

Research Article

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Enhancement of air conditioning system using direct evaporative cooling: Experimental and theoretical investigation

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Abstract: Air conditioners (ACs) are more commonly used nowadays in residential and commercial buildings to achieve thermal comfort in the summer season. Due to the high outside temperature, condenser pressure was highest and ultimately resulted in high electricity consumption. One of the ways to reduce the energy consumption of AC systems and increase cooling capacity is by reducing air temperature entering the condenser by using the evaporative cooling principle. This article presents an experimental and theoretical investigation of improving the performance of the conventional air conditioning unit supported by a direct evaporative cooling system to increase the cooling capacity and reduce the consumption of power in hot and dry climates. A window-type AC unit was implemented in the experiment where the AC system is modulated to provide a wide range of various weather conditions. The results show that using evaporative cooling assist enhanced the system to overcome the many challenges by which the refrigeration capacity was increased in the range of 10–20%. Also, the results show a decrease in outlet temperature by 6–10°C, and the power consumption was reduced by about 3%. MATLAB program was used to analyze different data that were obtained. The input parameters for this program are the inlet conditions such as the weather conditions of the located city, namely the outdoor dry temperature and the outdoor relative humidity. The effectiveness and cooling capacity were calculated based on the frontal air velocity and the inlet air temperature. A comparison between the experimental and theoretical work

showed a good agreement, as the relative difference is less than 9%.

Keywords: air conditioning system, cooling pad, direct evaporative cooling, energy saving, hot climate, thermal performance

Nomenclature

A	area (m^2)
H	pad height (m)
W	pad width (m)
c_p	specific heat ($\text{kJ kg}^{-1} \text{K}^{-1}$)
\dot{m}_a	mass flow rate of the air (kg/s)
a_p	total surface area (m^2/m^3)
EER	energy efficiency ratio
AC	air conditioning system
DBT	dry bulb temperature
t_a	free air temperature
t_w	saturation temperature of the air
w_a	free air humidity ratio (kg_v/kg_a)
w_{sat}	saturation humidity ratio of air (kg_v/kg_a)
k_c	convective mass transfer coefficient ($\text{kg}/\text{m}^2 \text{ s}$)
h_c	convective heat transfer coefficient ($\text{kW}/\text{m}^2 \text{ }^\circ\text{C}$)
NBR	nitrile butadiene rubber

Greek symbols

ε	saturation efficiency
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Subscripts

sat	saturated
1	inlet
2	outlet
i	inlet condenser
o	outlet condenser

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1 Introduction

A nation's development and economic expansion are significantly influenced by its access to energy. Research is being done on ways to lower and save energy consumption due to the rising energy demand owing to the growing population. In recent years, the growing energy demand is the result of the promotion of electricity generated from renewable energy sources. In future energy scenarios, biomass will play an important role in the energy supply [1,2].

Due to adverse weather conditions, the development of infrastructure and advances in people's quality of life, air conditioners (ACs) are now often utilized in commercial and residential structures. HVAC systems use about 10% of the total energy used in affluent nations [3].

Since the air-cooled condenser temperature is directly related to the ambient air temperature, it follows that in Iraq, where the ambient air temperature in the summer continues to be very high, the condenser pressure and temperature increase dramatically, increasing the power consumption of the AC. The VCR cycle's cooling capability likewise decreases. These factors reduce the AC's efficiency. Geothermal heat sources, which are employed in building cooling systems and constitute an efficient mechanism for energy efficiency, are one of the ways to increase the operation of the AC. Because they utilize generally consistent ground or water temperatures and can consume up to 60% less energy than traditional refrigeration and air conditioning systems, geothermal heat pumps offer minimal running costs [4,5].

The alternative option is to lower the temperature of the air entering the condenser. This lowers the pressure ratio across the compressor, which lowers power consumption while increasing the cooling capacity and system-wide coefficient of performance (COP). Common methods to reduce the incoming air temperature include using an evaporative cooling device before the condenser coil. In this system, the wetted medium is sprayed with water, which cools the air traveling through it before it reaches the condenser [6].

Over the past two centuries, evaporative cooling has been used. The use of modern evaporative cooling, which has two main forms, direct and indirect, is used in air conditioning to improve performance; it began around the start of the twentieth century. One of the simplest and earliest evaporative cooling methods is the direct system, which is also one of the greenest because it does not produce any greenhouse gases or contribute to global warming [7,8].

The transformation of heat transfer to latent heat is the core concept of direct evaporative cooling (DEC). The

pad that a fan pushes air through is made of a porous or plastic mesh, the surface of which is continually wet by the spray or vertical drip of water from a hydraulic pump. The water absorbs the energy from the air and converts part of the sensible heat into latent heat by evaporating some of the water. As a result, the relative humidity increases while the temperature of the leaving air decreases. Evaporative cooling systems work extremely well in hot, dry climates, where their maximum cooling capacity can be experienced [9].

