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EXPERIMENTAL AND MATHEMATICAL EVALUATION OF THE REFRIGERATION SYSTEM PERFORMANCE WITH DIFFERENT AMBIENT TEMPERATURE

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Abstract: The present work includes two main parts. Firstly: the experimental part which takes respect of the effect of changing magnitude of supplied voltage to compressor ,condenser air flow rate and evaporator air flow rate on system performance . The effect of ambient temperature on system performance is also considered .The experimental study has been done on a split air- conditioner with a 1 TR nominal capacity .The experimental results show that, reducing the supplied voltage to compressor by 23% caused the refrigeration capacity and $COP)_{tot}$ to decrease by 7.7% and 5.7% ,respectively and when condenser air flow reduced by 35.8%, cause the refrigeration capacity and $COP)_{tot}$ to decrease by 1.6% and 7.1%, respectively . Also the reduce of the evaporator air flow by 46.7%, the refrigeration capacity and $COP)_{tot}$ decreased by 11.4% and 9.6% ,respectively . Secondly the theoretical part, in which a mathematical model has been developed for the vapor compression refrigeration cycle to predict the system performance under the various ambient temperatures. The mathematical model was performed using Matlab software. The comparison between the mathematical results and experimental results, show that, the maximum deviation of condenser capacity, refrigeration capacity, power input to compressor and COP are 1.75%, 3.2%, 3.34% and 4.84%, respectively.

Keyword: *Compressor Voltage, Mathematical Analysis, Refrigeration Cycle*

حساب اداء منظومة التثليج عمليا ورياضيا عند درجات حرارة جو مختلفة

الخلاصة: البحث الحالي يتضمن جزئين رئيسيين .اولا الجزء العملي الذي يتعلق بدراسة تأثير تغيير كمية الهواء المارة على المكثف ، كمية الهواء المارة على المبخر و مقدار الفولتية المجهزة للضاغط على اداء منظومة التثليج. تأثير درجة حرارة الجو على أداء المنظومة اعتبرت ايضا في هاذ الجزء . تم اجراء الدراسة العملية على منظومة تكييف منفصله ذات سعة ١ طن تبريدي. النتائج العملية اظهرت عند تقليل الفولتية المجهزة للضاغط بنسبه ٢٣ % فان سعة التجميد ومعامل الاداء الكلي يقل كل منهم بمقدار٧,٧ % و٥,٧ % على التوالي و عند تقليل كمية الهواء المارة على المكثف بنسبة ٣٥,٨ % فان سعة التجميد ومعامل الاداء الكلي يقل كل منهم بمقدار ١,٦ % و ٧,١ %على التوالي . كذلك عند تقليل كميه الهواء المارة على المبخر بنسبة ٤٦,٧ % فان سعة التجميد و معامل الاداء الكلي يقل كل منهم بمقدار ١١,٤ % و٩,٦ % على التوالي. ثانيا الجزء النظري فقد تم بناء نموذج رياضي لدورة التثليج الانضغاطية لغرض تخمين اداء المنظومة تحت تأثير تغير درجه حرارة الجو ،النموذج الرياضي نفذ بواسطة (Matlab software). من خلال المقارنة بين نتائج النموذج الرياضي والنتائج العملية ،تبين ان اقصى انحراف في سعه المكثف ،سعة التجميد ،القدرة الداخلة الى الضاغط و معامل الاداء هو ١،٧٥ %، ٢,٣ %،٣،٣٤ % و٤،٤٨ % على التوالي.

1. Introduction

Compressor is one of essential component of basic vapor-compression refrigeration system. The compressor circulates refrigerant throw the system and increase vapor pressure

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covered the deferential pressure between the condenser and evaporator [1] If the supplied voltage decreases the circulate mass flow rate of refrigerant decreases so it effect on refrigeration capacity of the system. Maza et.al [2] focused on the analysis of the voltage supply effects on the operation of home air conditioning system from an experimental point of view. Two types of air conditioning technologies were usually installed in the residential sector. The first one is based on a hysteresis control of the temperature, performed by switching on/off the motor driving the compressor of the air conditioning unit.

On the other hand, the inverter based applications are also used; in this type of appliance, the motor driving the compressor is fed through an inverter that adjusts the frequency in order to precisely match the requirements of the thermodynamic process .Showed that the current demanded by the conventional unit in case of voltage reduction is higher than the rated current. William et.al [3] was purchased and tested, 15-year-old, single package heat pump with a capillary tube expansion device on the indoor coil in a set of environmental chambers to determine its cooling performance under various conditions.

The system was also modeled to estimate its existing performance with original reciprocating compressor and that with two different types of retrofitted efficient compressor with about 30% less capacity than the original compressor. Modeling estimated that the retrofit would increase the system's energy efficiency ratio (EER) at 35 ℃ by 30%, increase the seasonal energy efficiency ratio (SEER) by 34%, and reduce power demand by 39% compared to the existing unit.

In air cooled condenser the heat is rejected from the refrigerant high temperature to air low temperature. The condenser air flow rate effects directly on the heat rejection from a condenser which appears on the refrigeration capacity and the power consumption by compressor. As known when the air flow rate on air cooled condenser will be increase the amount of heat transfer (rejected) between refrigerant side and the air side and will be increase. If the air flow rate is decreased, the amount of heat transfer will be decrease between them. Hosein et.al [4] investigated the effects of thermodynamic, hydrodynamic and geometric of an air cooled condenser on COP of vapor compression cycle for a fixed condenser facing surface area. The system is utilized with a scroll compressor, modeled based on thermodynamic and heat transfer equations employing Matlab software. This simulation shows that vapor compression cycle can be designed by different configurations and COPs, economical and optimum working condition can be obtained via considering these parameters.

In the force convection and fin and tube type evaporator, the liquid refrigerant reaches the evaporator, it much cooler than the air flowing around it. This causes the refrigerant to absorb heat from the warm air and reach its boiling point. The refrigerant then vaporizes, absorbing the maximum amount of heat. When blower fan turned on to its highest speed will deliver the large amount of air flow across the fins and coils, this lead to give more heat exchange between the refrigerant side and air side. While when the blower fan turned on to its lowest speed *will* deliver the small amount of air flow across the fins and coils, this lead to give little heat exchange between the refrigerant side and air side. Palani [5] discussed and measured degradation in performance of a residential air conditioning system operating under reduced evaporator air flow. Experiments were conducted using an R-22 three-ton split-type cooling system with a short-tube orifice expansion device. Measurements showed that cooling capacity reduced by 7.5% at 25% reduction in evaporator air flow to 14.5% for 50% reduction in air flow.

Also the ambient air temperature affects directly on the heat rejection from a condenser which appears on the refrigeration capacity and the power consumption. When the outdoor air temperature increases, the refrigeration capacity decrease and the power consumption increase, this effect can be seen on the condenser and evaporator operation. Al-Hazeen, [6] used a split unit air- conditioner with a 2 TR nominal capacity, taking into consideration the effect of outdoor ambient temperature and cooling load and developed a numerical model for the actual vapor compression refrigeration cycle to predict the cycle performance before and after adding a counter-flow Tube-with in- Tube heat exchanger in series with the system. The average deviation in refrigeration capacity of the computational results is about (7.3%) higher than the experimental results without extra sub-cooling. Where at sub-cooling ($\Delta T_{sc} = 5℃$), the deviation of computational results is about (5.92%) higher than experimental results.

The performance of refrigeration system is depend on performance of individual component, so to predict the performance of overall system and find the balance point the characteristics of the individual components must be known. There was two method to predict the system performance first a graphical method and second approach called system simulation. The deference between the two method that, in the analytical simulation it is not necessary to combine the components of the refrigeration cycle in pairs as in graphic analysis, instead the three components can be simulated simultaneously [7]. Mustafa [8] analyzed and studied experimentally the effect of outdoor air temperatures on the instrumented air-conditioner unit performance .

Graphical and mathematical analysis are performed on experimental results as well as evaluation is carried out in order to compare graphical analysis results against mathematical analysis results. The graphical analysis results obtained from experimental curves show an increase in refrigerating capacity, compressor power consumption, and heat rejection rate when evaporating temperature increases. The mathematical analysis results are obtained from computer program using compressor, condenser, and evaporator performance equations.

1.1. *The aim of present work*

The goal of the present work is to know which of these parameters (condenser air flow, evaporator air flow and supplied voltage to compressor) has the dominant influence on the system capacity, and how it effects on other components. This information will form a guide line for the designer to take care of regarding parameters of the most influence on the system performance when designing the components of vapor-compression refrigeration systems. Also, if you have to invest money, it is better that you invest money on the parameters of the most influence on system capacity.

