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Original Article

DESIGN AND PERFORMANCE ANALYSIS OF A HEAT EXCHANGER USED IN A VAPOUR COMPRESSION REFRIGERATION SYSTEM

ADNAN M. AL SAFFAWI[1] & MAAN S. AL DABBAGH[2]

[1]*Assist Professor, Department of Mechanical Engineering, College of Engineering, University of Mosul- Mosul, Iraq*

[2]*Lecturer, Department of Mechanical Engineering, College of Engineering, University of Mosul- Mosul, Iraq*

ABSTRACT

The research aims at designing a heat exchanger added to an air conditioning system of 2 ton capacity with R-407c as a working refrigerant in order to enhance its performance and then compare the performance with a simple conventional system. A computer program of engineering solver equations language (EES), which contains the thermal and physical properties of the refrigerant, is setup to design a heat exchanger and to predict the coefficient of performance of the system.

Results indicate that adding the heat exchanger enhances the coefficient of performance of the system and it is increases as the length of the exchanger is increases. The percentage enhancement reached (59%) when a heat exchanger of length 26 mm was added to the system.

KEYWORDS: Air conditioning systems, Heat exchanger, Performance

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Nomenclature:

A	Area	m^2
Cp	Specific heat at constant pressure	kJ/kg.K
COP	Coefficient of performance	
D	Diameter of the tube	m
h	Enthalpy	kJ/kg
hi	Heat transfer coefficient of inner fluid	$W/m^2.K$
ho	Heat transfer coefficient of outer fluid	$W/m^2.K$
k	Thermal conductivity	kJ/kg.K
$\dot{m}$	Mass flowrate	kg/s
NTU	Number of Transfer Unit	
Q	Heat transfer	W
U	Overall heat transfer coefficient	$W/m^2.K$
V	Velocity	m/s
W	Work done	kW
ρ	Density of refrigerant	kg / m^3
μ	Dynamic viscosity of the refrigerant	$N.s/m^2$
ε	Effectiveness	

Subscripts:

$1,2,3,4,1',2'$	Number of states
cond.	Condenser
evap.	Evaporator
cold	cold refrigerant
hot	hot refrigerant
max.	maximum
min.	minimum

Dimensionless Number Unit

Nu	Nusselt number
Pr	Prandtl number
Re	Reynold number

INTRODUCTION

A refrigeration system is defined as a system that takes heat from the low temperature region and rejects it to high temperature region according to the second law of thermodynamics. A number of researchers have been interested in improving the performance of the refrigeration systems and decreasing the size and weight of each part of the system. In spite of this improvement, the basic notion for system operation does not vary and this is causes difficulties which must be treated. The most important thing is that a large amount of energy is consumed to operate the mechanical compressor.

The coefficient of performance of a refrigeration system is; “the ratio of refrigerating effect to the compression work”. Therefore, the coefficient of performance can be increased by decreasing the compressor work or by increasing the refrigerating effect. The researchers are interested in how much heat is extracted from the space to bring it at a desired temperature and how little electrical energy is consumed in the compressor. There have been several efforts to improve the performance of the system. Some researchers used alternative refrigerants and varying pressures of both condenser and evaporator using two or multi - stage compression to improve the system performance. Other works have been interested in the installation of a heat exchanger between a liquid line and suction line in a vapour compression system.

In an experimental investigation made by Yadav et al. [1] on a domestic refrigerator of a capacity (160) liters, using (R - 134a) and (R - 404a) as a refrigerant, the liquid line tube is welded to the suction line tube forming a counter flow heat exchanger. The study involved different lengths of heat exchanger. They concluded that:

- The refrigerating effect increased when the length of heat exchanger is increased and the higher value was for (R-134a) at the length of (30) cm.
- The coefficient of performance (COP) increased when the length of heat exchanger is increased and the higher value was for (R-404a) at (30) cm length.
- There is a limitation to increase the length of heat exchanger due to the space limitation.
- Domanski et al. [2] carried out a theoretical estimation of the performance of vapour compression estimation refrigeration systems when a liquid – suction heat exchanger was installed in it considering 29 different refrigerants. They concluded that the benefits of adding the heat exchanger between the liquid line and suction line depends on the combination of fluid properties such as latent heat, thermal expansion and heat capacity. But the heat capacity being the most influential property.

