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Performance Improvement of an Air Cooled Air Conditioning System Using an Evaporative Cooled Condenser

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Abstract: The aim of this paper is to investigate the performance improvement of an air-cooled air conditioning system utilizing an evaporative cooled condenser. Air-cooled condensers in many refrigeration and air conditioning systems when used in hot climate are less efficient and have technical, economical, and environmental constraints. As an alternative, the use of evaporative air-cooled condensers, seem to be a unique option to mitigate the limitations above and improve the energy performance of such systems. Another advantage of using evaporative air-cooled condensers is to protect the compressor and keep the system working without interruptions at high outdoor temperatures.To characterize this energy benefit, a model was developed and applied to predict the performance of a variable refrigerant flow (VRF) system under various ambient air temperatures up to 42 °C using an engineering equation solver (EES) software. The results show that the application of the evaporative precooled air in an air-cooled condenser has significant effect on the performance improvement of the air conditioning system. In Khartoum's hot and dry climate, the rate of improvement is increased as ambient air temperature increases. It is also found that, compared to an air-cooled condensers system, the refrigerant effect and the coefficient of performance of evaporative cooled condensers could be increased by 23% and 60%, respectively. In addition, the compressor work is decreased by 35% followed by a considerable reduction of the operational costs of the system.

Keywords: *Air cooled condenser, evaporative condenser, Performance Improvement, COP, and HVAC.*

1. INTRODUCTION

The continuous increase in energy demand and the decline in global energy supply have resulted in high energy costs. In 2008, it was reported that 20% of total energy in the USA and 17% of the total global energy were consumed in air conditioning [1]. Hence; the enhancement of the coefficient of performance (*COP*) of air conditioning system will contribute to the reduction of global energy consumption.

Due to extremely high summer temperatures in Sudan, most of the total power generated is consumed then by air-conditioning. Air-conditioning units use condensers in order to change vapor refrigerant into liquid on the hot side of the air-conditioning system [2-4]. These systems which use air-cooled condenser operate by forcing the air over the condenser's tubes while the refrigerant flows inside the tubes. The air flowing over the tubes absorbs heat from the refrigerant, causing the refrigerant to condense.

As the outdoor temperature increases, the performance of the condenser decreases, thereby increasing the power required for cooling. In addition to more cooling load, another drawback is the decrease in the compressor life expectancy. A possible solution to meeting the extremely high demand of electrical power consumption during summertime is to pre-cool the air entering the condenser, resulting in higher performance of air-conditioning units, and hence, lower the power required for cooling.

Improving air conditioning performance has always been an issue in this part of the world, where the outside temperature may reach 50 ºC during the summer. The performance of the unit depends directly on the ambient temperature and is known to decrease with the increase in ambient temperature. Ambient temperatures in hot climates significantly reduce the air-cooled air conditioning systems' performance by as much as 30% [5]. Power consumption is a major concern in vapor compression cycle air conditioners especially those which are using air-cooled condensers instead of water cooled condensers. The concern is increased much more if the air-cooled condensers work in very hot ambient conditions. Therefore, in the area with very hot ambient temperatures in summer; the condenser temperature and pressure are increased considerably which consequently increases the power consumption of the air conditioner due to the increase in the pressure ratio. In some cases the pressure increase is so high that pressure control system in the air conditioners shut down the compressors [6].

In order to increase the performance of air conditioner in this situation, one of the best solutions is decreasing the condenser temperature. Reducing the condenser temperature reduces the pressure ratio across the compressor which results in power consumption reduction. It also decreases the refrigerant liquid entropy after the expansion valve and more liquid refrigerant would be available at the evaporator's inlet. Therefore, the mass flow rate and the cooling capacity of the refrigerant are increased.

2. LITERATURE REVIEW

Air-cooled condenser is popularly used in air conditioning system due to its advantages of convenient size and easy maintenance. However, it consumes high energy in summer weather, which causes a peak-load in electricity demand [7]. Although the water and air-cooled condensers are relatively simple to model accurately, the evaporative condenser presents some difficulties because of water evaporation into the air stream. Early evaporative condenser models assumed that the temperature of water stream would stay constant. Then, it was found that this assumption gave incorrect results for the heat performance of the system [8]. Accepting that the water temperature would change, investigators presented a simple model requiring only analytical solution [9]. Based on the work by Parker and Treybal [9], another analytical model was developed and tested on an evaporative condenser. Peterson et al. [10] found that this model underpredicted the heat load by 30%. The performance of the evaporative condenser was also compared with that of the same device operating as an air-cooled condenser in Ettouney et al. [11].