Figure 1 shows a schematic of the thermal process of the DEC on the psychometric chart.

In general, DEC involves drawing dry, hot air over a porous material that has been provided with water. As a result, water evaporation causes the air's moisture content to increase and decreases its temperature. When the air reaches the temperature of the wet bulb, it is entirely saturated and is the maximum cooling that can be accomplished [10,11].

Figure 2 depicts the energy changes in an air conditioning system without and with DEC. The solid line in the figure indicates how the dry bulb temperature (DBT) increases when air flows over the condenser, while the dotted line represents the refrigerant's phase shift. The air from the system of evaporative cooling gets increasingly humid as it flows over the pads. On the other hand, as the DBT falls, the air that passes over the wet pads is precooled. The graph of this adiabatic process depicts it as an angled line. Horizontal lines are used to represent the procedure. When the air reaches the condenser, it undergoes a sensible heat conversion after leaving the pads colder and more humid. The relationship between air velocity and heat transfer rate has already been demonstrated.

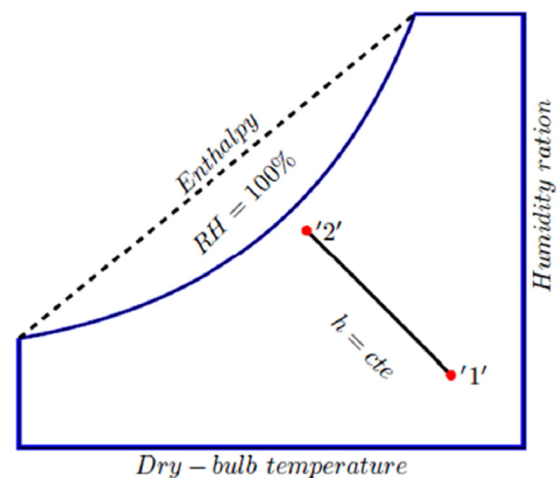


Figure 1: Psychometric chart of the DEC process [9].

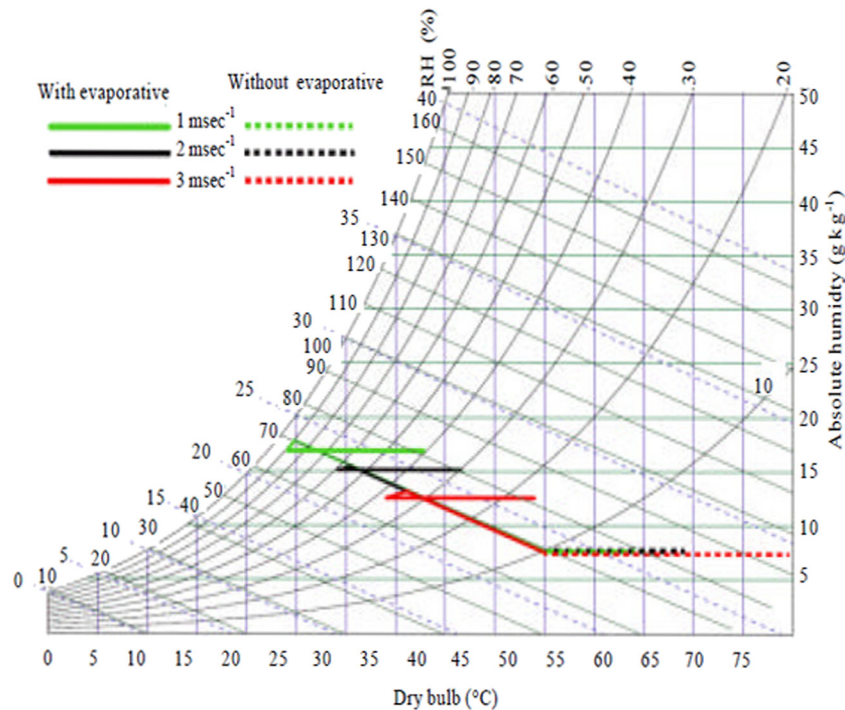


Figure 2: Air conditioning performance when velocity changes [12].

Large (3 m/s), moderate (2 m/s), and weak (1 m/s) air velocities were investigated as a result [12].

2 Recent developments

Numerous studies have demonstrated that evaporative cooling techniques enhance the efficiency of AC systems. The performance of vapor compression systems can be improved and energy consumption can be decreased, thanks to the research team's efforts to propose more practical strategies and techniques. The DEC performance was examined by Lakniziab et al. [13] when the highest temperature was above 45°C. According to the modeling results, the DEC may bring the feed-in air temperature down to 26.7°C from 44°C. By utilizing a cellulosic pad, Malli et al. [14] carried out an experiment on direct evaporating cooling. They discovered that as the frontal velocity and pad thickness increased, the pressure decreased and the rate of evaporation of water increased. On the other hand, by increasing the frontal velocity, the efficiency and variation of the humidity increased.

