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Effect of Enhanced Evaporative Cooling on the Performance of Air-Conditioning in Severe Hot Weather

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Abstract: In this research, a study to use direct evaporative cooling supported by a heat exchanger to enhance the performance of conventional air conditioning unit experimentally is presented. Window type air-conditioner unit is implemented in the experiment where the A/C system is modulated to provide a wide range of various weather conditions. The proposed setup simulates severe hot weather condition where the temperature reaches up to 55°C. Several tests are conducted in this investigation and the study addresses four different challenges, namely, COP, cooling capacity, energy saving and the compressor auto-shutdown in very high weather temperature. The experimental results show that using evaporative cooling assist can significantly enhance the system to overcome the previous challenges. The refrigeration capacity is increased in the range of 10-30% whereas the electric demand in a compressor is reduced by 0.12-0.2 for each air temperature degree reduction (for one ton of refrigeration). The air-conditioning unit can run even with the voltage drop of 170 V instead of 220 V which cannot be performed in conventional air condenser.

Key words: Evaporation cooling, AC system, hot climate, COP, compressor, Iraq

INTRODUCTION

Currently, the most efficient air conditioning system for residential units is the vapor compression cycle where it is widely used in very hot weather and high humidity air content region. However, the challenge represented by high energy consumption in such air-conditioning systems is still the subject of ongoing studies. It is reported that approximately 30% of the global total energy consumption is used for air-conditioning applications (Islam *et al*., 2015). Moreover, using ACMV (Air Conditioning and Mechanical Ventilation) system in domestic buildings costs more than 65% of energy consumption bills (Hughes *et al*., 2014). It is reported that the entire world energy consumption in 2016 increased about 6% with $35,685\times10^6$ metric tons of carbon components emission Ibrahim *et al*. (2017). Hence, entire world energy consumption is expected to reach 2.7×10^8 GWh in 2020 with $48,800\times10^6$ metric tons of carbon components emission. It is believed that, the harmful gases emission and energy consumption challenge is inevitable in the near future (Anonymous, 2013). Many researchers have been working on presenting more effective approaches and methods to enhance the performance of vapor compression systems and reduce the energy consumption (Vakiloroaya *et al*., 2014). Hajidavalloo (2007) conducted an experimental study to enhance cooling capacity and energy saving using direct evaporative cooling of a condenser with and without pads. Nasr and Hassan (2009) developed a simple theoretical model to an evaporative-cooled condenser in a small size refrigeration system. Yau and Pean (2014) conducted an experimental study on the performance of split unit A/C and they concluded that each 1°C increment in DBT implies a reduction of 2% in both COP and refrigeration effect. Another experimental study was presented by Wang *et al*. (2014) to compare the effect of using direct evaporation and conventional air cooling condenser. Sharma and Singh (2014) implemented the wastewater of water-cooler in evaporative cooling in window A/C system to reduce the power consumption and humidity in very hot weather condition. Martineza *et al*. (2016) investigated the use of different pads thicknesses as pre-cooling mean at the condenser unit in a conventional air conditioning system to improve power consumption. An improvement to the COP in an evaporate-cooled air-conditioning unit was investigated experimentally and numerically by Islam *et al*. (2015). Ibrahim *et al*. (2017) conducted an experimental study o use the condensate water in split A/C system to reduce the energy consumption and improve the performance. For a thorough review about performance

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improvement of vapor compression cooling systems using an evaporative condenser, the reader can refer to (2016). For most vapor compression systems there is a designated limit of operating voltage (minimum operating voltage threshold) which is designed by the manufacturer where the compressor shuts down when the voltage drops below the threshold during the excessive increase in weather temperature. This has contributed to serious problems in some Middle East countries for instance in Iraq where the temperature significantly increases during summer and reaches up to 52°C (Hachim *et al*., 2017). Thus, during peak time and because of the weakness of national electric power network, the voltage drops below minimum operating voltage threshold and hence, the compressor shuts down which exacerbates the suffering since, the air conditioning systems become useless. In the most recent research an enhancement of air conditioning unit was gained using direct cooling evaporative method (Eidan *et al*., 2017). This research presents a study of using direct evaporative cooling supported by the heat exchanger to enhance the performance of the vapor compression systems in severe weather condition in addition to improving energy saving and increasing COP. Also, the problem of minimum operating voltage threshold is addressed.