2. Experimental Set Up and Procedure

2.1. *Test Rig*

The Photograph of test rig and a schematic diagram are shown in figure 1-a and figure 1-b. The test rig consists of four main component of refrigeration cycle, two voltage regulator, test room and measuring devices. The voltage regulator had been connected to compressor motor in order to change the magnitude of supplied voltage for changing the volumetric flow rate of refrigerant .Another voltage regulator has been used to change the magnitude of supplied voltage to condenser fan motor in order to change the rate of condenser air flow; while the evaporator air flow rate changed by using remote control. Two open ducts were constructed to measure the air flow rate on condenser and evaporator .The room which contain the indoor unit provided with extra air conditioner of 2Ton to fix the indoor temperature.

A measuring devices for pressure, temperature and refrigerant flow rate were also used during experimental test. A turbine flow meter type (KF 500) was installed after the DX evaporator to measure the volumetric flow rate of refrigerant. The data logger plus extension are connected with 15 temperature sensors type (LM 35 DZ) and personal computer to save reading of temperature sensor. Data acquisition unit of 12 channels propped with 2GB SD card to save the reading of thermocouple.

2.2. *Method of Changing the Supplied Voltage to Compressor*

The voltage regulator was used to control manually the amount of voltage that supplied to the compressor motor to change the input power, so when it's set on (220 v) the motor is rotate with its original speed. Before the voltage regulator the automatic voltage regulator (stabilizer) is installed to maintain the voltage supplied to voltage regulator about (220V).

2.3. *Method of Changing and Measuring Condenser Air Flow*

Voltage regulator was used to control manually the amount of voltage that supplied to the motor of condenser fan to changing the input power, so when it's set on (220 v) the motor is rotate with its original speed and gives the standard rate of air flow. To decrease the magnitude of air flow the voltage supply must be decrease. Open duct was constructed to calculate the condenser air flow rate with dimensions (0.5*0.5*2 m).The duct is contain 4 holes away (1.8 m) from the discharge air to measure the average air velocity. The common method used to measure air flow in rectangular duct is equal area method this method divides the traverse plane in to equal area. [9] The velocity was measured by hot wire (anemometer).

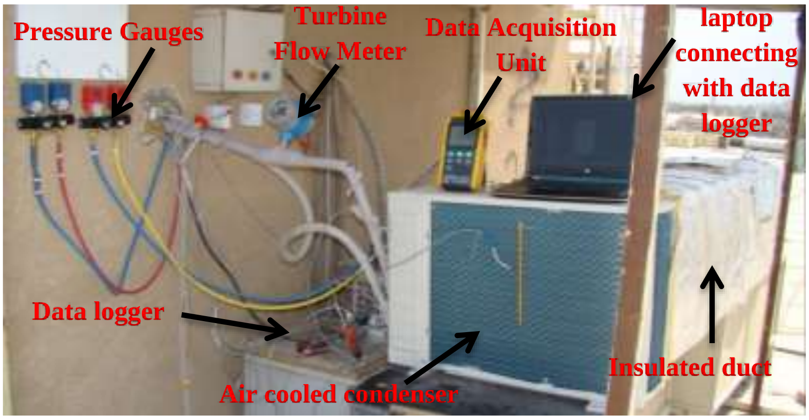

Figure 1-a. Photograph of the test rig

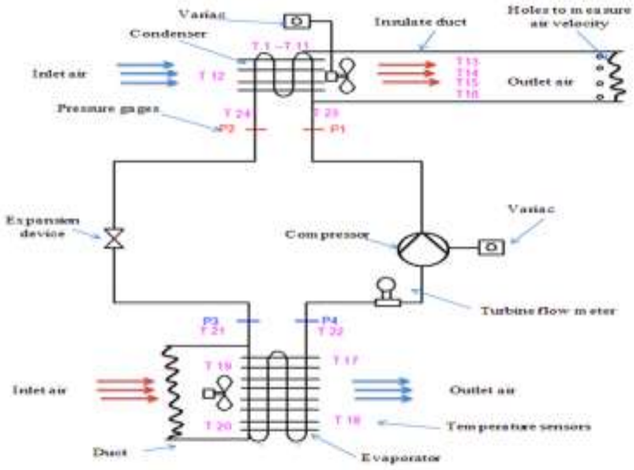

Figure 1-b. Schematic diagram of the test rig.

2.4. *Method of Changing and Measuring Evaporator Air Flow*

The remote control is used to change the speed of evaporator fan then the rate of air flow will be changed .The med speed is taken the base. Open duct was constructed to measure the average evaporator air flow rate with dimensions (0.78*0.17*0.37) m. The vane anemometer was used to measuring the rate of air flow. The number of point taken is 18 point.

3. Mathematical Model

The purpose of this mathematical model is to predict the performance of the overall system when the characteristics of the individual components are known. A further function of the techniques to be explained is to analyze the influence of externally imposed conditions. For example, system analysis can predict the influence of a change in ambient temperature of the air serving the condenser on refrigeration capacity.

3.1. *Compressor Performance*

The expected trends of the refrigeration capacity is increased with an increases in the evaporating temperature and decreases with an increase in the condensing temperature. The power required by the compressor in general increases with an increase in the condensing temperature as shown in figure 4 and figure 5. The Specifications of compressor are shown in table 1.

Table 1. Specifications of compressor

Specifications of compressor	
Type	Rotary
Manufacturer	Toshiba company
Model	PH210X2C-4FTS1
Refrigerant	R22
Input power	1130 W
pistons displacement	20.8 cm3
Cooling capacity	3620 W

One choice of the form of the mathematical equations that represent performance data of present work in figure 4 and 5 are: [7]

$$Q_e = C_1 + C_2T_e + C_3T_c + C_4T_e^2 + C_5T_eT_c + C_6T_c^2 + C_7T_e^2\,Tc + C_8T_eT_c^2 + C_9T_e^2\,T_C^2 \qquad (1)$$

$$P_{comp} = D_1 + D_2T_e + D_3T_c + D_4T_e^2 + D_5T_eT_c + D_6T_c^2 + D_7T_e^2Tc + D_8T_eT_c^2 + D_9T_e^2T_c^2 \qquad (2)$$

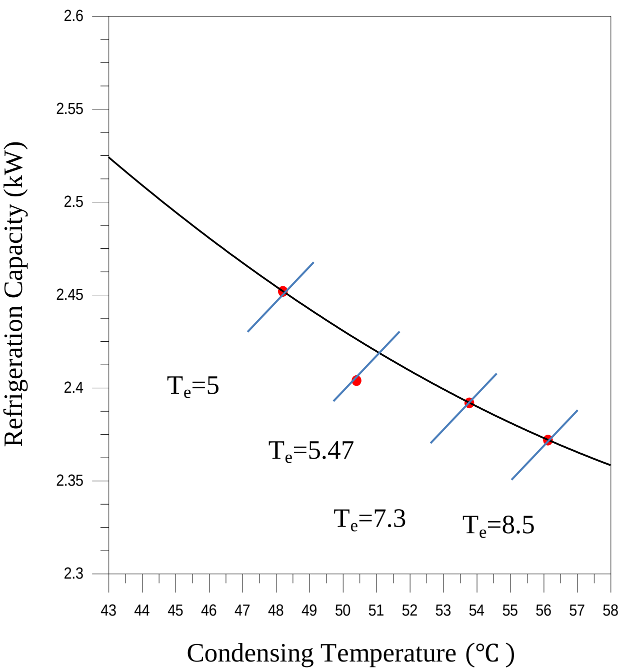

Figure 2. The variation of refrigerant capacity of the system via Condensing Temperature.

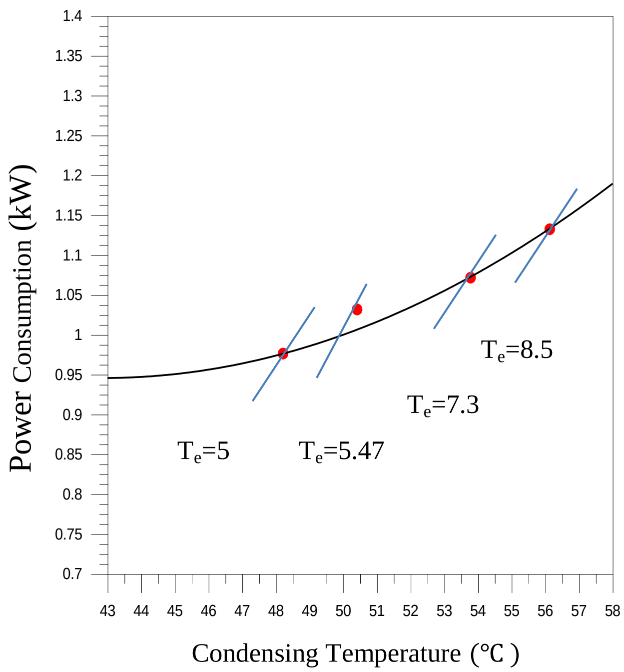

Figure 3. The variation of power consumed by the compressor via Condensing Temperature.