Farkade and Inamdar [3], studied the enhancement in the performance of refrigeration cycle by adding a heat exchanger between the discharge line and suction line. They concluded that a liquid – suction heat exchanger leads to improve the performance for all types of refrigerant. Also, the power of compressor is slightly affected by the change in state of the refrigerant at the inlet of the compressor, which causes the reduction in mass flow rate of refrigerant due to that liquid – suction heat exchanger increases the temperature and reduces the pressure of the refrigerant entering the compressor causing a decrease in the density of refrigerant and volumetric efficiency of compressor.

It is therefore, the object of the present work to design a heat exchanger added to an air conditioning system of 2 ton capacity with R-407c as a refrigerant and to calculate the coefficient of performance of this system and compare it with that of conventional systems.

Proposed System and Cycle Analysis

The proposed system is a simple vapour compression system with a heat exchanger added between the discharge line and the suction line. This heat exchanger will superheat the vapour leaving the evaporator and subcooled the liquid refrigerant leaving the condenser. Also, this heat exchanger will protect the system component by helping to ensure pure liquid to expansion valve and pure vapour to the compressor.

Figure (1 a,b) illustrates the schematic diagram of proposed system and the pressure – enthalpy diagram showing effect of adding the heat exchanger.

The analysis of the cycle is based on the following assumption:

- The flow of refrigerant through the cycle is steady and one – dimensional.
- The compression process is reversible adiabatic.
- The pressure drops of refrigerant though condenser, evaporator, and connecting tubes are neglected.
- The cooling capacity of the system is 2 ton.

According to the thermodynamic cycle of the simple refrigeration system shown in Figure (2 a,b) , and at a certain temperature of condenser and evaporator, the coefficient of performance was calculated after the values of enthalpies for different states where known. The mass flow rate of refrigerant can be calculated from the following equation [4];

$m = Q_{evap.} / (h_1 - h_2)$ (kg/s) .... (1)

The work consumed by compressor is [4];

$W = m * (h_2 - h_1)$ (kJ/s) .... (2)

And the coefficient of performance will be calculated from [4];

$COP = Q_{evap.} / W$ .... (3)

When the heat exchanger is added between the discharge line and suction line, the heat will transfer from high temperature liquid leaving the condenser to a low temperature vapour leaving evaporator, and the refrigerating effect ($Q_{evap.}$)becomes;

R.E or $Q_{evap.} = (h_1 - h_5)$ (kJ / kg) .... (4)

And the work required to operate the compressor is;

$W_{actual} =$ 1

m $(h_2' - h')$ (kJ/s) .... (5)

The coefficient of performance will be;

$COP = R.E / W_{actual}$ .... (6)

Heat Exchanger Design

A concentric tube, counter flow heat exchanger type is proposed to be used, in which the refrigeration liquid from the condenser (hot refrigerant) flows through the inner tube, while the refrigerant vapour from the evaporator (cold refrigerant) flows through an annular space.

In order to determine the dimensions of the copper tube which is selected for a heat exchanger, the following assumptions were considered.

- The overall coefficient of heat transfer, U, is constant over the length of the heat exchanger.
- The properties of refrigerant are constant.
- No heat is lost to the surrounding.

For a certain condenser temperature ($T_{cond.}$) and evaporator temperature ($T_{evap.}$), and for inner and outer diameters of (Di) and (Do) respectively, we can estimate the velocity of the refrigerant in inner tube and in annular space by the following equation [5,6]:

V =

And

m / (ρ Ac) (m/s).. (7)

$Re = (\rho V D) / \mu$ .... (8)

It is recommended that the film coefficient at either surface of the annulus be evaluated by the following equation [6];

$Nu = h D / k = 0.023 (Re)^{0.8} (Pr)^{n}$ (Re < 2500).. (9)