MATERIALS AND METHODS

Experimental rig setup and uncertainty: In this research, a window type air conditioner unit is used to conduct experimental tests. R22 is used as working fluid along with direct and enhanced evaporative cooling system. The main parameters, temperature, air speed and relative humidity are kept controlled by the system. Figure 1 shows the details of the experimental rig.

A 7 kW cooling capacity refrigeration unit is used in this research with technical specification listed in Table 1. The system pipes are insulated to reduce ambient heat

Table 1: Design specifications of the window A/C system

Specifications	Values
Cooling capacity at indoor design condition DBT 25°C and RH 50%, outdoor design condition DBT 40°C and RH 50%	7 kW
Electric power used by hermetic reciprocating compressor and fan	2.464
Rated current	11.2 A
Refrigerant (R22) charge	1.8 Kg
Expansion device, capillary tube with diameter	2mm
Evaporator	48 cm×61 cm×2 rows with 3.15 FPCM
Condenser	63.5 cm×76.2 cm×2 rows with 3.15 FPCM

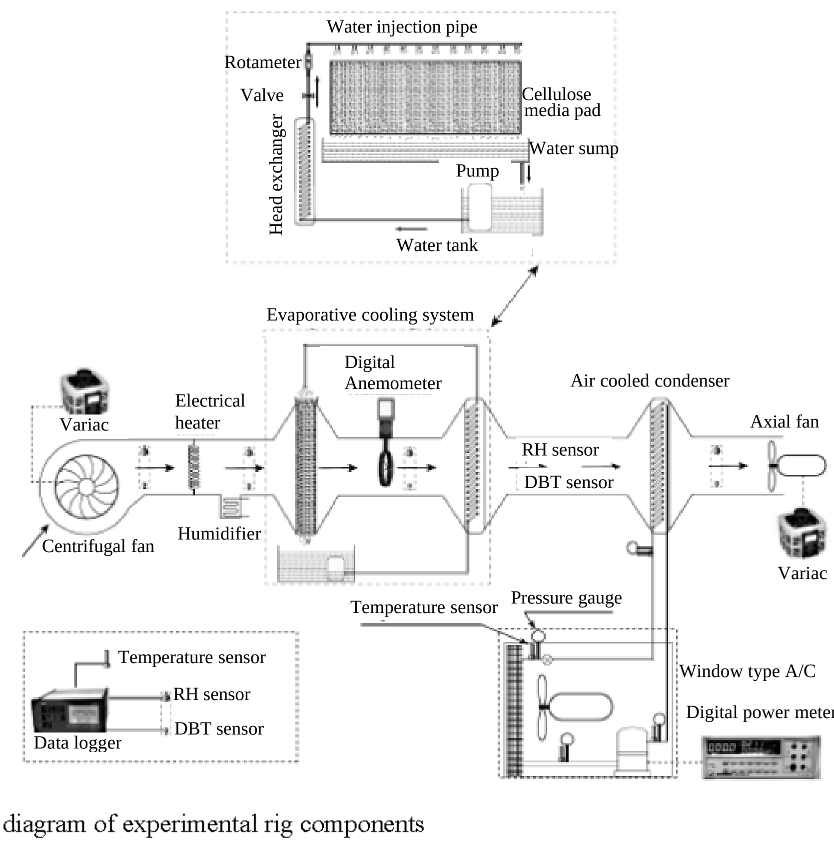

Fig. 1: Schematic diagram of experimental rig components

Table 2: Uncertainty for experimental results with hybrid system

Specification	Mean values	Total uncertainty values	Total uncertainty (%)
Measured parameters			
Ambient DBT (°C)	45	±0.41	±0.91
Ambient relative humidity (%)	10	±0.5	±1.6
Compressor exit temperature (°C)	83	±0.8	±1.6
Condenser exit temperature (°C)	40	±0.38	±0.74
Capillary tube exit temperature (°C)	-6	±0.07	±0.12
Evaporator exit temperature (°C)	0.3	±0.01	±0.09
Electric current (A)	9.8	±0.09	±1.3
Compressor exit pressure, bar	19.85	±0.285	±0.79
Condenser exit pressure, bar	19.43	±0.282	±0.781
Capillary exit pressure, bar	4.1	±0.097	±0.232
Evaporator exit pressure, bar	4.01	±0.095	±0.296
Water circulation rat (l/min)	4.5	±0.781	±2.5
Air face velocity (m/sec)	2	±0.12	±2.56
Calculated parameters			
Refrigeration effect (kJ/kg)	158	±1.2	±4.6
Refrigerant mass flow rate (kg/sec)	0.0641	±0.321	±2.1
Cooling capacity (kW)	10.127	±0.627	±3.4
Compressor work (kJ/kg)	2.688	±0.312	±2.43
Coefficient of Performance (COP)	3.6744	±0.21	±6.1