In addition to the refrigerant capacity and the power requirement of the compressor, another quantity of interest is the rate of heat rejection required in the condenser. It is simply the sum of the refrigerating capacity and compressor power at a given combination of evaporating and condensing temperatures. [7]

$$Q_{c\,E.B} = P + Q_e \qquad (3)$$

A graph of the heat rejection rate form the condenser of a tested refrigeration system is shown in figure 6, which has been obtained from the experimental data. In the form of the mathematical equations that represent the performance data of figure 6 is:

$$Q_{cEx} = B_1 + B_2T_e + B_3T_c + B_4T_e^2 + B_5T_eT_c + B_6T_c^2 + B_7T_e^2\,Tc + B_8T_eT_c^2 + B_9T_e^2T_c^2 \qquad (4)$$

3.2. *Condenser Performance*

The precise representation of the heat transfer performance of a condenser can be quite complex, because the refrigerant vapor enters the condenser superheated and following the onset of condensation in the tube. The fraction of liquid and vapor changes constantly through the condenser. A satisfactory representation of air-cooled condenser performance for most engineering calculations is available, however, through an assumption of a constant heat exchanger effectiveness for the condenser, namely [7]

$$Q_c = F\,(T_c - T_{amb}) \tag{5}$$

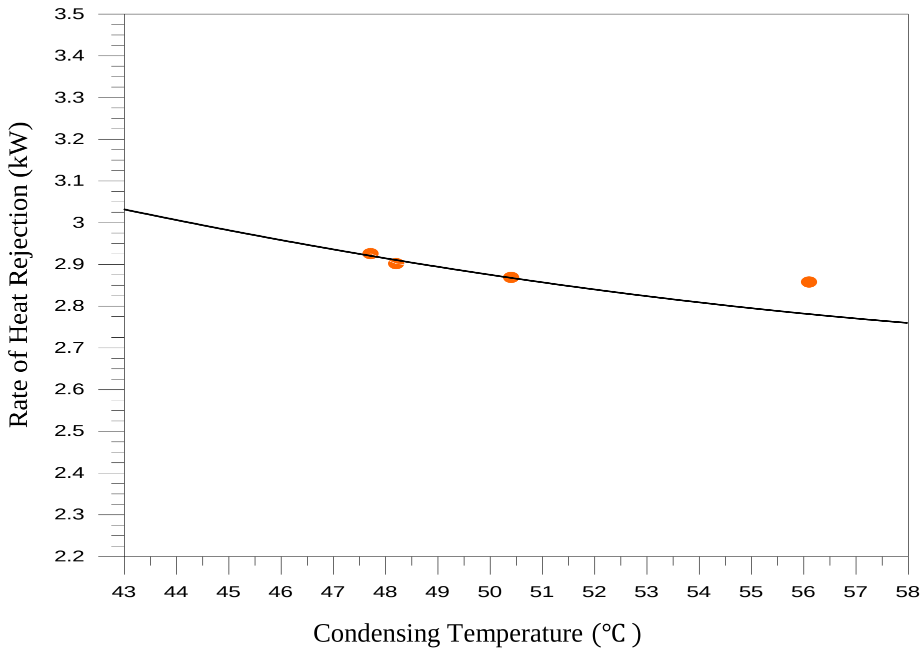

Figure 4. The variation of Rate of Heat Rejection via Condensing Temperature.

3.3. *Evaporator Performance*

Several parameters influence the evaporator performance, such as heat-transfer coefficient of air, the boiling coefficient of a refrigerant flow in evaporator and the rate of air flow through evaporator. For subsequent mathematical simulation, an equation is needed to express the evaporator capacity.[7]

An adequate equation could originate from:

$$Q_e = G(T_{ain} - T_e) \tag{6}$$

3.4. *Mathematical Analysis*

The performance of each component in for split air-conditioner, and a combination of these components needs to determine the constants of equations (1), (2) and (4) , and factors of equations (5) and (6). The constants applicable to equations (1), (2) and (4) in figure 4, 5 and 6 are determined by surface-fitting procedures, e.g., nine points of the graph were needed to determine the constants, but for best fit seventeen points was selected and substituted into equation (1) ,(2) and (4) to develop a set of nine simultaneous equations for the (B) , (C) and (D) constants. The numerical values shown in table (2) Depending on the Matlab software version R2014a, and the surface fitting method.

Table 2. Constants in Equations (1), (2) and (3)

NO	Constants		
	B	C	D
1	11	1.386	-5.873
2	1.518	-0.9572	-2.409
3	-0.4236	0.1053	0.4338
4	-0.09595	-0.02286	-0.2269
5	-0.04445	0.03528	0.09261
6	0.005653	-0.001923	-0.006837
7	0.004314	-0.0002276	0.004046
8	0.0001379	-0.0002382	-0.0005588
9	-3.606e-05	6.11e-06	-2.003e-05

To determine the factor (F) the condenser capacity, condensing temperature and ambient temperature must be substituted in equations (5) while to determine the factor (G) the evaporator capacity, evaporator temperature and temperature of air entering to evaporator must be substituted in equations (6).

$F= Q_{c\ E.B} / (T_c-T_{amb})= (3.44013)/(47.71-31.26)=0.2091$ kW/K

$G=Q_e /(T_{ain}-T_e)=(2.485)/(26.3477-4.47)= 0.1135$ kW/K

4. Data Reduction

A/C unit is installed after a lot of preparations to become suitable for the experimental work. To study the effect of any parameter on system performance, other parameter must be fixed as possible, for example to study the effect of condenser air flow rate on system performance the test must be taken approximately at same ambient temperature, fixed indoor temperature, supplied voltage to compressor and fixed evaporator air flow .In order to compute the Refrigeration capacity, the Cool Pack package is used [10].

The evaporator cooling capacity, Q_{ev}, can be calculated as:

$$Q_e= m_{ref} (h_{in}-h_{out}) \quad (7)$$

The common approach in determining the refrigeration cycle performance is to use the coefficient of performance, COP, depending on the compressor power consumption as; [11]

$$COP = Q_e/ P_{comp} \quad (8)$$

$$COP)_{tot} = Q_e / (P_{comp} + P_{eva\ fan}+ P_{con\ fan}) \quad (9)$$

5. Results and Discussion

5.1. *Effect of Variation the Supplied Voltage to Compressor*

The compressor is one of essential component in the VCRS, the compressor circulate and compressed refrigerant throw the system in continues cycle. If the input voltage to compressor decreased the ability of compressing the refrigerant also decreased this lead to decreasing in the condensing pressure and temperature by 1.6% and 1.2% at (170) V and (190) V respectively as shown in (p-h) diagram figure 5. Also causes decreasing in mass flow rate of refrigerant and less refrigeration capacity as shown in figure 6 and 7 because the rotation speed of compressor is decreased, when the input voltage decreased the rated of input current increased to overcomes the reducing in input voltage this led to increase the surface temperature of compressor which reduce the density of refrigerant .

At ambient temperature 39 ℃ the condensing pressure is low compared with 41 ℃ and 44 ℃ ,therefore when the input voltage decreased the power consumption also decreased as shown in figure 8 except at ambient temperature 44 ℃ the power consumption increased because compression ratio increased rapidly than 39 ℃. The $COP)_{tot}$ shown in figure 9 decreased because voltage drop causes reduction in refrigeration capacity and sometime increased the power consumption as discussed above.