Hajidavalloo and Eghtedari [15] demonstrated that when an evaporative cooler was attached to an AC's condenser, the system could operate more efficiently, increasing its COP in a hot and dry environment by up to 50%, while consuming up to 20% less power. In order to evaluate the efficiency of heat and

mass transmission in a cooler of direct evaporative constructed with durable honeycomb layers as a pad material, Wu et al. [16] performed a numerical study. The results show that efficiency increases with the decreasing pad depth and average air velocity. Aglawe et al. [17] investigated how well an evaporative window AC performed throughout the sweltering summers. He discovered a 12% decrease on the evaporator side and a 20% fall in the condenser pressure. In comparison to a straightforward window AC, the system's performance coefficient was increased with the lowering of pressure throughout the entire cycle.

Evaporative cooling was combined with a number of additional techniques by Alhamdo et al. [18] in order to evaluate the efficiency of the air conditioning unit in the oppressive heat of Iraq. They experimented with several configurations of a water spray, a spraying nozzle, and a wet pad, over the condenser in addition to a heat exchanger between the condenser output and evaporator input. They found that an air-cooled condenser increased the performance coefficient by 102%, compared to a water-cooled condenser which gave a 44.5% improvement. The most productive technical combinations turned out to be the heat exchanger and wet pad. Mohammed et al. [19] created an AC for windows that employed evaporative cooling and had a 2 ton capacity with R-22 as the refrigerant for high-temperature conditions in Iraq. It was observed that the machine continued to operate at a low voltage of 185 V while using a low current of 0.12 A.

Martínez et al. [20] employed a 2.5 kW air conditioning unit utilizing an R-407C refrigerant with varied wet pad thicknesses. They used 50, 100, and 150 mm thick sheets. The most effective wet pad thickness, according to their research, was 100 mm. The performance coefficient started to decrease as the wet pad thickness increased beyond 100 mm. While the compressor work was lowered by 11.4%, the refrigeration impact increased by 1.8%.

A theoretical performance assessment of an evaporative air system utilizing a poplar fiber cooling medium in six distinct geometric configurations was carried out by Dhamneya et al. [21]. They found 97% to be the maximum saturation efficiency for the triangular cooling media design. A mathematical model was created by Sellami et al. [22] to assess the effectiveness of an evaporative air cooler that uses porous ceramic plates as the wet medium. The model was solved using the finite volume approach. The results show that a cooler with a drop in the temperature of 15°C below the ambient might provide the cooling needs in the dry area. For the direct evaporation cooling system, Camargo et al. [23] presented experimental findings and a mathematical model, which demonstrated that greater saturation efficiencies may be attained at low wind speeds and high DBTs.

A DEC was employed by Eidan et al. [12] to improve the efficiency of an air conditioning unit in a hot, dry environment. The COP of the AC increased in a range of 17.8–33.24% with a decrease in the electrical current from 0.12 to 0.16 A per each degree in temperature. The power generation of an R408C AC with a maximum cooling capacity of 2,500 W may be increased experimentally by employing a DEC to precool the condenser air, and Borirak [24] established a right cooling pad thickness that produced the highest overall COP. Using an available commercially porous cellulosic sheet with a depth of 10 mm, the best overall COP was generated, which increased by 10.6% relative to the device without a DEC when the external DBT was 45°C and the indoor wet bulb temperature was 24°C.

Jassim [25] employed a DEC on an air conditioning system. He observed a 73% improvement in the COP in an open environment, and a 16% decrease in power usage. The DEC method was used to adiabatically pre-cool the air, which decreased power use and boosted COP for the AC system. Overall, the efficiency increased by 20–25%. Shaheen and Hammadi [26] conducted a theoretical and experimental study for a hybrid system consisting of a conventional refrigeration unit and an evaporative air cooler. This research aims to improve the performance of the evaporative air cooler, reduce the moisture content of the air leaving the system, and produce fresh water. The effect of several parameters

such as the inlet temperature, evaporator temperature, relative humidity, and wetted pad thickness was studied Islam [27]. The results showed that the outlet temperature decreased by 1–3, the amount of freshwater also increased when the relative humidity increased, the coil temperature decreased, and the front air velocity decreased. The results also showed that the effectiveness increases with the increase in the thickness of the pad by pre-cooling the air before it came in contact with the condenser surface.

Wang et al. [28] used the evaporative cooling approach in an AC with an 11 kW condenser capacity. He saw that the evaporator's performance coefficient increased by 18% as a result of the saturation temperature being lowered and the mass flow rate being raised. It was found that 33.1°C is the optimum temperature for the most evaporative cooling effect in American climate conditions. Hajidavalloo [29] used cooling mats for evaporation, which may inject water on both sides of the window unit to chill the air entering the condenser. When compared to a window AC without an evaporative cooling pad, they found that the latter consumed around 16% less power and had a 55% better COP.