loss. Three different fan speeds are considered, namely (1, 2 and 3 m/sec) such that the condenser and evaporator have the same speed in all runs and hence, each experimental run simulates the real performance of residential air conditioning unit (ASHRAE, 2009; Hajidavalloo, 2007). The water circulation process starts from a water pump immersed in the water tank, the water pump discharges water firstly to heat exchanger before the condenser where it has the same condenser face area with a single row of copper tube (16 mm OD, 3.15 FPCM and 0.5 mm of thickness). When the water leaves the heat exchanger it flows through a disturbing panel with 13 spraying holes with 2 cm apart located above the cooling pad to provide a continuous water dropping and keeps the pad saturated. When the pad is fully saturated, the excess water is to be recirculated back by means of the water pump as shown in Fig. 1. The sawdust has a dry weight of 20.4 kg/m^3 and a wet weight of 49.4 kg/m^3 and its porosity is 84.5% for the whole saturated medium. The porosity of such medium can be measured by calculating the volume difference before and after immersing the medium in filled water tank (Chenguang and Nnanna, 2012).

T-type thermocouple probes are inserted before and after each system component to measure the refrigerant temperature. A digital data logger is used to record and display the measured temperatures. The thermocouples detect the temperature in the range of -100-400°C and it is pre-calibrated by the manufacturer in the accuracy of ±0.2%. Pressure gauges are installed to monitor the refrigerant pressure before each component in the refrigeration cycle. The air enters the system by a variable speed centrifugal fan and flows through an electric heater which is controlled by a digital switch setting device for various temperature ranges. The digital anemometer with a range of 1.5-34.5 m/sec is used where its accuracy is ±1.0% of reading and resolution of 0.01 m/sec. The relative humidity of the air at each measuring point is monitored using the Resistance Temperature Detector Sensors (RTD) where sensors are connected to humidity meter. The working range for the relative humidity sensors is 0-100% with an accuracy of ±5%. The water flow rate through the evaporative cooling (pads) is controlled manually and a rotameter is used to measure the flow rate. A digital AC power meter is used to measure and display voltage, current and power usage with an accuracy of ±0.1%. For each experiment run, the reproducibility is ensured by repeating the experiment several times under same conditions till the very close result is obtained. Each experiment run is performed for 90 min period as follows:

Switch the heater and fan on with predetermined temperature, relative humidity and fan speed and keep the system running for 30 min to simulate the weather condition accurately. Switch the A/C system on for another 30 min to ensure the steady state conditions.

Start recording the resulted data (temperature, relative humidity and pressure) where this process continues for another 30 min with a time interval of 30 sec for each record.

The effect of uncertainty for the entire set-up is an accumulation of the effect of the uncertainties for each element used in the set-up. Taylor (1997) method is used in this research to combine uncertainties for all elements. The main inherited and calculated uncertainties in this work are summarized in Table 2. The error can be obtained by using the Root-Sum-Squares (RSS) uncertainty method Taylor (1997) as follows:

$$U_{RSS} = \sqrt{\sum_{i=1}^{i=n} \left(\frac{\partial R}{\partial X_i} \Delta X_i \right)^2} \quad (1)$$

where X_i represents the uncertainty of the variable X_i in the objective function R.