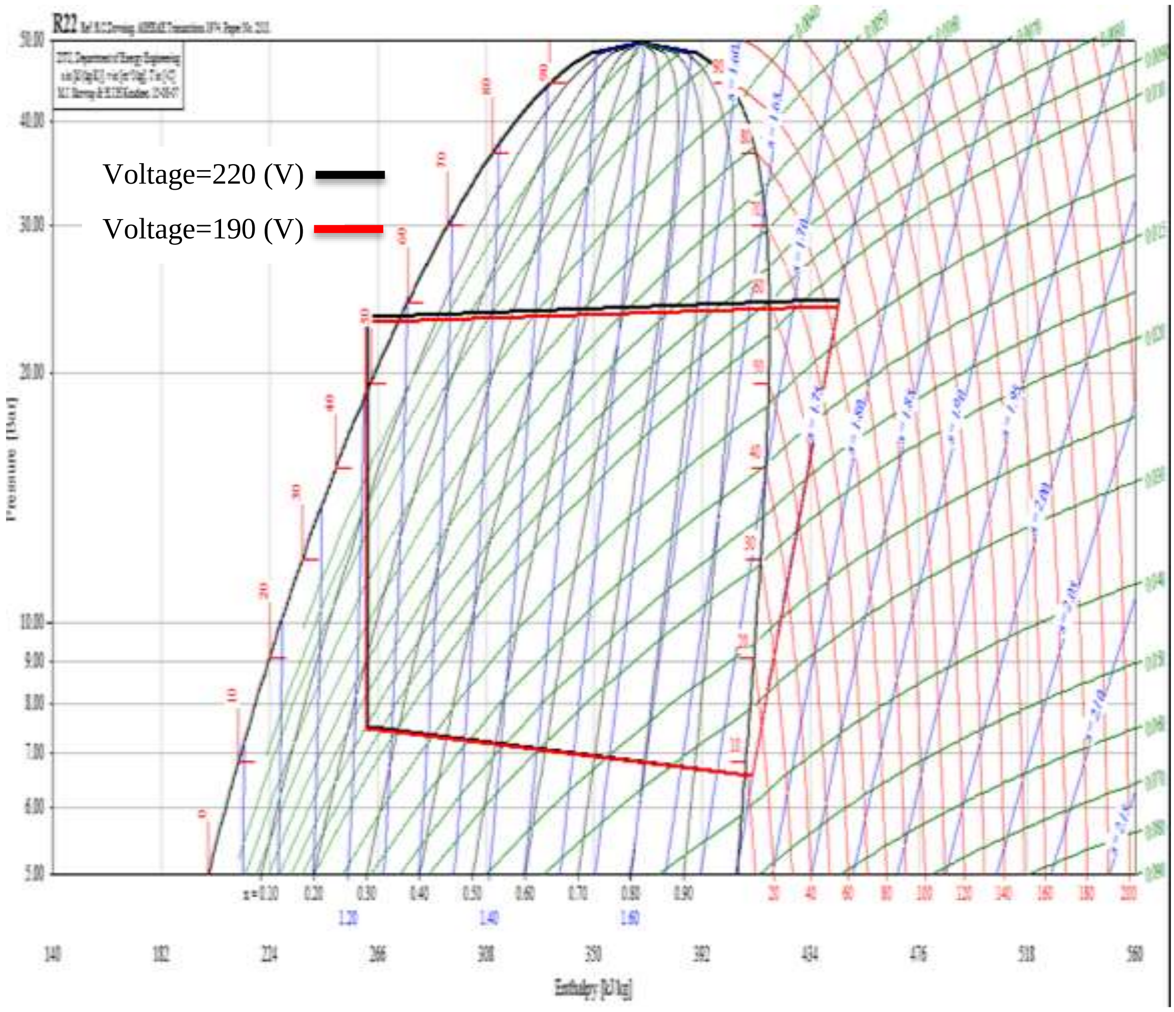

Figure 5. The effect of supplied voltage to compressor variation on the system performance at ambient air temperature 44 ℃ .

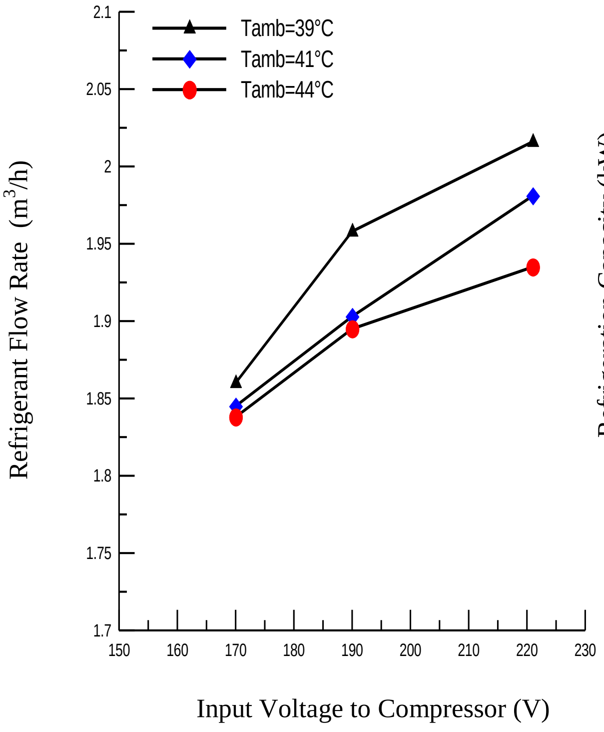

Figure 6. The variation of input voltage to compressor via volumetric flow rate of

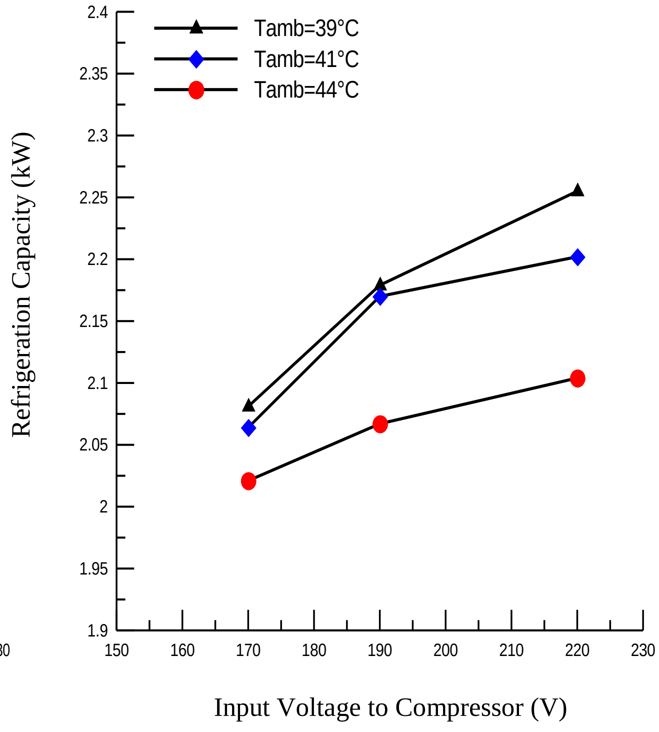

Figure 7. The variation of input voltage to compressor via refrigeration capacity.

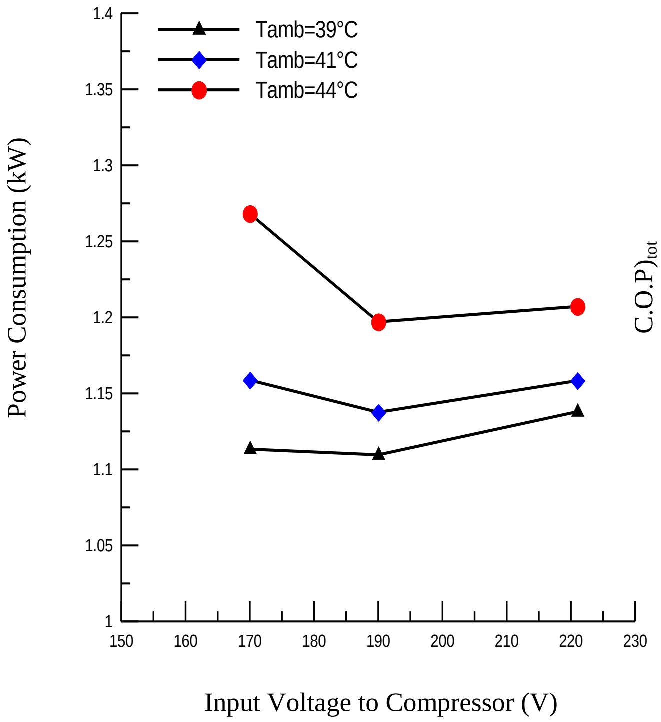

Figure 8. The variation of input voltage to compressor via power consumption by compressor.

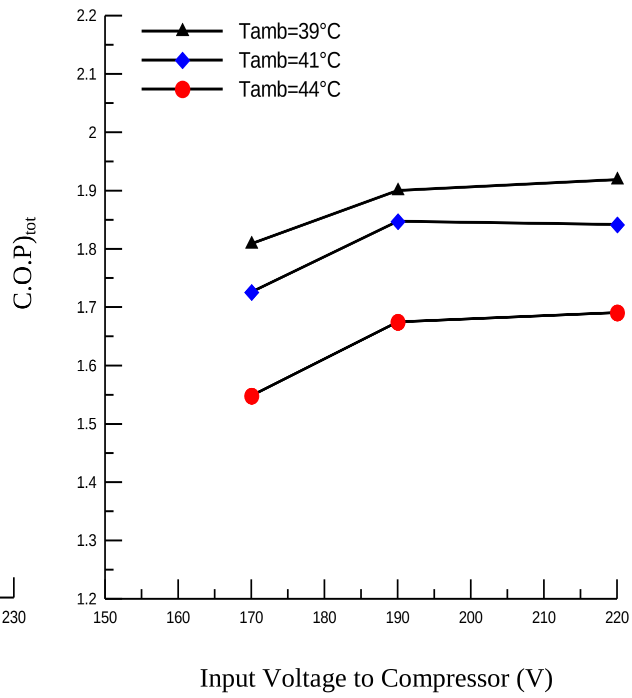

Figure 9. The variation of input voltage to compressor via $COP)_{tot}$.

5.2. *Effect of Condenser Air Flow Rate*

When the air flow rate throw air cooled condenser decreased the rate of heat transfer between the refrigerant side and air side also decreased ,so the rate of heat rejection from condenser decreased this causes increasing in condenser pressure and temperature and increase in evaporator pressure and temperature this as shown on (p-h) diagram figure 10. As the mass flow rate of air serving on condenser decreased the condenser capacity and evaporator capacity also decreased because the rate of heat rejection decrease this causes reduction in rate of condensation refrigerant this which effect on evaporator capacity as shown in figures 11 and 12.