An experimental investigation of the coefficient of performance augmentation of an air conditioning system utilizing an evaporative air cooled condenser was presented by Tianwei et al. [12]. The experiments compared the effect of direct evaporative air cooled condenser with conventional air-cooled condenser. By conducting multiple tests on condenser driven conditions, the thermal performance in terms of temperature showed that direct evaporative air-cooled condenser could drive the system into subcooled operation condition, resulting in the increase of saturation temperature drop through the condenser from 2.4ºC to 6.6ºC. It also increased the liquid mass flow that enters the evaporator, reduced the compressor work, and consequently resulted in an increase of *COP* from 6.1 % to 18% [12].

Some attempts have been done by Nittler [13] using water vaporization instead of sensible heat of air to cool air condenser. A water-cooled condenser accompanied with a cooling tower or combining two of them in an evaporative condenser are used in order to reduce condenser temperature, which can result in reducing pressure ratio between the condenser and the evaporator. Those are mostly used in medium or large scale air conditioning systems [10]. A conventional evaporative condenser, in which water is pumped to spray directly to the condenser's coils, has been in commercial use in an outdoor unit of split air-conditioning systems [10].

According to the company reports, their product provides a saving of 39% of cooling for statewide California weather conditions. Because of direct contact of water and heat-transfer surface, condenser coil may suffer from mineral deposits which can decrease the performance. So as to avoid this problem, as well as expense for water treatment system, indirect evaporative cooling process has been applied to pre-cool air before entering the condenser coils by using cellulose media pad wetted by pumped water.

An 8.8-kW split air-conditioning system was investigated by Goswami et al [14] in Florida weather. The results show that about 20% of electric energy was saved [14]. Using the same principle, Hajidavalloo [15] applied evaporative cooling for a window-air-conditioner in dry and high temperature area. The experimental results showed that in the new system power can decrease by about 16% and *COP* increase by 55% at outdoor dry-bulb temperature of 45 - 46 ºC [15]. Cellulose pad has also been used in water-cooled condenser of residential split air-conditioner of 3.52-kW cooling capacity, Hu and Huang [16].

Their experimental results showed that the COP reached 3.45 higher than 2.96 in the conventional system [16]. Youbi et al. [17] proposed a water spraying system in front of the air-cooled condenser to reduce air temperature and developed a semi-local numerical model for a sprayed air-cooled condenser coupled with a refrigeration system. They did not do any experiment but by using the model prediction found that the *COP* of the refrigeration system could be improved by up to 55% [17].

Indirect evaporative cooling has been studied in the past decades. As reflected by the significant research effort dedicated to this subject, the main results are well summarized in a couple of recent review articles [18,19].

Substantial growth in refrigeration and air conditioning industry has made a significant impact on net energy consumption. Condenser pressure is one of the critical parameters in the energy efficient operation of refrigeration and air-conditioning systems. A novel system is developed to use the condensate, available at the cooling coil, for condenser cooling of a window air conditioner unit by employing evaporative cooling. Performance testing of the system has shown 13% savings in energy and up to 18% enhancement in coefficient of performance. The maximum benefit of the evaporative cooling cycle over the basic cycle was found to be in the region of moderate climatic conditions [20].

3. MATHEMATICAL MODEL DESCRIPTION

As mentioned previously, this study aims to predict the performance when an evaporative air cooler was used in an existing air conditioning system. Below is a brief description of the model.

Figure 1 shows a schematic of the proposed system. An existing air cooled VRV system with six outdoor units (12 *HP* each) was used in this study. Consistent with the shape of the units, a frame was assumed to be built and the evaporative cooler was placed in the air path.

A water circulation system including a water pump, a tank, and connecting pipes were assumed to be assembled on the system to inject water to the top of an evaporative cooler cooling pads. Water circulation rate was assumed to be constant for all tests. Hot ambient air passes over the evaporative cooler and gets cooled and then passes through the condensers coils and finally exits from the top of the condensers suction fans.