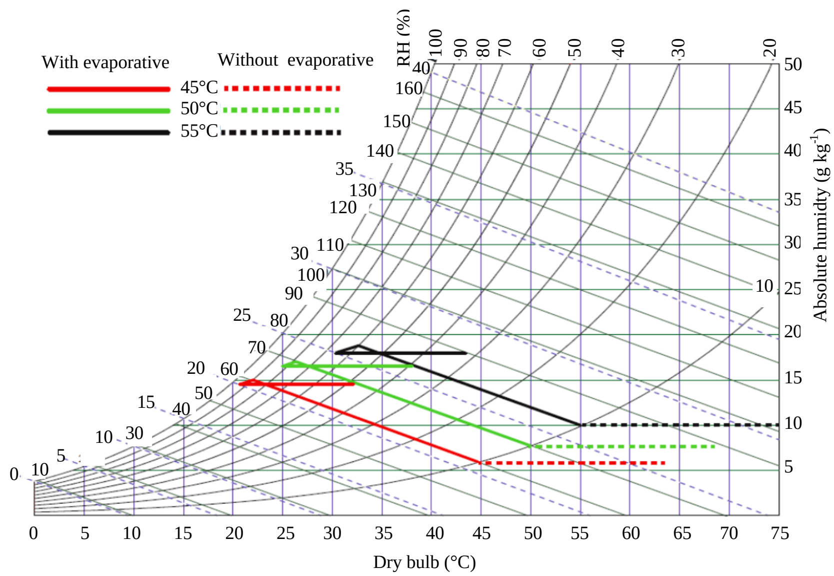

Fig. 2: The effect of DBT on the performance of A/C without and with/with HE evaporative cooling

RESULTS AND DISCUSSION

Many factors and parameters play crucial roles in the study of the thermal performance of a condenser with evaporative cooling. In this study the following parameters are considered:

The velocities of the air are 1, 2 and 3 m/sec. Ambient temperatures are 35, 40, 45, 50 and 55°C. Ambient relative humidity is 10, 20, 30, 40 and 50% where for each DBT there is a corresponding reachable relative humidity. All of the parameters above are considered to study the performance of A/C system with evaporative cooling, evaporative cooling and heat exchanger presence and without evaporative cooling to evaluate the energy saving and system characteristics.

One can notice from the number of parameters listed above that a wide range of steady-state DBT and RH are used to represent the air processes in the psychometric chart for the climate outside air conditions. However, only the air processes for 45, 50 and 55°C at 10% RH are plotted in Fig. 2 where it shows the total energy change across the systems with evaporative cooling, evaporative cooling and heat exchanger presence and without evaporative cooling.

It is noticeable that, the DBT across the air-cooled condenser increases sensibly (the moisture content remains constant) from the phase change in refrigerant as shown by a process in dashed-line for the three cases where the heat is added to the air due to the refrigerant phase change in the condenser. First, the air passes through the pad which has the double effect of the air by increasing moisture content and precooling DBT by compound heat transfer process (cooling and humidification) due to water vaporization as the air passes through wetted pad which is illustrated as inclined line and which physically represents constant enthalpy process. When air leaves the pad it passes through the heat exchanger which has the surface temperature close to WBT of the outside air. In this process, moisture is removed (de-humidification) and the air is cooled. As a result, a reduction in the moisture effect on the process of evaporative cooling in the condenser will be noticed as an enhancement in the condenser operation. When the air leaves the heat exchanger it passes through condenser coil which causes sensible heat exchange, since, the air is cooler. Humid and horizontal lines represent this process.

Data from Fig. 2 shows the air processes. It is obvious from the figure that air without evaporative cooling, air process for evaporative cooling assist and evaporative cooling and heat exchanger presence have 1, 2 and 3 processes, respectively.

Influence of air velocity: The evaporative cooling is quite sensitive to air velocity since it is scientifically proven that the amount of heat and mass transfer are proportional to the air velocity. The total performance (COP) and energy consumption are strongly influenced by the air velocity that is with low air velocity, the pressure drop decreases and effectiveness of evaporative cooler increases. One can see that the lower velocity (1 m/sec) is the more efficient as shown in Fig. 3. Moreover, the

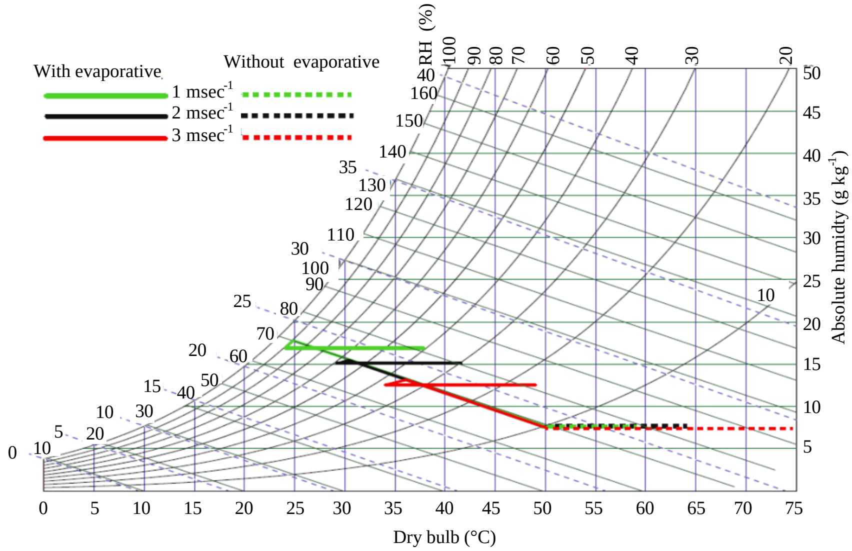

Fig. 3: The effect of air velocity on the performance of A/C with and without evaporative cooling