The increased condensing temperature results in a considerable additional in compressor electric demand as shown in figure 13. Although the decreased of airflow causes the reduction in fan electric power demand but this decreases is not covered the increasing in compressor power so the C O P)tot decreased as shown in figure 14.

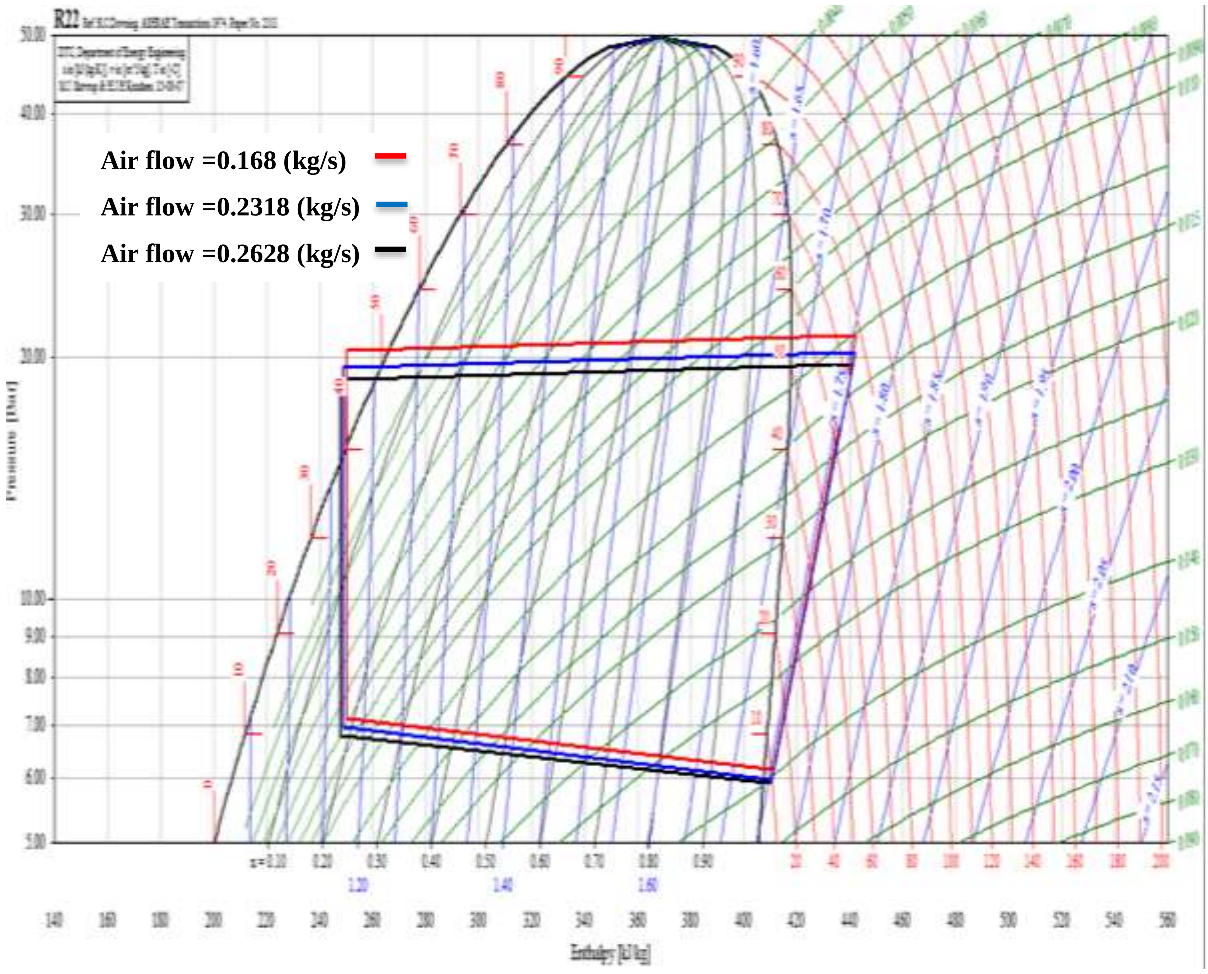

Figure 10. The effect of condenser air flow variation on the system performance at ambient air temperature 35 °C .

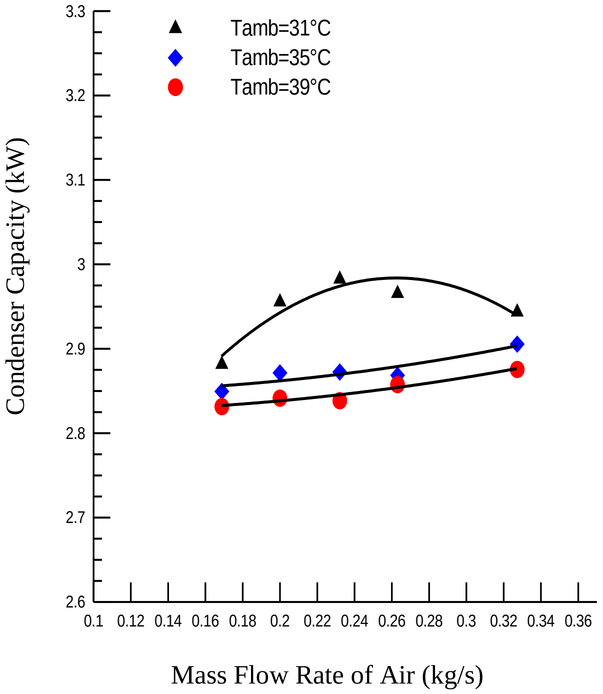

Figure 11. The variation of mass flow rate of air on condenser via condenser capacity.

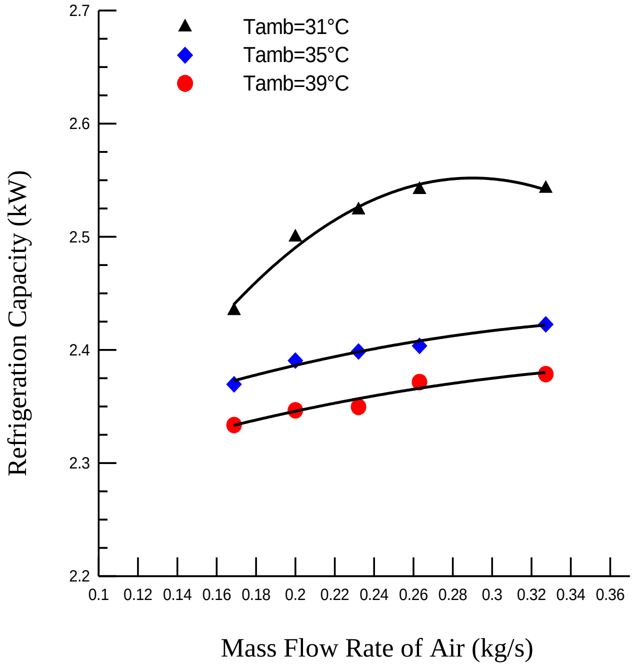

Figure 12. The variation of mass flow rate of air on condenser via Refrigeration capacity.

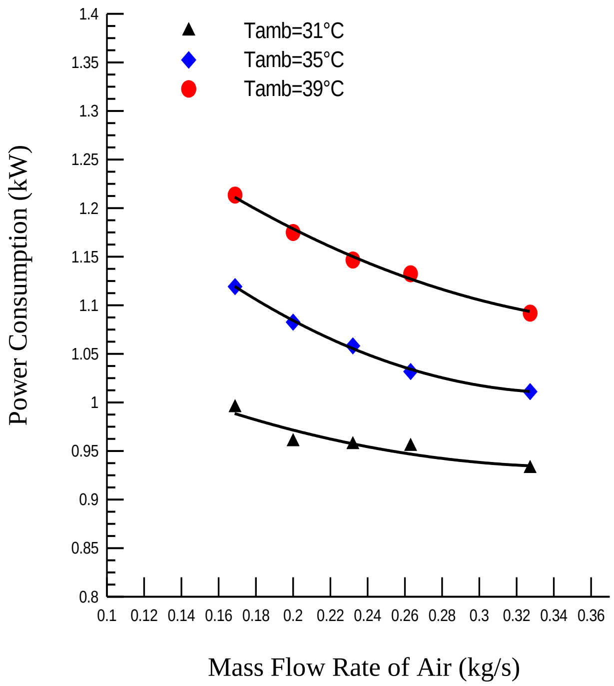

Figure 13. The variation of mass flow rate of air on condenser via power consumption by compressor.