Where;

n = 0.4 for heating the refrigerant and n = 0.3 for cooling the refrigerant

The overall heat transfer coefficient, neglecting the fouling resistance, is given by [5]; $1/U_i = (1/hi) + (ri/k) \ln (ro/ri) + (Ai / Ao) (1/ho)$.. (10)

Since only the inlet temperature of hot and cold fluids are known, the effectiveness

- NTU method is used to design and simplify the analysis of the heat exchanger. The effectiveness of heat exchanger (ε), is calculated from [6],

ε = Actual rate of heat transfer / maximum possible rate of heat transfer

$= \Delta T_{min} / \Delta T_{max} = (T_1^{/} – T_{evap.}) / (T_{cond.} – T_{evap.})$.. (11)

Where ΔT_{min} is the difference between the outlet and inlet temperatures of the refrigerant with the smaller heat capacity. ΔT_{max} is the maximum temperature difference in the heat exchanger which is the difference in inlet temperatures between the hot and cold refrigerants , that is,

$\Delta T_{max} = T_3 – T_1 = T_{cond.} - T_{evap.}$

The surface area required can be obtained from the number of transfer units, NTU , which, in turn, can be obtained from knowledge of heat capacity rate, and the number of transfer units can be calculated from [6];

$NTU = (1/ C_r) \ln [(\varepsilon -1) / (\varepsilon C_r – 1)]$.. (12)

Where C_r is the heat capacity ratio, $C_r = C_{min} / C_{max}$

Where C_{min} is the smaller of C_{hot} = and C_{max} is the larger one .

m hot Cp_{hot} & C_{cold} =

m cold Cp_{cold}

The required surface area can be calculated from [6]; NTU = U A / C_{min}

And the length of tube of the heat exchanger is , $L = A / \pi D_i$

Computer Program

A computer program, in EES language, was setup to design a double tube heat exchanger and to calculate the coefficient of performance of the system [7]. The basic input parameters for calculations are:

The condenser temperature, which is fixed at 40 °C. The evaporator temperature, which is fixed at -10 °C. The refrigeration capacity 2 ton.

The thickness of the inner tube = 0.002 m.

The inner diameter of the inner tube = 0.0127 m. The inner diameter of the outer tube = 0.0254 m.

The program starts to call for the properties of refrigerant (R-407c) for different stats corresponding to the condenser and evaporator temperatures (enthalpy, entropy, specific heat and others). Then it calculates the mass flow rates of refrigerants, work done and coefficient of performance as well as the design calculations for the heat exchanger.

RESULTS AND DISCUSSIONS

Effect of the degree of superheat on Refrigerating Effect

The refrigerating effect of the system means the heat amount that is extracted by the refrigerant in the evaporator. Figure (3) shows that the refrigerating effect is increased with increasing the degree of superheat. It can be noted from the figure that the refrigerating effect is (147.7 kJ/kg) when the degree of superheat is (4°C) while it reaches (153.1 kJ/kg) when the degree of superheat is (10°C). The percentage increment in refrigerating effect is 6% compared with that of a conventional system when degree of superheat is (10°C). This is due to the fact that increasing the degree of superheat means increasing the temperature of vapour leaving the evaporator and this leads the amount of heat lost from the refrigerant to increase which is caused by decreasing the enthalpy of the refrigerant entering the evaporator and as a result the refrigerating effect is increased which represents the difference in enthalpy across the evaporator.

Effect of the Degree of superheat on Compressor Work

The increase in the degree of superheat means increase in the enthalpy of refrigerant vapour entering the compressor, and the compressor work represents the difference in enthalpy between the vapour leaving the compressor and the vapour entering the compressor. Therefore, the work of the compressor will decrease with increasing the degree of superheat as shown in Figure (4). The decrement in system work reached 33% compared with that of a conventional system when the degree of superheat is (10°C).

Effect of the degree of superheat on coefficient of performance (COP):

It can be noted from Figure (5) that the coefficient of performance increases with increasing the degree of superheat. The percentage increase reaches (27%) when the degree of superheat varying from (4°C) to (10°C) and reaches (59%) compared with that of a conventional system at (10°C) superheat. The increment in COP is due to the increase in degree of superheat leading to increase in refrigerating effect and decrease in work required to operate the compressor as mentioned above. Therefore, the coefficient of performance will increase, since it represents a ratio of refrigerating effect to compressor work.