Table 3: The experimental Runs A, B and C without and with/ with HE evaporative cooling

		Run A			Run B			Run C		
Parameters	Units	Without evaporative	With evaporative	With evaporative and HE	Without evaporative	With evaporative	Without evaporative and HE	Without evaporative	With evaporative	With evaporative and HE
Ambient DBT	°C	45	45	45	50	50	50	55	55	55
Ambient WBT	°C	21.3	21.3	21.3	23.9	23.9	23.9	26.5	26.5	26.5
Compressor exit temperature (T_2)	°C	109	84	80	112	83.4	81.2	119	84.8	82.1
Condenser exit temperature (T_3)	°C	58	40	38	62	43	41.3	71	46	42.3
Capillary tube exit temperature (T_4)	°C	0	-6	-7	2.5	-1	-1.7	4.5	2	0.8
Evaporator exit temperature (T_1)	°C	9	0	-0.5	11.5	3	1.6	15	5.2	3.8
Condenser air exit temperature	°C	59	40	38	62	43	40.7	68	46.2	43.2
Electric current	A	12	9.8	9.5	13.1	10.1	9.7	14.2	10.6	10.1
Power saving (%)	-	-	22.45	26.32	-	29.703	35.05	-	33.96	40.6
Compressor exit pressure (P_2)	bar	24.75	19.85	19.3	27.21	20.06	19.7	30.6	21.6	20.7
Condenser exit pressure (P_3)	bar	24.64	19.431	18.9	27.98	19.912	19.3	30.4	5.2	5.01
Capillary exit pressure (P_4)	bar	4.98	4.1	4.0	5.468	4.864	4.61	5.821	5.11	4.93
Evaporator exit pressure (P_1)	bar	4.891	4.01	3.92	5.294	4.751	4.6	5.672	4.227	4.156
Compression ratio	-	5.06	4.95	4.82	5.21	4.223	4.239	5.4	4.227	4.156
Water evaporation rate	l/min	-	0.2	0.25	-	0.3	0.38	-	0.41	0.51
Water circulation rate	l/min	-	4.5	4.5	-	4.5	4.5	-	4.5	4.5

pressure drop is proportional to air velocity (• $\frac{1}{2}\times V^2$)) and hence when the air velocity increases, the pressure drop increases, as shown in Fig. 4a. As a result, the fan power is proportional as well to the air velocity, this is a common penalty for all air processing where any increase in pressure drop leads to more power consumption as shown in Fig. 4b.

Air conditioning performance: Several tests are conducted to investigate the performance of air conditioning under the influence of using evaporative cooling. In Table 3, the three experimental runs (A, B and C) are listed, since, they have the maximum performance effect of evaporative cooling on the A/C system. The subscripts 1-4 indicate the thermodynamic states. States

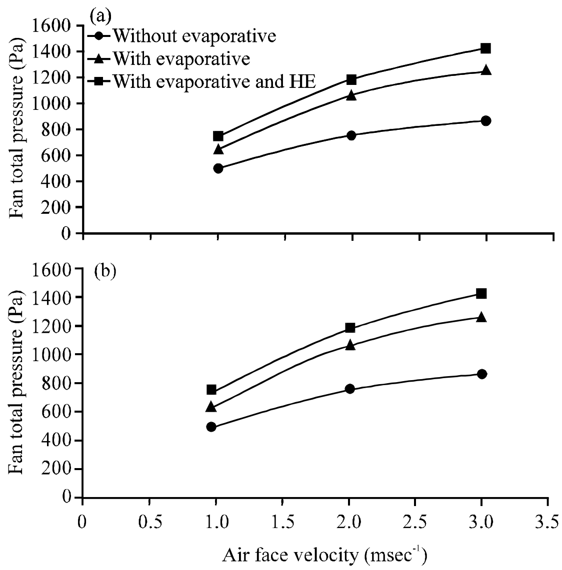

Fig. 4: a) Effect of evaporative cooling installed on pressure drop and b) Effect of evaporative cooling installed on fan power