The aim of this work is not to develop a model directly linked to an existing plant but rather to investigate some trends for an effective and rational use of an evaporative air cooler in the refrigerating and air conditioning systems. Service checker was used to measure the electrical current of the components, pressures in the inlets and outlets of the condenser and the evaporators.

4. PERFORMANCE PARAMETERS EQUATIONS

The total power consumption can be obtained by using equation (1-a) and equation (1-b) which consider power consumption of each component separately in air cooled condenser and evaporative air cooled condenser respectively.

$$W_T = W_c + W_f = V(I_c + I_f)\cos\phi \quad (1\text{-a})$$

$$W_T = W_c + W_f + W_p = V(I_c + I_f + I_p)\cos\phi \quad (1\text{-b})$$

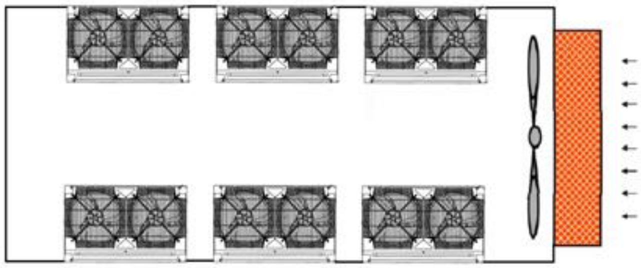

FIG.1. A SCHEMATIC OF THE SYSTEM

5. Outdoor units specifications

TABLE 1. SPECIFICATION OF THE SYSTEM.

Number of outdoor units		6
Capacity range		12 HP
COP		3.89 (cooling),4.3 (heating)
Dimensions		1,680 * 1,240* 765 (H*W*D) mm
Heat Exchanger	Dimensions	2,088 mm length
	No of Rows	54
	No of Passes	21
	Face Area	2.481 mm^2
	No of Stages	2
	Tube type	Hi-XSS (8)
	Fin type	Non-symmetric waffle louver
Fan	Type	Propeller
	Quantity	2
Air Flow Rate	Cooling	233 m^3/min

A schematic *p-h* diagram of the vapor compression cycle as shown in Figure 2 is used in conjunction with equations (1-4) to illustrate the mathematical model. In all equations, subscripts (1), (2), (3) and (4) stand for exit conditions from evaporator, compressor, condenser and electronic expansion valve respectively. The mass flow rate can be obtained by equation (2).

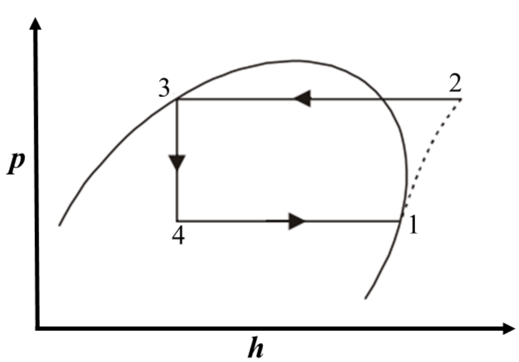

Figure 2 *P-h* Diagram of a vapor Compression refrigeration cycle

$$m^{\cdot} = \frac{W_c}{h_2 - h_1} \quad (2)$$

Cooling capacity and *COP* can be obtained by using equation (3) and equation (4), respectively.

$$Q_r = m(h_1 - h_4) \quad (3)$$

$$COP = \frac{Q_r}{W_T} \quad (4)$$

As can be seen, the total power consumption was used in the definition of *COP* not just the compressor power, in order to get a comparison between overall performance of the two systems.

6. RESULTS AND DISCUSSION

Based on the data collected using the air conditioning service checker, the engineering equation solver (EES) is used to simulate the refrigeration thermodynamic cycle. Table 2 shows the data which are used to be the inputs for the software for three different conditions 35, 39, and 42 ºC. To study the effect of using an evaporative air cooled condenser the temperature of air after the pad should be calculated. Using the ambient air temperature and relative humidity from table 2 and the evaporative cooler efficiency which was assumed to be 85% the software was used to calculate the temperature and relative humidity after the pads. Also the condensing temperature was assumed to be greater than the temperature after the pads by 7 ºC. Table 3 shows the results of the refrigeration thermodynamic cycles which are simulated using the software.