A condenser with an evaporative cooling system was explored by Sarntichartsak and Sirichai [30] in an inverter AC. With three distinct temperature scales and a constant ambient temperature, they tested the system with a variety of water spray rates and frequencies. As a consequence, COP might increase by up to 35% at higher frequencies of 80–90 Hz and lower water spray rates of 100 L/h. This study's goal was to theoretically and empirically examine how well air-cooled AC function thermally in the environment of Iraq, in addition to enhancing energy efficiency and raising COP.

Hammadi and Japer [31] developed a mathematical model for a DEC system based on the equations of heat and mass transfer. A number of hypotheses were put in place to simplify the proposed mathematical model: a full wet pillow was taken into consideration, the thermal properties of water and air were fixed, as well as the heat transfer coefficient and mass were constant. One of the most significant findings was the fact that effectiveness decreased with increasing airflow rate, the ideal wet pad thickness was 30 cm, and when a hybrid system was employed, the time steady state for air temperature reduced.

This study involves both practical and theoretical research on the use of direct evaporative cooling to enhance the efficiency of vapor compression systems under adverse weather conditions, in addition to boosting the energy saving ratio, cooling power, and AC system efficacy.

3 Experimental system

3.1 Experimental rig setup

The experimental setup involves a window-type AC unit with a cooling capacity of 2 ton, a climate duct with dimensions 2 m length \times 0.32 m width \times 0.35 m height made of 0.001 m galvanized iron, a centrifugal fan, and an axial fan installed at the entrance and exit of the duct, respectively, to obtain the required speed for the air entering the duct, and DEC unit which consists of the following:

Cooling pad. A cooling pad with dimensions of 0.35 m height, 0.32 m width, and 0.04 m thickness was made from honeycomb paper, as shown in Figure 3.

Water sump. It was made from galvanized iron with dimensions 0.7 m in length, 0.25 m in width, and 0.3 m in height.

Water pump. It is a centrifugal pump of 20 W and is connected to a plastic tube that has holes that allow for water to drip on the cooling pads.

High-temperature, unsaturated air was forced through a cooling pad that was evenly water impregnated. The temperature of the exit air decreased as a result of the water evaporating as it absorbs heat from the air. The intended location might receive this cold air transmission.



Figure 3: Honeycomb paper cooling pad.

A K-type standard thermocouple was used for measuring temperatures in the range of -150 to 400°C . In this experiment, the key variables including relative humidity, air speed, and temperature were investigated. Figures 4 and 5, respectively, depict the experimental rig's schematic diagram and pictorial view.

3.2 Experimental procedures

For a comparative investigation of their cooling capabilities, the standard AC systems without and with DEC were put to the test. The testing was done at 30 – 55°C , which is what occupational temperatures are. The AC systems without an evaporative cooled condenser were turned on to begin the experiment. Tests began in the summer when it was over 40°C . After the system had been running for an hour, test measures were done to make sure it was running steadily. In each experiment, a total of 18 readings were taken and measurements were recorded every 10 min. Each test took approximately 2 h. It was conducted at three different speeds (1, 2, and 3 m/s and each reading was taken under different weather conditions (morning, noon, and night).

The first experiment was conducted to simulate weather conditions, where a duct was installed on an iron structure and isolated with 10 cm of nitrile butadiene rubber. In order to reduce the heat released to the outside environment, we then measured the temperature of the air and humidity at the entry and exit of the duct. The second experiment was conducted to evaluate the performance of the DEC system: the evaporative cooling system was added to the system and then