1-2 refer to the isentropic compression suction and discharge, states 2-3 represent the superheated vapor inlet and saturated or subcooled liquid exit conditions of the condenser, states 3-4 refer to the throttling process condition across the capillary tube and states 4-1 refer to the inlet and saturated or superheated vapor at exit conditions across the evaporator. For each state, the thermodynamic properties are measured for the three systems with and without direct evaporative cooling supported by a heat exchanger. It is worthy to mention that the precision and accuracy of the experimental results, namely pressure and temperature are precise in comparison to the results measured independently across each of the four components (compressor, condenser, capillary and evaporator). As shown in Table 3, the saturation temperature for the condenser in the two systems test for run A is 60 and 49°C, respectively and from thermodynamic tables for R22 the saturation pressure at these temperatures are 24.3 bar and 19.35 bar. Furthermore, the reading pressures in run A shows that the pressures at these temperatures are about 24.64 bar and 19.53 bar which have small differences with the saturation pressures.

Figure 5 shows the three runs on the P-h chart. It is obvious from these figures that the system with evaporative cooling has a reduction in condenser pressure, 24.7-35.6 and 41.7% for the three runs, respectively whereas the evaporator pressure reductions are 21.4-11.43 and 11%. This reduction in the two pressure values is an indication of energy saving in the A/C system. As shown in Table 3, the electric current demand reductions are 22.45-29.7 and 33.96% for the three cases. It is worth mentioning that subcooling occurred in the condenser with evaporative cooling enhances evaporative cooling (presence of HE) at dry air as shown in Fig. 5. This implies an increase in the refrigeration capacity in the range of 10-30% for each ton of refrigeration. As a result it reduces the initial and running cost.

In order to calculate the power consumption in the compressor, refrigerant effect, refrigeration capacity and COP it is required to specify thermodynamic properties of a refrigerant at different sections of the cycle based on the experimental results given in Table 3 and P-h chart. The actual compressor work can be measured directly from the digital wattmeter used in the experimental rig. The refrigerant mass flow rate can be calculated by Eq. 2. The refrigerant effect, cooling capacity and COP can be calculated by using Eq. 3 and 5, respectively:

$$\dot{m}_r = \frac{\dot{W}}{h_2\text{-}h_1} \tag{2}$$

$$R_{eff} = h_1\text{-}h_2 \tag{3}$$

$$Q_{cooling} = \dot{m}r\left(h_1\text{-}h_4\right) \tag{4}$$

$$COP = \frac{Q_{cooling}}{W} = \frac{h_1\text{-}h_4}{h_2\text{-}h_1} \tag{5}$$

The results for refrigerant mass flow rate, power consumption, refrigerant effect, cooling capacity and COP for the three runs are presented in Table 4. Data in Table 4 show the power saving when using the evaporative cooling is reduced by 22.45-29.703 and 33.96%, the refrigerant effect is increased by 10.2-12.8 and 15.87%, cooling capacity also is increased by about 27.12-30.37 and 33.4%. The refrigerant mass flow rate is increased by 12.5-12.1 and 10.95%. The COP increased by 17.8-22.87 and 33.24% which implies that cooling capacity is increased in addition to the reduction in the power consumption.

Influence of RH on the energy saving: The energy saving is illustrated in Fig. 6 which shows the effect of inlet RH (10-50%) for the ambient air on energy saving by using evaporative cooling assist condenser where the energy saving is reduced when the air inlet RH increased. These results imply that the precool and energy reduction capability for the A/C system with evaporative cooling is decreased as air inlet RH increased. The higher relative humidity with the same DBT leads to poor performance for evaporative cooling.