Figure (6) shows a comparison between three systems operating at different condenser temperatures which are (35°C, 40°C, 45°C) with a constant evaporator temperature of (-10°C). It is observed that the value of COP is higher for low condenser temperature. This is due to the fact that when the condenser operates at a low temperature, it operates at low pressure and this leads to decrease the compressor work.

From Figure 7, it is found that COP is higher when the system operate at high evaporator pressure due to the fact that the work required to raise the vapor pressure to condenser pressure is lower.

Effect of the degree of superheat in Heat Exchanger Tube Length

The effect of the degree of superheat on heat exchanger length is illustrated in Figure 8. The length of heat exchanger is (9.29 cm) when the degree of superheated is 4 °C but the length is equal to (25.8 cm) when the degree of superheat is increased to 10°C. The increase in the degree of superheat means more heat must be absorbed by vapour leaving the evaporator which needs larger area of heat exchange or longer tube for a certain tube diameter.

Effect of the length of Heat Exchanger tube on the Coefficient of Performance

Figures (9), (10) and (11) illustrate the relation between the tube length with refrigerating effect, compressor work and coefficient of performance respectively. Figure 11 shows that as the tube length of heat exchanger increases, the coefficient of performance increases. COP is (4.098) for the system with no heat exchanger but COP of the system reaches (5.2) when adding a heat exchanger of 9.29 cm tube length and it increases when increasing the tube length since it’s value reaches (6.539) when using a heat exchanger of 25.8 cm tube length.

The increase in COP is due to two reasons; the first is the increase in heat losses from the liquid refrigerant leaving from the condenser, caused by decreasing the enthalpy of liquid entering to the evaporator resulting in high refrigerating effect as illustrated in Figure (9). The second reason is that both temperature and enthalpy of the vapour entering the compressor will increase and cause decreasing of the work of compressor as indicated in Figure (10).

As a result of both reasons above, the coefficient of performance will increase, since it represents the ratio of the refrigerating effect to compressor work.

The variation of the coefficient of performance with a heat exchanger tube length is shown in Figure (12).

CONCLUSIONS

- The refrigerating effect of the system increases with increasing the degree of superheat.
- The work required to operate the compressor decreases with increasing the degree of superheat.
- The coefficient of performance increases with increasing the degree of superheat.
- The heat exchanger length increases with increasing the degree of superheat.

- It can be concluded that the performance of an air conditioning system can be increased by increasing the length of tube of a heat exchanger, but there is a limitation to increase the length due to the space limitation.