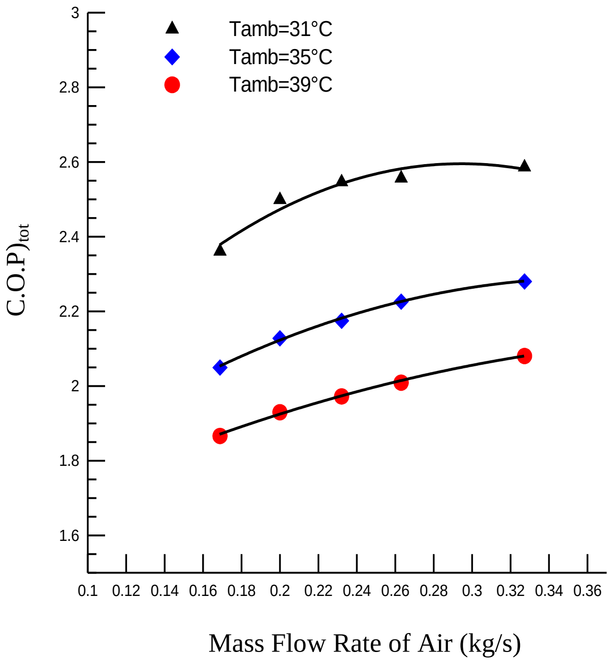

Figure 14. The variation of mass flow rate of air on condenser via the $COP)_{tot}$.

5.3. *Effect of Evaporator Air Flow Rate*

As the evaporator air flow increased the rate of heat transfer between the refrigerant side and air side increased so the rate of refrigeration effect also increased this causes higher evaporator pressure and temperature and higher condensing pressure and temperature compressor as shown on (p-h) diagram in figure 15. Figures 16, 17 and 18 show the increased in condenser capacity, evaporator capacity and power consumption by compressor due to increasing in evaporator air flow because when the rate of evaporator air flow increase the rate of refrigerant evaporation increase which gives more cooling capacity ,need more work to compress refrigerant and need heat rejected in condenser . Figure 19 explain, as the rate of evaporator air flow increased the $COP)_{tot}$ also increased because the rate of increasing in cooling capacity is more than the rate of increasing in input power to compressor and evaporator fan .

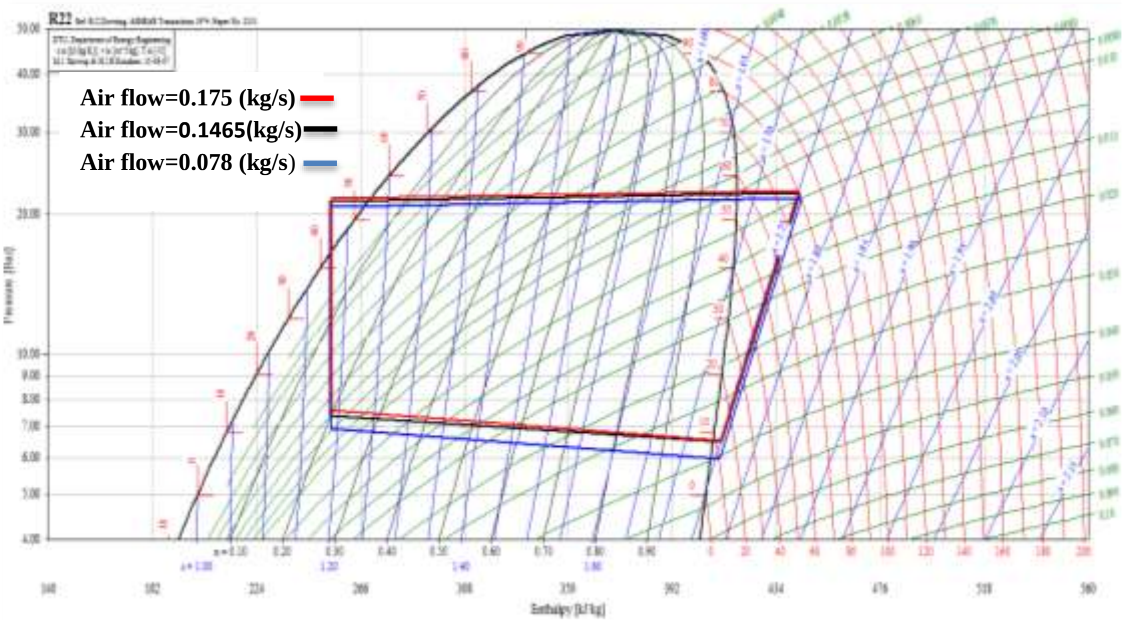

Figure 15. The effect of evaporator air flow variation on the system performance at ambient air temperature 39 °C .

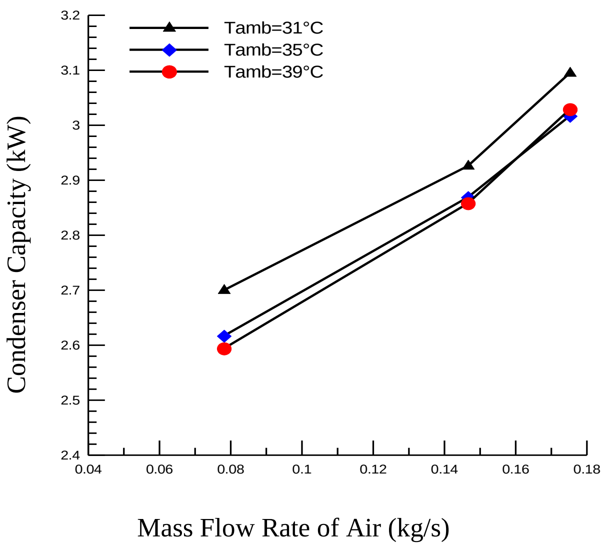

Figure 16. The variation of mass flow rate of air on evaporator via condenser capacity.

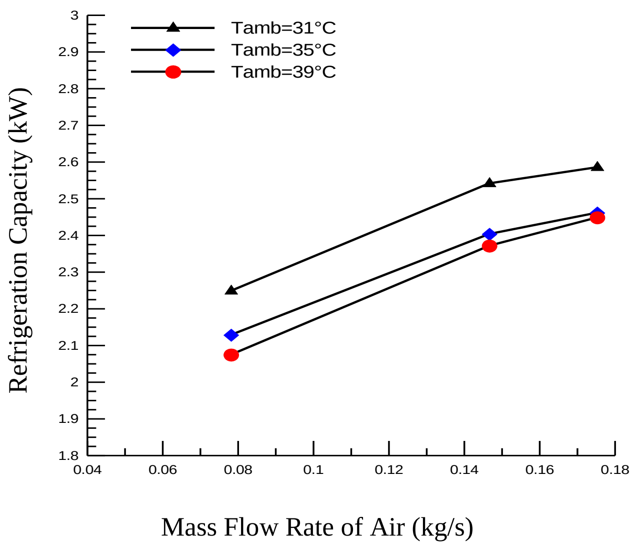

Figure 17. The variation of mass flow rate of air on evaporator via Refrigeration capacity.

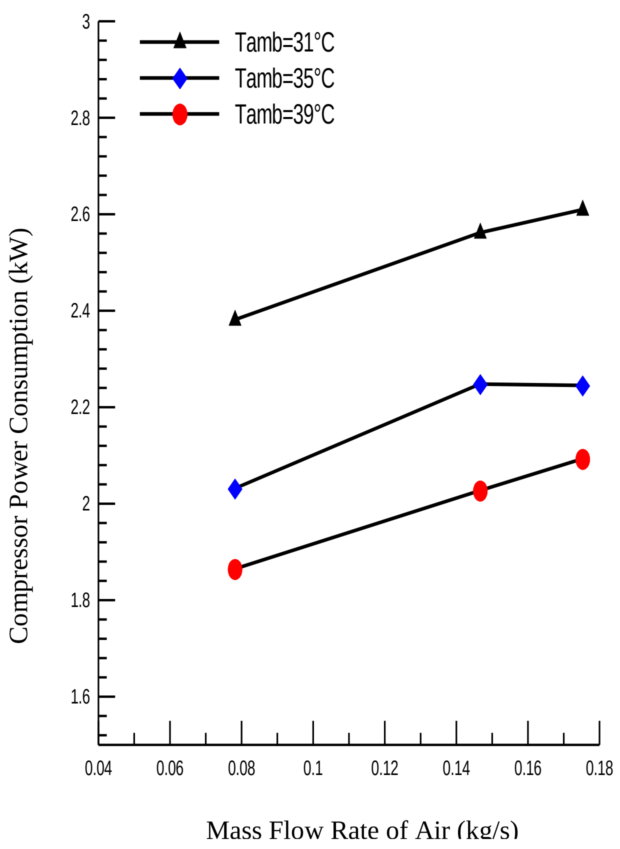

Figure 18. The variation of mass flow rate of air on evaporator via power consumption by compressor.