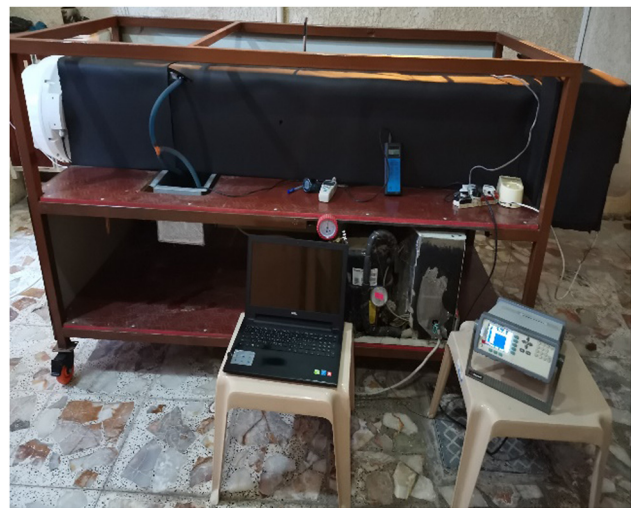
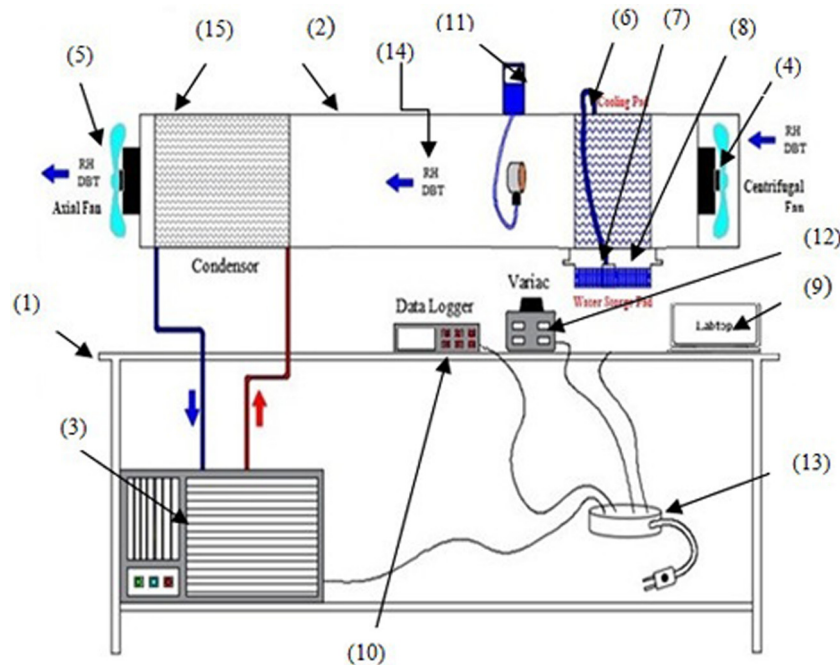


Figure 4: Pictorial view of the DEC system.



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|--|-------------------------------|
| (1) An Iron Structure. | (2) Climate Duct. |
| (3) Window Air Condition. | (4) Centrifugal fans. |
| (5) Axial fan. | (6) Cellulose Pad. |
| (7) Water Circulating Pump. | (8) Basin to collect water |
| (9) Lap Top. | (10) Temperature Data Logger. |
| (11) Digital Anemometer. | (12) Variac. |
| (13) Water Circulating Pump Switch | (14) DBT and RH Meters. |
| (15) Condenser installed at the end of the lower duct. | |

Figure 5: Schematic diagram of the DEC system.

the temperature and humidity of the air at the entry and exit of the duct and the pad exit were measured by using a T/H meter.

4 Theoretical model and methodology

Sensible heat is transformed into latent heat in a DEC, which operates on this principle. By coming into direct contact with warm, dry air and a water film that has passed through an evaporative medium, this humidification process is accomplished. The pads that make up this

evaporative medium provide a very broad contact surface area. One of the most common types of pads is the honey-comb cellulose pad. The following presumptions are presented [32] in order to define energy balance and the mass between the water film and air within the evaporative pad:

- 1) A very thin water film layer and saturated air are in balance.
- 2) The Lewis number equals 1.
- 3) Both mass and heat transport occur steadily and in a single dimension.
- 4) The process of humidification is adiabatic.
- 5) The pad's surface area is completely and consistently moist.
- 6) The characteristics of air and water are constant.
- 7) There is very little heat transmission to the environment.

4.1 The mass balance of the combination of air and water in the x direction

The rate of water evaporation (quantity of water consumed) ($d\dot{m}_w$) to air through the pad element, as determined by Fick's law, is expressed as follows [30]:

$$d\dot{m}_w = k_c(w_{\text{sat}} - w_a) \times dA. \quad (1)$$

According to the packing pad arrangement, the air and sprayed water film's elemental surface area is calculated as follows (Figure 6):

$$dA = H \times W \times dx \times ap, \quad (2)$$

$$A = H \times W \times X \times ap. \quad (3)$$

By substituting equation (2) into equation (1), we obtain

$$\dot{m}_a dw_a = k_c(w_{\text{sat}} - w_a) \times H \times W \times dx \times ap. \quad (4)$$