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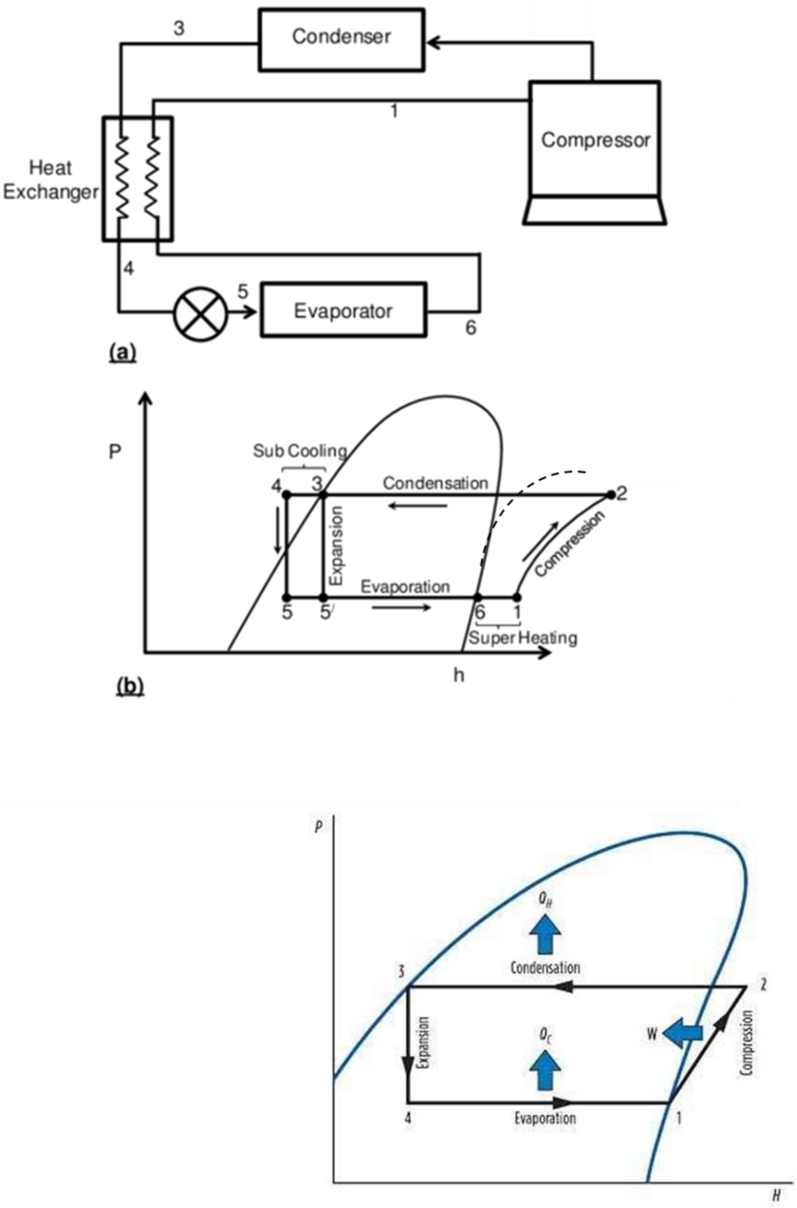