Also, the thermodynamic properties of the refrigerant at different points, of a simulated cycle at 35 ºC ambient temperature, were obtained by EES, figure 2, and the parameters such as the mass flow rate, the cooling capacity, and the *COP* of the system were calculated. As shown in table 3 the total electric current, the condenser pressure, and the compressor exit temperature of the air-cooled condenser increase considerably as ambient temperature increases, from 35 ºC to 42 ºC, but the evaporative cooled condenser shows better performance.

Figure 3 shows the *P-h* diagram when the ambient air temperature and the relative humidity are 35 ºC and 9% respectively. The results show that the condenser pressure of the evaporative air cooled condenser system and the cycle pressure ratio are reduced by 34%. And, while the evaporator temperature is assumed to be constant, the condenser exit temperature drops down by 16.5 ºC.

The total electric power consumption of the system is reduced by 26%. The compressor consumes most of the electric current comparing it to the condenser fan. Thus, the condenser fan power is assumed small and remains unchanged when the evaporative air cooled condenser is used.

7. EFFECT OF AMBIENT TEMPERATURE ON THE CYCLE PERFORMANCE

Many tests at different ambient conditions were performed in order to have a better understanding of the system behavior. Figure 4 compares the amount of compressor work when air. cooled condenser was used, with and without evaporative air cooled condenser starting from 35ºC to 50ºC. It is clear that, with increasing in ambient air temperature the compressor work for the two systems is increased, but it is important to get quantitative results.

TABLE 2 COLLECTED DATA OF THE TWO SYSTEMS AT THREE DIFFERENT AIR TEMPERATURES

Parameter	Unit	AC	EC	AC	EC	AC	EC
Ambient air temperature	**ºC**	**35**	**35**	**39**	**39**	**42**	**42**
Ambient air relative humidity	**%**	**9**	**9**	**4**	**4**	**3**	**3**
Compressor inlet temperature	**ºC**	8.1	8.1	8.1	8.1	8.1	8.1
Compressor exit temperature	**ºC**	69.6	47.3	75.2	48.4	79.2	50
Condenser exit temperature	**ºC**	40	23.5	44	24.3	47	25.5
Evaporating temperature	**ºC**	-1.9	-1.9	-1.9	-1.9	-1.9	-1.9
Evaporator pressure	**Bar**	7.5	7.5	7.5	7.5	7.5	7.5

TABLE 3 RESULTS OF THE TWO SYSTEMS AT THREE DIFFERENT AIR TEMPERATURES

Parameter	Unit	AC	EC	AC	EC	AC	EC
Ambient air temperature	**ºC**	**35**	**35**	**39**	**39**	**42**	**42**
Ambient air relative humidity	**%**	**9**	**9**	**4**	**4**	**3**	**3**
Air temperature after the pad	**ºC**	-	16.9	-	19.3	-	20.5
Relative humidity after the pad	**%**	-	85.5	-	86	-	85
Condensing temperature	**ºC**	42	23.9	46	26.3	49	27.5
Condenser pressure	**Bar**	25.3	16.7	27.8	17	29.8	17.6
Total electric current	**A**	12	8.87	12.7	9.0	12.9	9.1

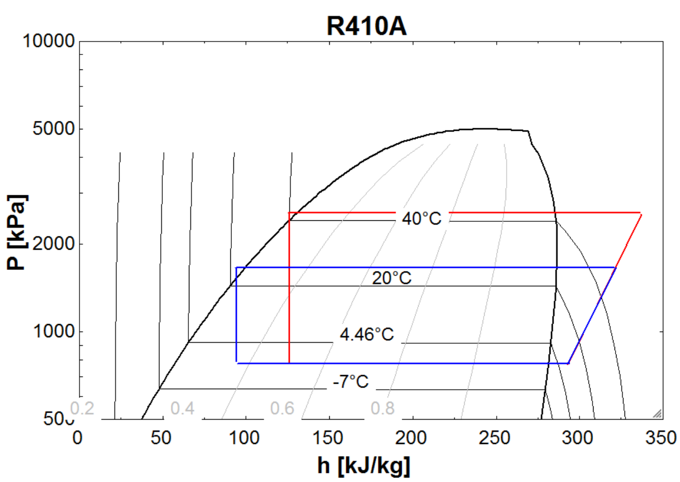

FIGURE 3 THE P-H DIAGRAM OF CONVENTIONAL AND EVAPORATIVE COOLING CYCLE AT AMBIENT TEMPERATURE 35°C AND RELATIVE HUMIDITY OF 9%.