Table 4: The calculated parameters for experimental Runs A, B, and C without and with/ with HE evaporative cooling

		Run A			Run B			Run C		
Parameters	Units	Without evaporative	With evaporative	With evaporative and HE	Without evaporative	With evaporative	Without evaporative and HE	Without evaporative	With evaporative	With evaporative and HE
Power saving (%)	-	-	22.45	26.32	-	29.703	35.05	-	33.96	40.6
Refrigeration effect	kJ/kg	140	155	157	134	152	153.5	129	149	152
Refrigerant mass flow rate	Kg/sec kg/sec	0.0569	0.0653	0.067	0.0572	0.0657	0.0659	0.055	0.0667	0.0656
Cooling capacity	kw	7.9662	10.127	10.45	7.657	9.983	10.12	7.1	9.932	9.98
Compressor work	kJ/kg	47	43	42	48	41	39.5	49	42	39
Coefficient of Performance (COP)	-	2.98	3.605	3.74	2.8	3.707	3.886	2.635	3.527	3.897
improvement of COP (%)	-	-	17.3	20.32	-	24.46	27.94	-	25.3	32.4
Refrigeration effect	kJ/kg	140	155	157	134	152	153.5	129	149	152

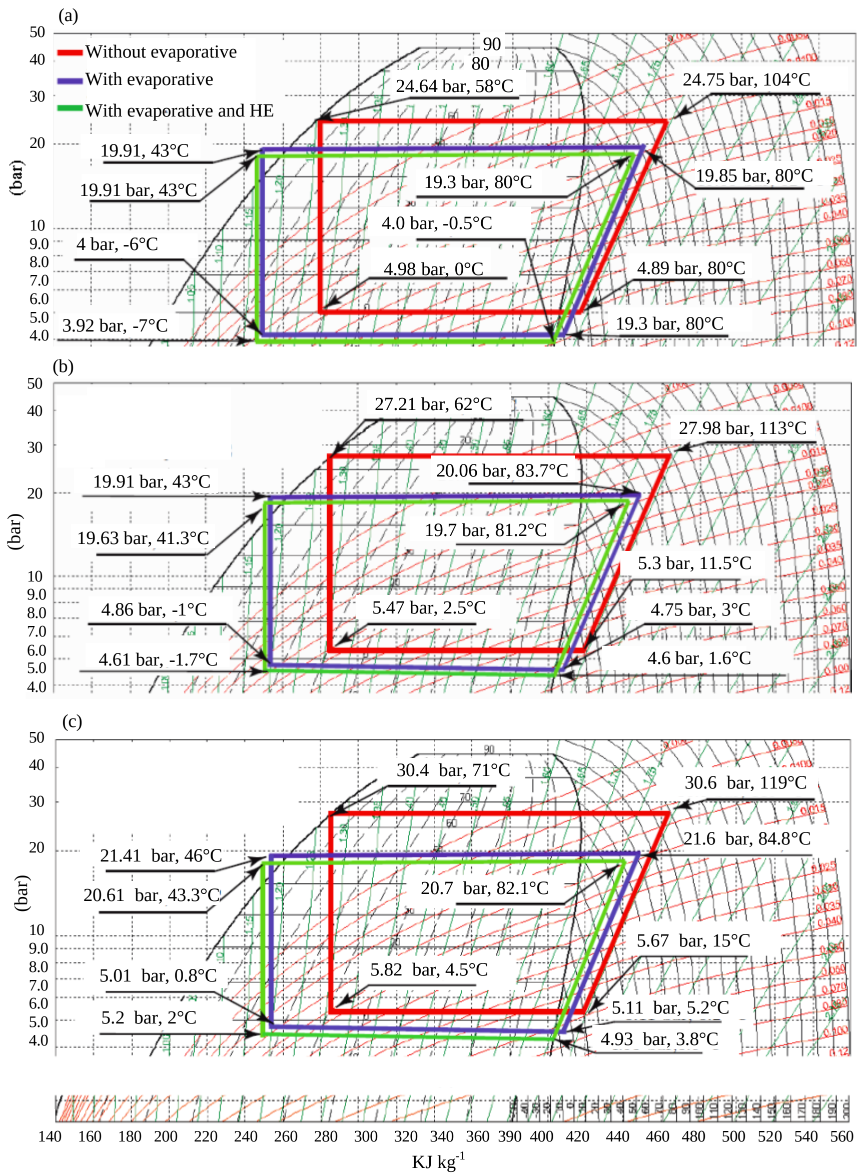

Fig. 5: The P-h charts of without and with/HE evaporative cooling cycle: a) For run A; b) For run B and c) For run C

Table 5: The effect of using evaporative cooling on the minimum voltage that the A/C operates with for experimental runs A, B and C