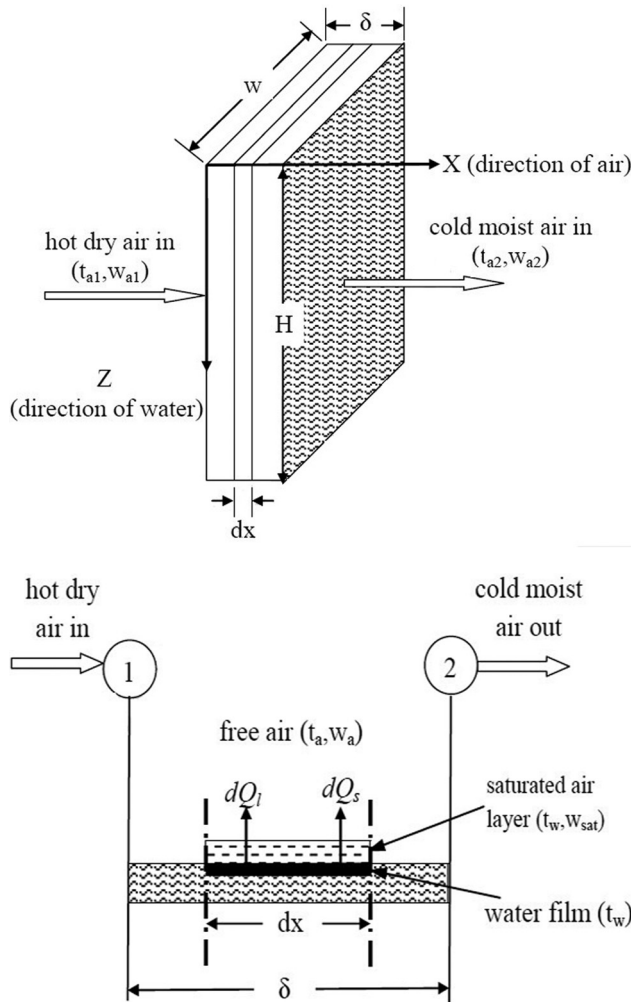


Figure 6: Packing pad and differential element schematic diagram [32].

Using boundary conditions from Figure 5, equation (4) is integrated as follows:

$$\frac{w_{a2} - w_{a1}}{w_{\text{sat}} - w_{a1}} = 1 - e^{-\frac{k_c \times A}{\dot{m}_a}}. \quad (5)$$

A similar introduction to the air/water mixture's energy balance in the x direction is given as follows:

$$\dot{m}_a C_{pm} dt_a = h_c(t_a - t_w)HWd_x ap. \quad (6)$$

By integration of equation (6), we obtain

$$\frac{t_{a2} - t_{a1}}{t_w - t_{a1}} = 1 - e^{-\frac{h_c \times A}{C_{pm} \times \dot{m}_a}}. \quad (7)$$

The saturation effectiveness (ϵ_{sat}) is expressed as follows:

$$\epsilon_{\text{sat}} = \frac{t_{a2} - t_{a1}}{t_w - t_{a1}}. \quad (8)$$

The moist air has a wet bulb temperature as follows:

$$T_w = 2.265 \times (1.97 + 4.3 \times T_{ai} + 10,000 \times W_i)^{0.5} - 14.85. \quad (9)$$

The wet air's saturation pressure is defined as follows [32]:

$$P_s = e^{\left(\frac{25.317 - 5,144}{T_w + 273}\right)}. \quad (10)$$

The saturated humidity ratio of wet air is calculated by the following equations :

$$W_s = 0.622 \times \frac{P_s}{P_b - P_s}, \quad (11)$$

$$T_{ao} = T_{ai} + (T_{ww} - T_{ai}) \times \left(1 - e^{-\frac{h_c \times A}{\dot{m} \times c}}\right), \quad (12)$$

$$W_o = W_i + (W_s - W_i) \times \left(1 - e^{-\frac{h_m \times A}{\dot{m}}}\right). \quad (13)$$

The program code was written in MATLAB for extracting the necessary thermodynamic properties of humid air. The input parameters for this program are the effectiveness saturation and the inlet conditions which are the weather conditions of the located city, namely the outdoor dry temperature and the outdoor relative humidity. The effectiveness was calculated based on the pad thickness and the frontal air velocity.

5 Results and discussion

The thermal performance of a condenser with evaporative cooling is studied using a variety of variables and parameters,

such as the ambient relative humidity, ambient temperature, and air velocity, where for each DBT, there is a corresponding reachable relative humidity. All of the aforementioned factors are taken into account when comparing the efficiency of an air conditioning system without and with evaporative cooling in order to assess system features and energy savings. Since it is scientifically established that the amount of heat and mass transfer is directly proportional to the air velocity in addition to the overall performance and energy consumption, the air velocity has a significant impact on DEC. As a result, when the air velocity is low, evaporative cooler efficacy and energy efficiency ratio both increase. It is clear that a lower velocity of 1 m/s is more effective.

Figure 7 shows the effect of the frontal velocity on the cooling capacity; the cooling capacity increases with increasing the frontal velocity. Moreover, the airflow increases with increasing frontal velocity, which is proportional to the cooling capacity of the pad cooling. The maximum value of the cooling capacity is 2.7 kW and is obtained at a frontal velocity of 3 m/s.

Figure 8 shows that using DEC lowers the compressor's pressure drop due to the air's lower input temperature at the condenser's entrance. Low air velocity causes the decrease in the pressure drop, increasing the effectiveness of evaporative cooling.

Figure 9 shows the influence of the condenser inlet air temperature on the energy efficiency ratio (EER). When the condensing temperature decreases, the refrigeration effect would be increased, which overcomes the increase in consumption power; therefore, the EER would be improved.