In the first stage when the ambient air temperature is 35ºC the amount of the compressor work is decreased by 12 kJ/kg from 36 kJ/kg to 24 kJ/kg when evaporative air cooled condenser is used. Air cooled condenser's compressor work shows rapid increase with ambient air temperature.

From 35ºC to 50 ºC the compressor work increases by 13 kJ/kg.That means the air cooled condensers efficiency is more sensitive to the ambient air temperature. On the other hand, when

The evaporative air-cooled condenser is used the amount of the compressor work is increased but gradually and sometimes remains constant with increasing ambient air temperature. Thus, at high ambient air temperature and low moisture content the evaporative air cooled condenser maintains stable working conditions, which results in low compressor work, even with changing ambient air temperature as previously stated and it is confirmed by figure 4.

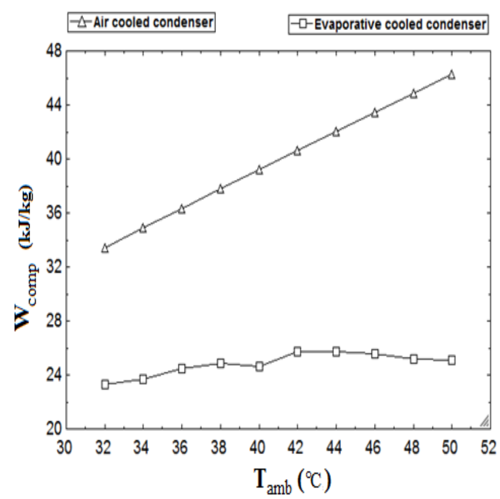

FIGURE 4 COMPRESSOR WORK VARIATION AT DIFFERENT AMBIENT AIR TEMPERATURE.

Figure 5 shows the variation of the *COP* versus the ambient air temperature for the two types of the condensers. It's clear that, when the evaporative air cooled condensers are used at (35 ºC, 9% RH) the coefficient of performance increased from that with air-cooled condensers by 1.6 from 3.7 to 5.3 approximately, and this difference between the two curves is increased as the ambient air temperature increases.

Air cooled condenser's coefficient of performance shows steady decrease with ambient air temperature. On the other hand, when the evaporative air-cooled condenser is used the coefficient of performance slightly decreases and the stays unchanged when the ambient air temperature increases, figure 5.

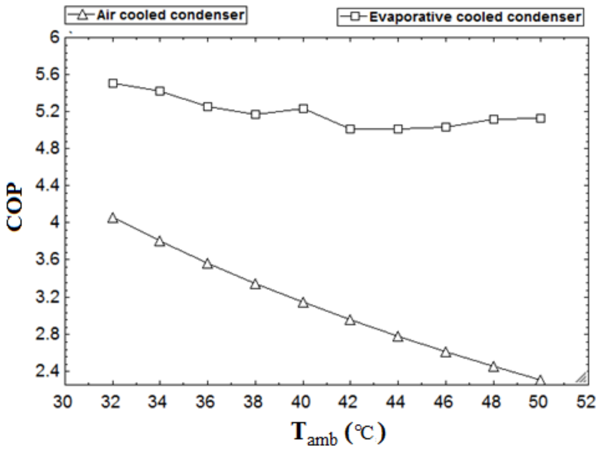

FIGURE 5 COP VARIATIONS AT DIFFERENT AMBIENT AIR TEMPERATURE.

Figure 6 compares the variation of the refrigeration effect of the two condensers in terms of the ambient air temperature. It can be seen that the refrigeration effect of the system that used an evaporative air cooled condenser is much higher than the other type. It is very clear that these results are similar to those depicted in figure 5.