Without evaporative			With evaporative			With evaporative and HE		
Temperature range			Temperature range			Temperature range		
45°C	50°C	55°C	45°C	50°C	55°C	45°C	50°C	55°C
220 V	220 V	220 V	220 V	220 V	220 V	220 V	220 V	220 V
210 V	210 V	210 V	210 V	210 V	210 V	210 V	210 V	210 V
200 V	200 V	Shutdown	200 V	200 V	200 V	200 V	200 V	200 V
195 V	Shutdown	Shutdown	190 V	190 V	190 V	190 V	190 V	190 V
Shutdown	Shutdown	Shutdown	180 V	185 V	185 V	180 V	180 V	180 V
Shutdown	Shutdown	Shutdown	175 V	180 V	Shutdown	175 V	175 V	Shutdown
Shutdown	Shutdown	Shutdown	Shutdown	Shutdown	Shutdown	Shutdown	Shutdown	Shutdown

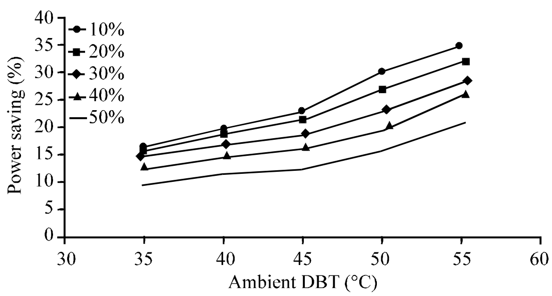

Fig. 6: Effect of RH on the power saving by using evaporative cooling assist

Influence of rating current and voltage DROP: The voltage drop during severe hot weather is one of the most challenging obstacles that is still unsolvable in Middle East region and especially in Iraq where the national power network is old and the voltage drops from 220 to about 190 V during the peak time in summer. The power that is consumed in A/C systems is related to the applied voltage and input current. For instance an A/C system takes 5-6 A when the voltage is 220 V. However when the voltage drops to 190 V, the required current will be about 6-7 A. Such increment in the input current will activate the overload switch in the A/C system and hence, the system will be automatically switched off. Moreover, the excessive input current leads to reduce the compressor efficiency and increase the maintenance cost in the A/C system. In the present research, the results from the enhanced direct evaporative cooling method showed a significant improvement in the A/C system during severe hot weather where the A/C system continues operating even with voltage drop reaches 170 V. Table 5 showed the thresholds where the system is automatically switched off when weather temperature increases.

CONCLUSION

In this research an experimental study to analyze the performance of an air conditioning unit with and without direct evaporative cooling supported by the heat exchanger is presented. The proposed design can be easily applied to any A/C system with an air-cooled condenser. The experimental setup is fabricated by using window type commercial A/C system where the A/C system is modulated to provide the wide range of various conditions. The experimental results show that using evaporative cooling assist could significantly enhance the coefficient of performance COP, increase cooling capacity and decrease power consumption. The experiment includes wide range of temperature and humidity conditions and in all running conditions, the subcool phenomenon has been observed in the condenser with using evaporative cooling and enhanced evaporative cooling. The precooling that occurs in condenser leads to increase the liquid mass flow rate and also, increase refrigeration capacity in the range of 10-30% and hence, the initial and running cost feasibly can be reduced in addition to a reduction in compression ratio which leads to significant improvement in COP. Also, the experimental results show that the electric demand in the compressor is reduced by 0.12-0.2. For each air temperature degree reduction associated with an air velocity of 2 m/sec, the ambient condition is above 45°C and the relative humidity is 15%. In addition, experimental results show that our model for the enhanced A/C system with evaporative cooling aid can run even with the voltage drop (170 V instead of 220 V). This cannot be performed in conventional air condenser when the voltage drops in national electric power due to overload during severe hot weather. Therefore, the system which is enhanced by direct evaporative cooling is recommended in extremely hot climates.

NOMENCLATURE

h	=	Enthalpy (kJ/kg)
m_r	=	Efrigerant mass flow rate (kg/sec)
P	=	Pressure (bar)
R_{eff}	=	Refrigeration effect (kJ/kg)
Q_{cool}	=	Cooling capacity (kW)
ng W	=	Compressor work (kW)
COP	=	Coefficient of Performance
DBT	=	(Dimensionless) Bulb Temperature of air (°C)

RH = Relative Humidity (%)
Evap. HE = Evaporative cooling assist Heat Exchanger
A/C = Air Conditioning system
• = Air density (kg/m^3)
V = Air Velocity (m/sec)
FPCM = Number of Fins Per Centimeter

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