Figures 10–12 present the comparison between the experimental and theoretical relationship of the effectiveness and velocity of the inlet air. The figures show the variation of effectiveness with the inlet velocity of air at one value of time. It is noted that the effectiveness decreases

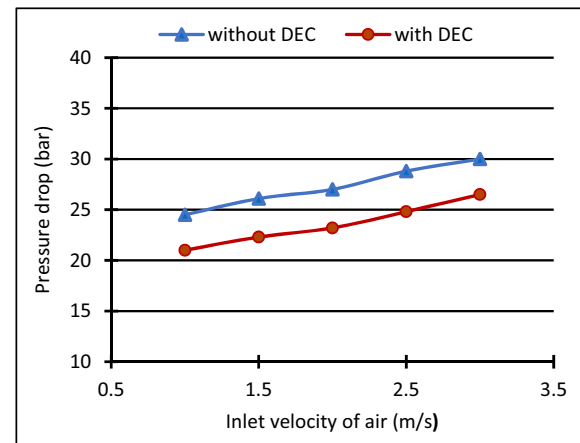


Figure 8: The effect of the frontal velocity on the pressure drop.

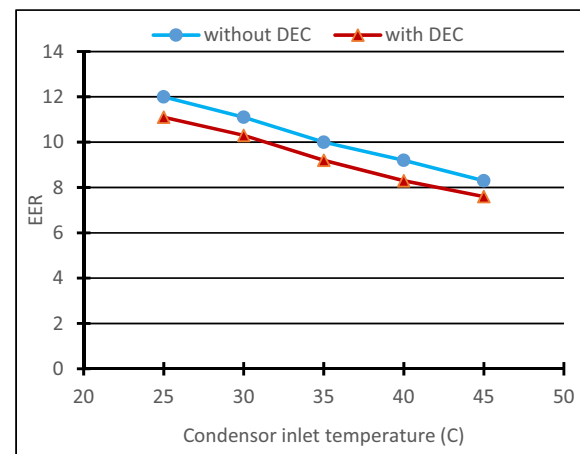


Figure 9: The effect of the condenser inlet temperature on the EER.

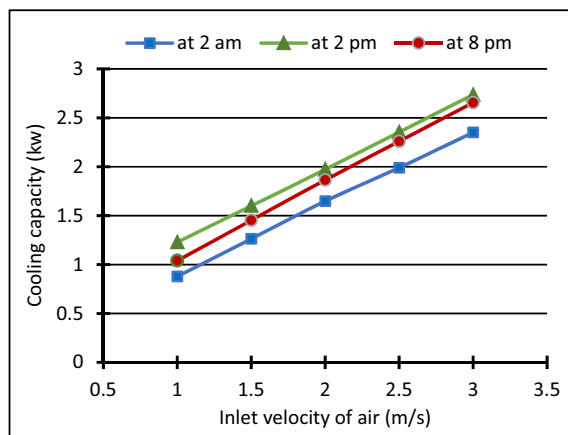


Figure 7: The effect of the frontal velocity on the cooling capacity.

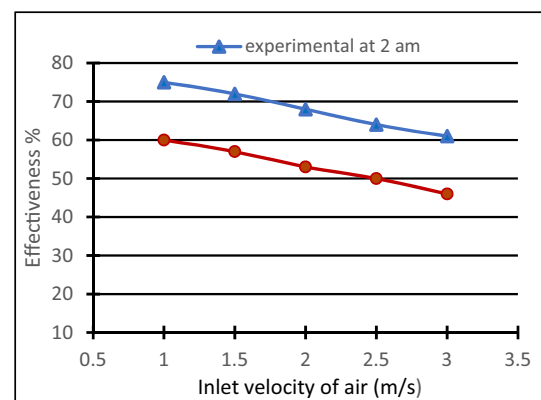


Figure 10: Comparison between the experimental and theoretical effectiveness at 2 a.m.

while increasing the inlet velocity because the decrease in the outlet air temperature decreases with the increase in

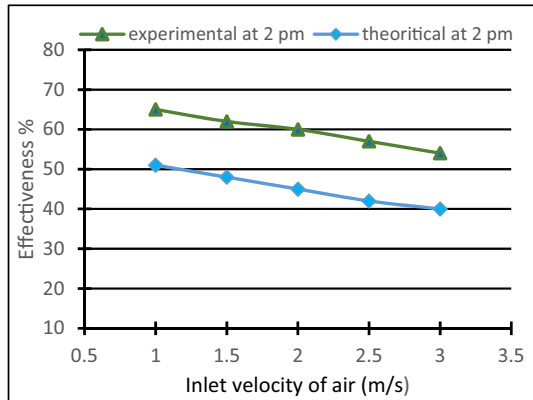


Figure 11: Comparison between the experimental and theoretical effectiveness at 2 p.m.

