooler. The cooling effectiveness of the developed/conventional evaporative air cooler in sunny/shaded places was analyzed. Moreover, the energy savings and latent energy analyzed, as well. The conclusions drawn from the results show that:

1) Analyzing measurements of wet air temperatures indicate that the cooling effectiveness obtained at low inlet relative humidity ranges between 10 to 15 percent.
2) The results demonstrate dry-bulb and wet-bulb temperatures drop in the range of 3-12°C and 0.5-4°C respectively for all cases. Hence, low wet-bulb temperatures produced from the evaporative cooler.
3) The cooling effectiveness, latent energy, and outlet air temperatures tend to rise for all cases when inlet dry-bulb temperatures increase between 26.3°C to 44.7°C. While the cooling effectiveness results decrease when the solar irradiance affects between 268 W/m^2 to 636 W/m^2.
4) The cooling effectiveness of the developed air cooler in shade is higher than that in sunny places with 10% due to the direct effect of solar irradiance. While the effectiveness of the developed evaporator is higher than the conventional by about 5% with irradiance effect, and the reason dates back to reducing the speed of the drawn air through the pads.
5) The energy savings of the developed evaporative air cooler are 80% and 84% in sunny and shade places, respectively, when compared to the identical vapor compression air conditioning unit.
6) Experimental relationships deduced for the case of the developed evaporator with direct solar effect. The relationships obtained indicate the behavior of the cooling effectiveness when dry-bulb temperatures and the solar irradiance changes.

Nomenclature

C_p: specific heat capacity (kJ/kg.K)
h: specific enthalpy (kJ/kg)
h_{fg}: latent heat of vaporization at $T_{db,i}$ (kJ/kg)
I: solar irradiance (W/m^2)
$\dot{Q}$: The cooling capacity (kW)
RH_i: entering relative humidity (%)
RH_o: leaving relative humidity (%)
$T_{db,i}$: entering dry-bulb air temperature (°C)
$T_{db,o}$: leaving dry-bulb air temperature (°C)
$T_{wb,i}$: entering wet-bulb air temperature (°C)
V_o: outlet air speed (m/s)
$\dot{V}$: Volumetric flow of outlet air (m^3/s)
v: specific volume (m^3/kg)
W_i: absolute humidity at $T_{db,i}$ (g/kg dry air)
W_o: absolute humidity at $T_{db,o}$ (g/kg dry air)
ρ: density of air at $T_{db,i}$ (kg/m^3)
ϵ: cooling effectiveness (%)

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