Figure (1 a,b) Schematic Diagram for Refrigeration System with Heat Exchanger

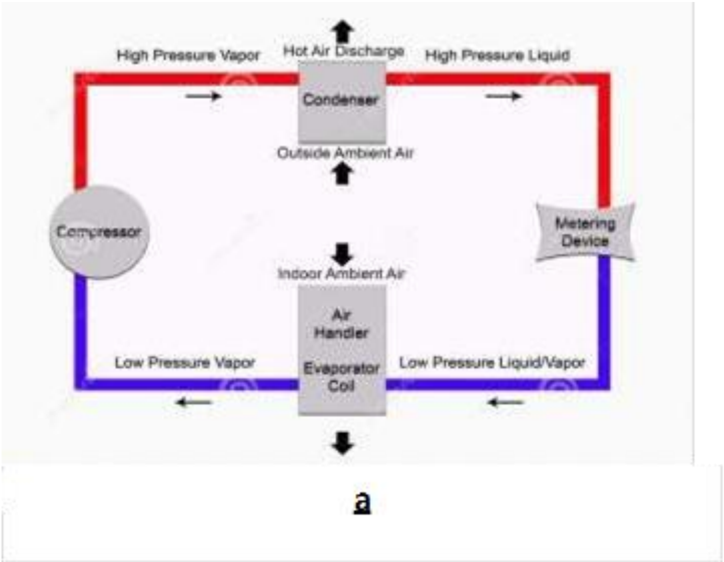

Figure (2 a,b): Schematic Diagram for a Simple Refrigeration System

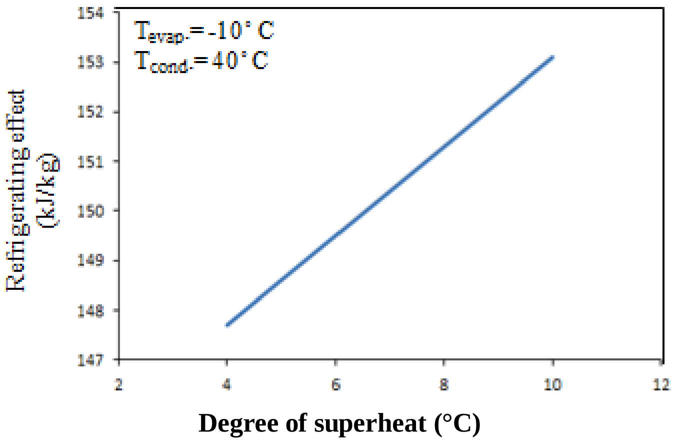

Figure 3: Effect of the Degree of Superheat on Refrigerating Effect

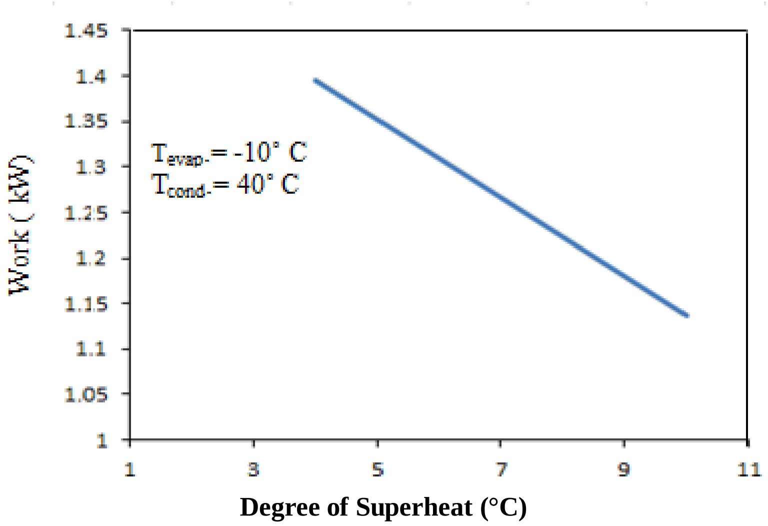

Figure 4: Effect of the Degree of superheat on Compressor Work

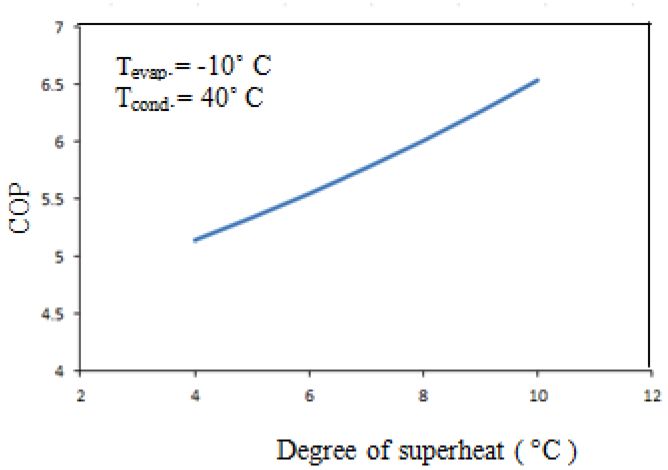

Figure 5: Effect of the degree of superheat on COP

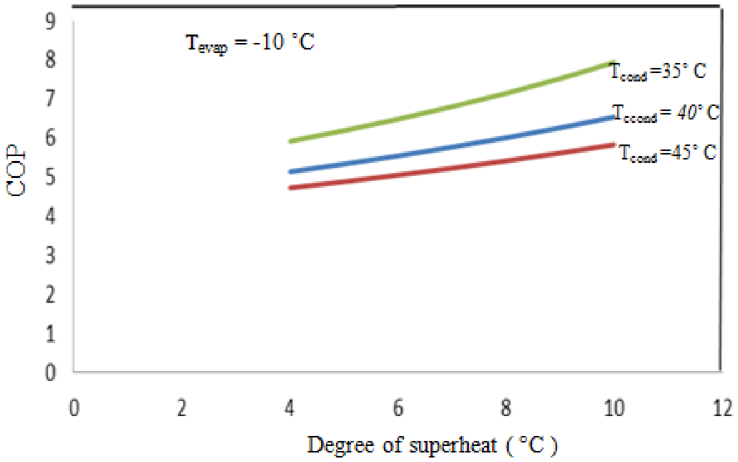

Figure 6: Effect of the Degree of superheat on COP at different Condenser Temperatures