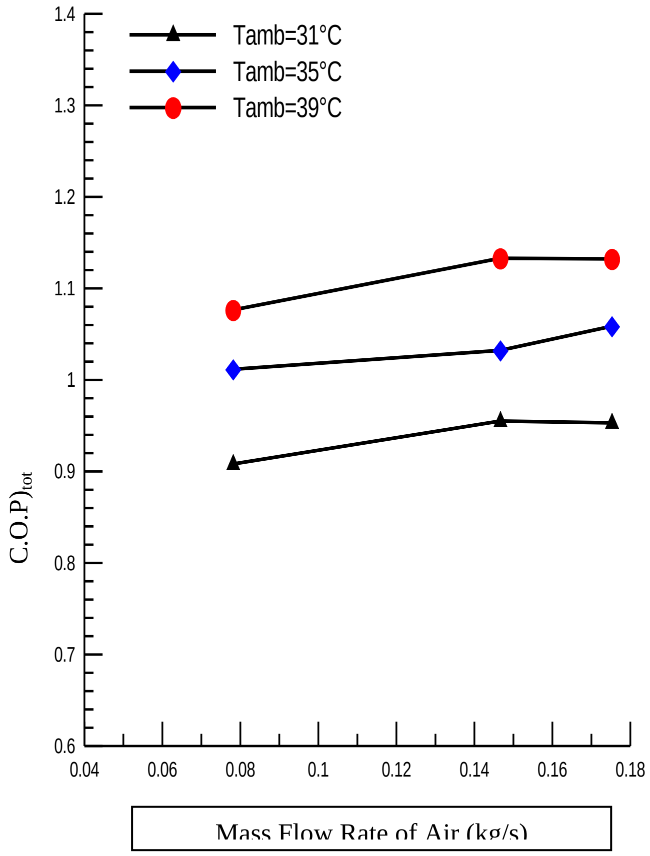

Figure 19. The variation of mass flow rate of air on evaporator via $COP)_{tot.}$

5.4. *Effect of Ambient Temperature*

The outdoor ambient temperature is a dominant parameters that effect on the refrigeration systems. Figure 20 show the effect of outdoor ambient temperature on the performance of the system represented on a (p-h) diagram.

As noticed from the figures, the increase in outdoor ambient temperature yields a decrease in refrigeration effect due to the increase in condensing temperature which consequently yields an increase in condensing pressure and reducing the amount of heat rejected from the condenser.

Also, this will yield an increase in power consumed by the compressor as a result the coefficient of performance will decrease. Figures 21 to 24, shows the variation of outdoor ambient temperature (31 °C, 33°C, 35 °C, 37 °C and 39°C) and its effect condenser capacity, compressor power consumption, refrigeration capacity and $C\ O\ P)_{tot}$ this results are agree with the Al-Hazeen, results.

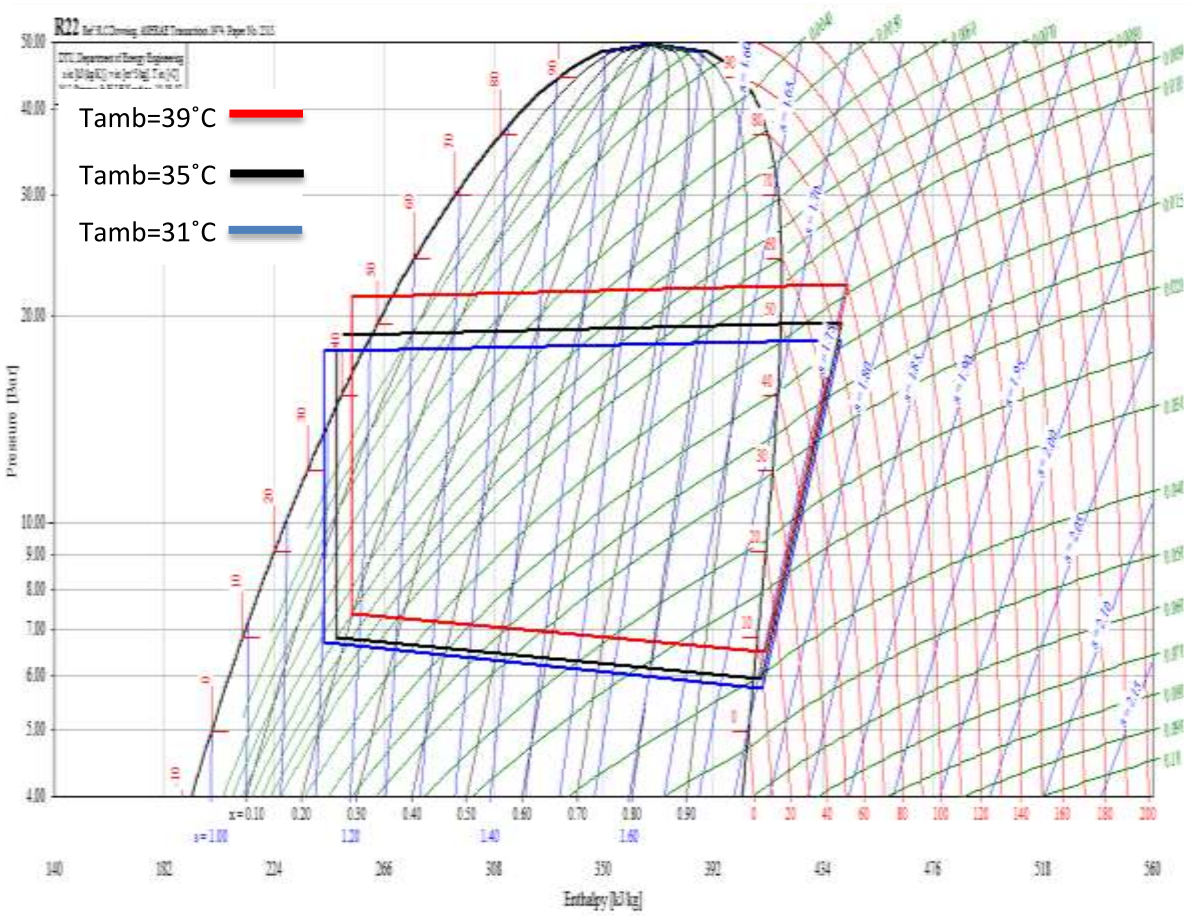

Figure 20. The effect of ambient air temperature variation on the system performance.

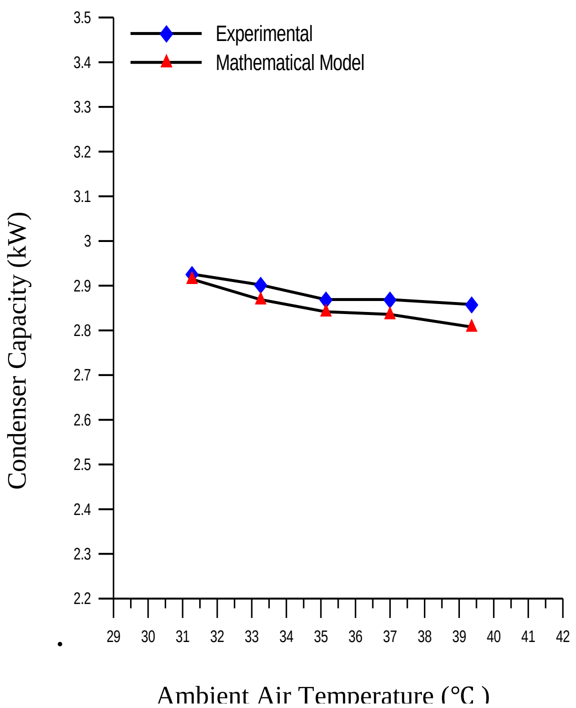

Figure 21. The variation of condenser capacity of the system via ambient air temperature.

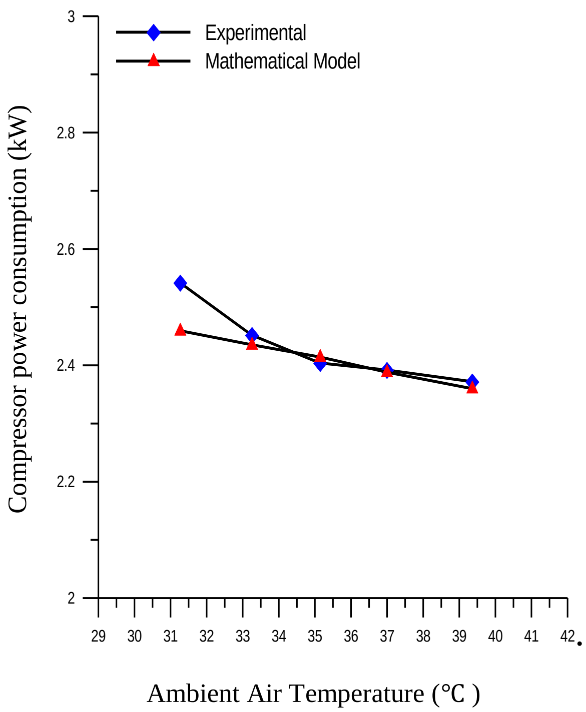

Figure 22. The variation of power consumption by the compressor via ambient air temperature.