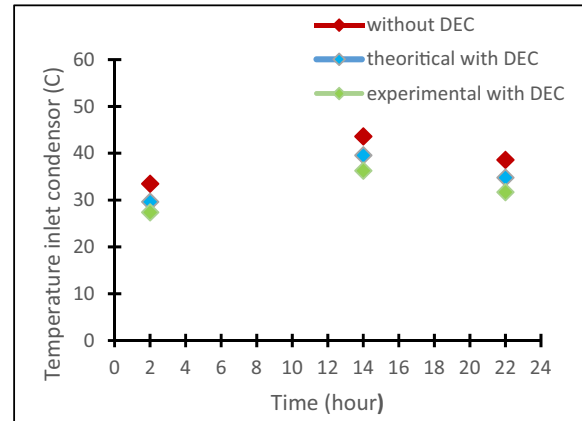


Figure 14: The effect of frontal velocity on effectiveness at $u = 2$ m/s.

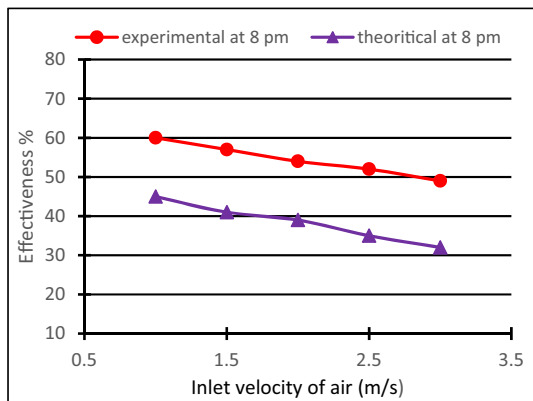


Figure 12: Comparison between the experimental and theoretical effectiveness at 8 p.m.

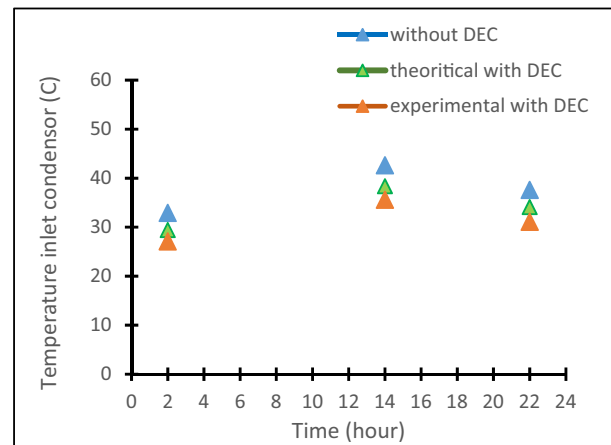


Figure 15: The effect of frontal velocity on effectiveness at $u = 3$ m/s.

velocity of the inlet air. The maximum effectiveness of 0.75 is found at 1 m/s and 2 a.m.

Figures 13–15 show the comparison between the temperature of the air entrance to the condenser before

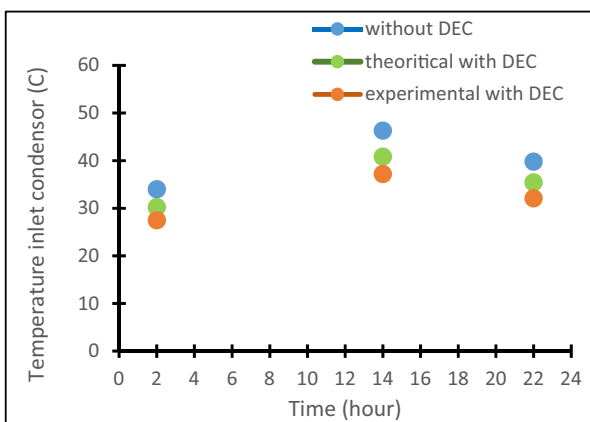


Figure 13: The effect of frontal velocity on effectiveness at $u = 1$ m/s.

adding DEC to the system and between the experimental and theoretical results of the temperature of air entrance to the condenser after adding DEC, which gives the variation of the outlet temperature with time. It is noticed that the temperature at the start of the day is minimum, then increases gradually to a maximum temperature between 12 and 15 h, and then decreases at the close of the day.

6 Conclusion

This research presented an experimental and theoretical study to use the DEC to enhance the performance of AC system and analyze the performance of an air conditioning unit by using DEC. The experimental setup is fabricated by using a window-type commercial AC system where the AC system is modulated to provide a wide range of various conditions. The results show that using DEC could

significantly enhance the COP, increase cooling capacity, and decrease power consumption. The experiment includes a wide range of temperature and humidity conditions in all running conditions. The precooling that occurs in the condenser leads to an increase in the liquid mass flow rate and also an increase in refrigeration capacity in the range of 10–20%. Also, the experimental results show that the electricity demand in the compressor is reduced for each air temperature degree reduction associated with an air velocity. The system which is enhanced by DEC is recommended in extremely hot climates.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Most datasets generated and analyzed in this study are present in this manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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