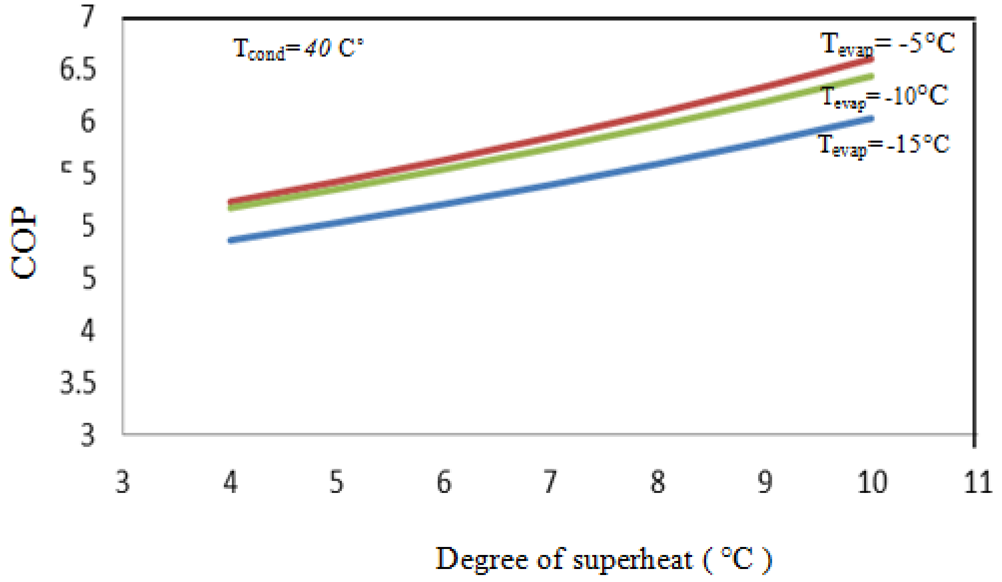

Figure 7: Effect of the Degree of Superheat on COP at different Evaporator Temperatures