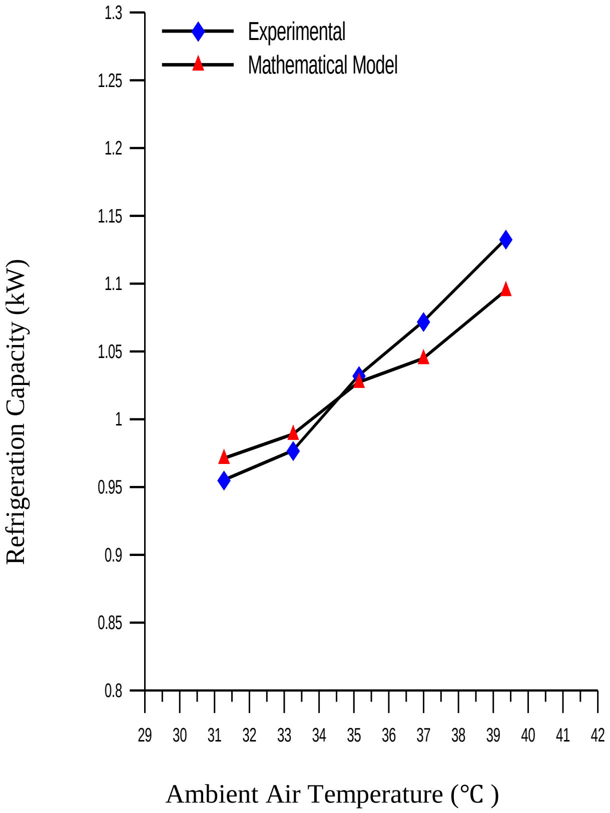

Figure 23. The variation of refrigeration capacity of the system via ambient air temperature.

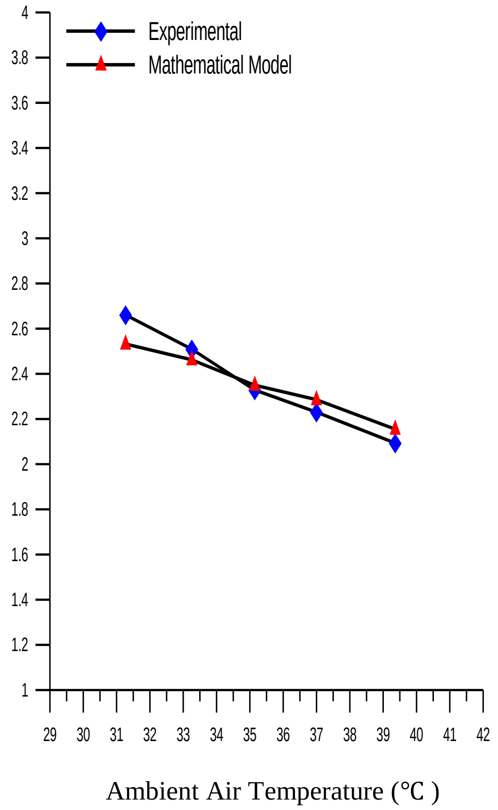

Figure 24. The variation of the COP via ambient air temperature.

5.5. *Mathematical analysis*

The mathematical analysis is used to predict and verify the influence of a change in ambient temperature of the air serving the condenser on refrigeration capacity. The results of first purpose are drawn with experimental results as shown in figures 21, 22, 23 and 24. The results of mathematical analysis are compared with experimental results, the maximum deviation of condenser capacity ,refrigeration capacity , power consumption and COP are 1.75% ,3.2% , 3.34% and 4.84% respectively. The flow chart which explain the simulation program are shown in figure 25.

6. Conclusions

The following points can be concluded from the present work:

1. The supplied voltage to compressor is the most important parameter which affects refrigeration capacity. The evaporator air flow was found to be of the second important effect and finally the condenser air flow.
2. As the ambient temperature decreases by (11%) the C.O.P increased by 14.27% while at ambient temperature increases by (11.9%) the C.O.P decreased by 10%.
3. The effect of ambient temperature on refrigeration capacity and COP is higher than the rate of condenser air flow**.**
4. The mathematical model could be used to product the performance of refrigeration system.

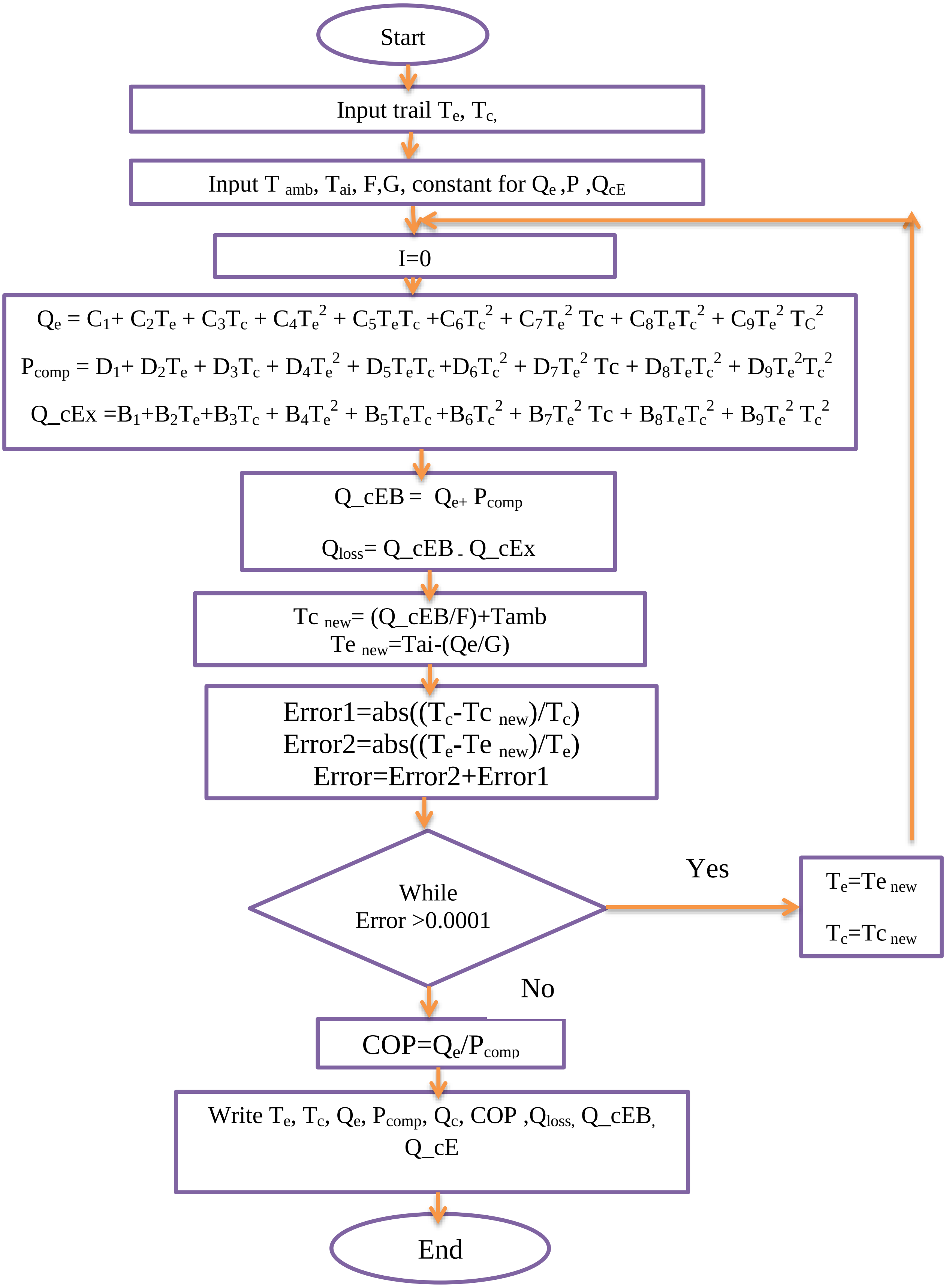

Figure 25. Flow chart of simulating the complete vapor- compression system.

Abbreviations

• *Latin Symbols*	*Description*	*Unit*
Q_e	Refrigerating capacity	kW
P_{comp}	Power consumption by compressor	kW
$Q_{c\ E.B}$	Rate of heat rejection at condenser obtained from energy balance	kW
Q_{cEx}	Rate of heat rejection at condenser obtained from the experimental data	kW
Q_{loss}	Rate of total losses	kW
$P_{eva\ fan}$	Rate of evaporator fan power	kW
$P_{con\ fan}$	Rate of condenser fan power	kW
h	Refrigerant enthalpy	kJ/kg
m_{ref}	Refrigerant flow rate	kg/s
T_{amb}	Ambient temperature	℃
F	Capacity per unit temperature difference	kW/K
G	Proportionality factor	kW/K
T_{ai}	Temperature of entering air to evaporator	℃
V	voltage	v
T_e	Evaporating temperature	℃
T_c	Condensing temperature	℃
COP	Coefficient of performance	----
$COP)_{tot}$	Total coefficient of performance	----

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