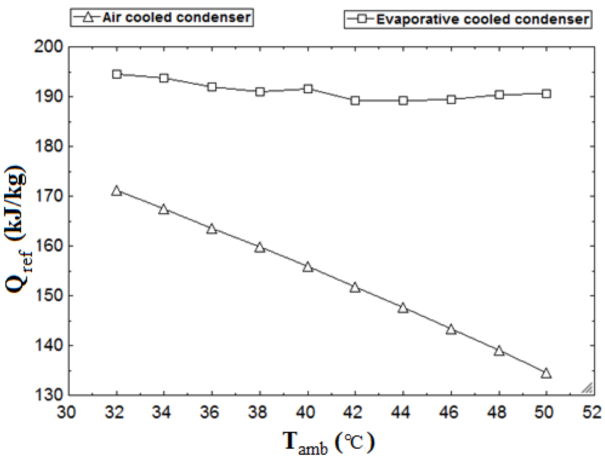

FIGURE 6 COOLING EFFECT VARIATION AT DIFFERENT AMBIENT AIR TEMPERATURE.

Tables 4 and 5 show the results of the tests at ambient temperatures 35 ºC and 42 ºC. The results confirm that as the ambient air temperature increases, the effect of using the evaporative air-cooled condenser is noticeable. For example the reduction in the compressor power is increased from 20.7% at 35 ºC to 36.8% at 42 ºC. Also the refrigeration effect is increased from 21.1% to 24.6% and *COP* increases from 45.1% to 71.2%. These results are consistent with other findings in the literature [9, 11].

TABLE 4 PERFORMANCE RESULTS OF AIR CONDITIONER AFTER RETROFITTING (35.0 ºC, 9% RH)

Parameter	Unit	AC	EC	Variation
W_c	kW	5.625	4.460	-20.7%
$\dot{m}$	kg/s	0.0961	0.0961	+00%
Q_r	kW	25.150	30.460	+21.1%
COP	-	3.68	5.34	+45.1%

TABLE 5. PERFORMANCE RESULTS OF AIR CONDITIONER AFTER RETROFITTING (42.0 ºC, 3% RH)

Parameter	Unit	AC	EC	Variation
W_c	kW	6.424	4.062	-36.8%
$\dot{m}$	kg/s	0.0925	0.0925	+0.0%
Q_r	kW	24.0	29.9	+24.6%
COP	-	3.02	5.17	+71.2%

8. ENERGY SAVINGS ANALYSIS

The energy savings due to the improvement of the *COP* can be calculated. The analysis is based on the following conditions:

- Cooling capacity 12 HP for each unit
- Daily operation time 5 h/day (the study case is a masjid)

The average ambient air temperature and the relative humidity are used with the system collected data in EES to compute the thermodynamic properties at all points in the cycle. The average values of the compression work per kilowatt are multiplied by the number of operation hours to give the number of kilowatt hours per day. Table 6 presents the average kWh per month as well as the annual kWh consumption. The total energy savings per year are about 33,957 kWh.

TABLE 6. AVERAGE KWH PER MONTH FOR THE TWO SYSTEMS

Month	kWh (AC)	kWh (EC)
January	6,335	3,862
February	5,939	3,642
March	6,950	4,170
April	7,088	4,181
May	7,570	4,270
June	7,352	4,191
July	7,053	4,171
August	6,824	3,558
September	6,868	4,035
October	7,324	4,294
November	6,619	4,018
December	6,443	4,015
Total kWh	**82,364**	**48,407**

9. CONCLUSIONS

In this paper, the performance improvement of an air cooled refrigeration system is introduced and investigated using an evaporative cooled air condenser. The results of these performance improvement effects are presented. The conclusions, of this work, are summarized as follows:

- At 35 ºC the compressor work, of the studied system, is decreased by 12 kJ/kg when the evaporative air cooled condenser is used. This value is increased with the ambient air temperature to exceed 20 kJ/kg at 50 ºC.
- The reduction in the compressor power increases with ambient temperature. For instance, the increase in the reduction is from 20.7% at 35 ºC to 36.8% at 42 ºC.
- The refrigeration effect is increased from 21.1% at 35 ºC to 24.6% at 45 ºC and *COP* increases from 45.1% to 71.2%.

- The annual energy savings is found to be approximately 41%.

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