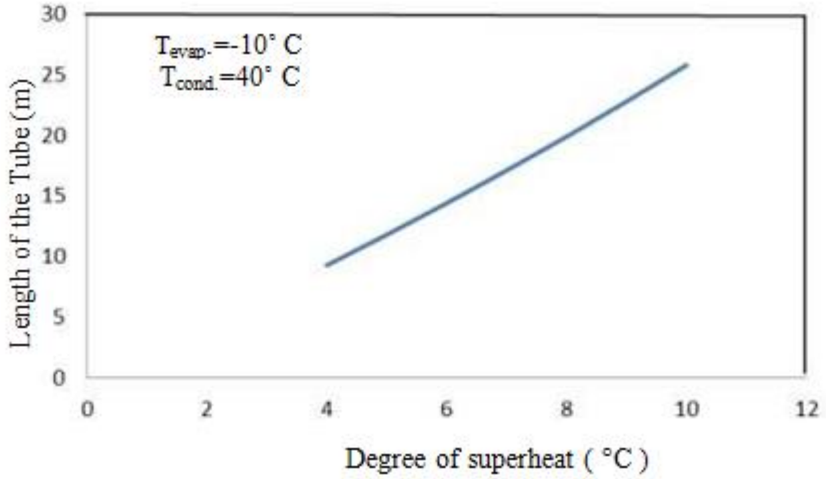

Figure 8: Effect of the Degree of Superheat in Heat Exchanger Tube Length

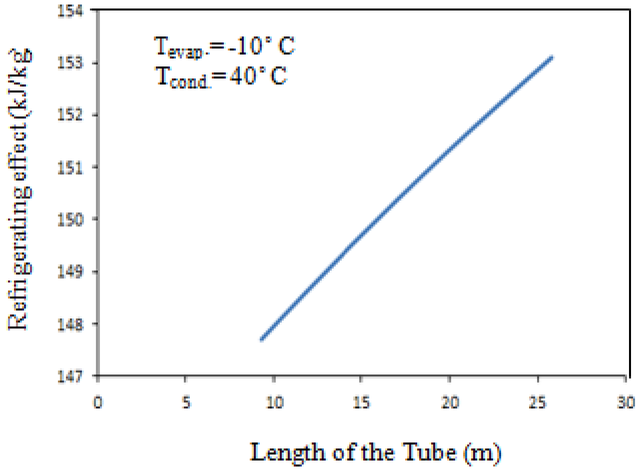

Figure 9: Effect of the Length of Heat Exchanger Tube on the Refrigerating Effect

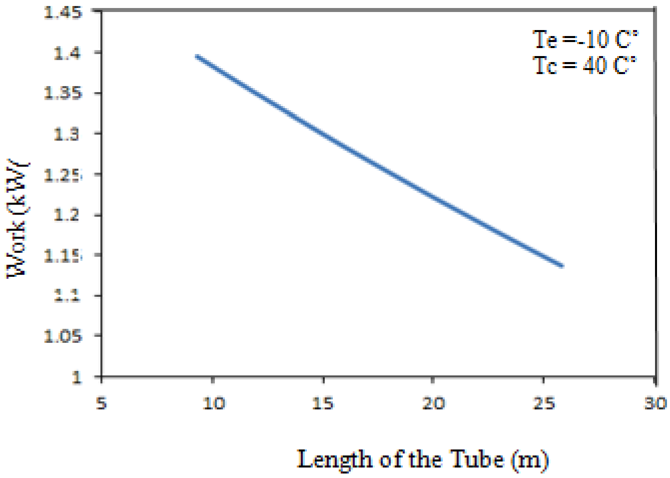

Figure 10: Effect of the Length tube on the Compressor Work

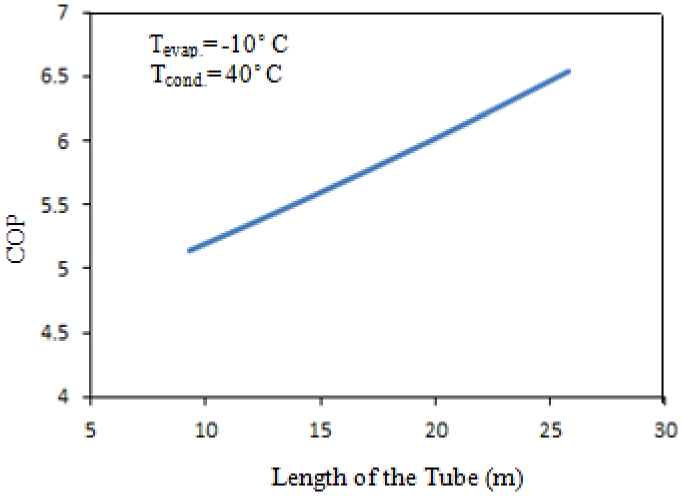

Figure 11: Effect of the Length Tube on the COP

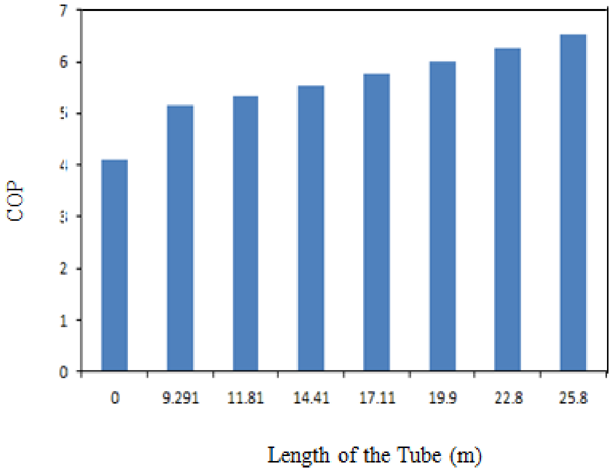

Figure 12: The Variation of the Coefficient of performance with a Heat Exchanger Tube Length