

# Numerical Simulation of the Performance of a Solar Assisted Vapour Compression Refrigeration System

K.M. Odunfa<sup>1</sup>, A.L. Lasisi<sup>2</sup>

<sup>1,2</sup>Department Of Mechanical Engineering, University Of Ibadan, Nigeria

**ABSTRACT:** Research has established that a considerable part of the electrical energy produced globally is been consumed by refrigerators and air-conditioning systems. In this area of cooling technology, research is therefore being geared towards energy reduction in the cooling devices. In addition to this approach, alternative sources of energy such as renewable energy, like solar is also being explored in this area of refrigeration and cooling technology. Studies have also been conducted generally both experimentally and numerically to simulate the performance of Vapor Compression Refrigeration System (VCRS) under different conditions. However, experimental study is often seems to be expensive and time consuming to carry out due the function of many variables. This study was therefore designed to numerically simulate the performance assessment of a solar assisted VCRS. A numerical model of a solar assisted vapour compression refrigeration system was developed using standard solar energy and thermodynamics relations of the major components of solar assisted refrigerating system such as solar power system, compressor, condenser, evaporator and an expansion valve to determine refrigeration effect, compressor work, and the Coefficient Of Performance (COP). Standard data of R134a refrigerant was utilized in the modelling. The model was then simulated on MATLAB source code with a CoolProp installed packages via python under two different simulation cases. In the first case, the evaporating temperature was varied for all while the condensing temperature was kept constant and a reversed condition was investigated in the second case. The results showed that both the refrigerating effect and the COP of the system increase as the evaporating temperature increased while the compressor work and the panel area decreased. Further, the refrigerating effect and the COP of the system were decreased as the condensing temperature was increased while the compressor work and the panel area remained constant. The coefficient of performance at evaporating temperature of -17.2 shows 2.91 giving a deviation of -5.37% from the literature. The viability of a solar assisted vapour compression refrigeration system was established. The vapour compression refrigeration system compressor powered with solar energy will perform well when the solar panel (PV) area is large.

**KEYWORDS:** Vapour compression; solar panel; refrigerating effect; refrigerant; coefficient of performance.

## INTRODUCTION

According to literatures, the most commonly used system in refrigeration and air-conditioning industry is vapor compression refrigeration system. A considerable part of the energy produced worldwide is consumed by refrigerators and it is crucial to manage the energy utilization of these devices and also provide cheap alternative source energy to power them especially in the case of a country that has a problem of

epileptic power supply. In order to achieve this, cheap alternative sources of energy such as renewable energy sources like solar could be harnessed to power the compressor of a vapor compression refrigeration system. Figure 1 illustrates a vapour compression refrigeration system powered by a solar panel. Its main components are shown in the figure below.

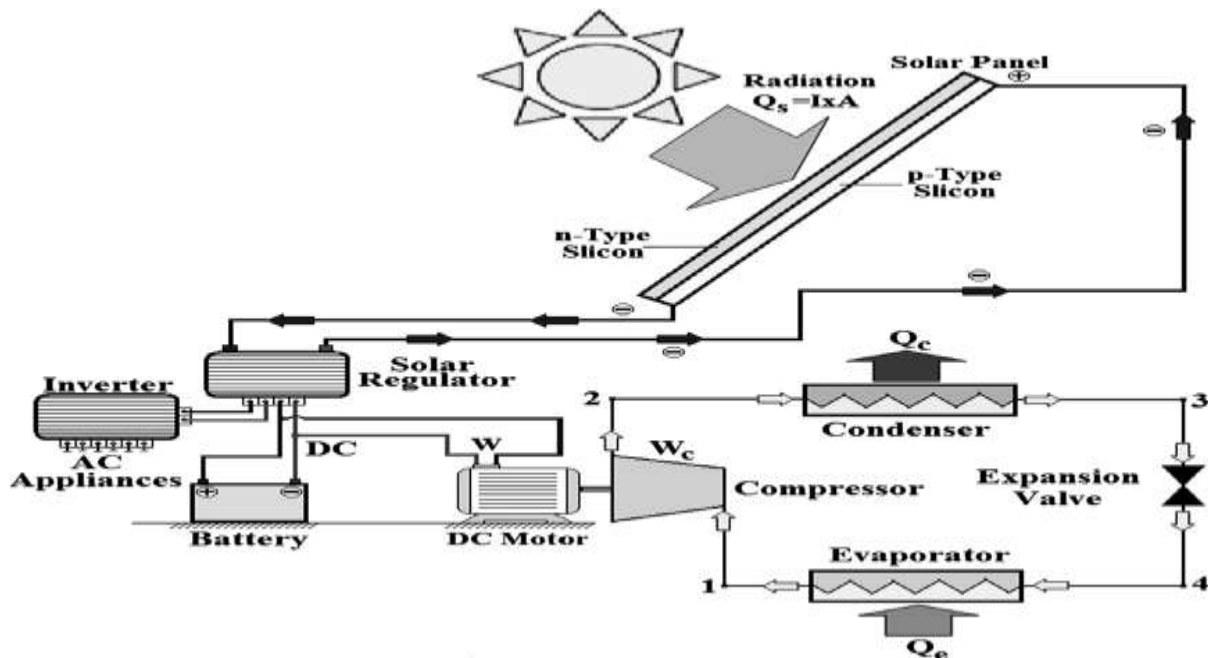


Fig.1: Solar assisted Vapor Compression Refrigeration System

The refrigerant vapour at low temperature and low pressure enters the compressor (state 1) where it is compressed isentropically to high temperature and high pressure. The energy required by the compressor to carry out this activity is provided by the photovoltaic (PV) panel. The higher this amount of energy, the higher the PV panel area. The high temperature refrigerant vapor then enters the condenser (state 2) where it is condensed to high pressure liquid. The high pressure liquid refrigerant then enters into expansion device (state 3) where its pressure is decreased. Ultimately the liquid refrigerant will attain lower temperature. This low temperature liquid refrigerant absorbs the latent heat from the evaporator (state 4) undergoes phase change to vapor state. This high temperature vapor refrigerant then sucked by the compressor and the cycle continues which keeps the temperature in the evaporator much below the atmospheric temperature. In some cases flash chamber is used after the expansion device which separates the vapor refrigerant from the liquid and sends it to compressor inlet.

From the previously published works, it has been observed that the simulation and performance assessment of vapor compression refrigeration system has been carried out by many researchers with little attention on alternative source of energy to power the compressor. To my best knowledge, there is a dearth of research work on the combined simulation and performance assessment of a solar assisted vapor compression refrigeration system. This justifies the need for this study. Thus, the present study deals with the numerical simulation and performance assessment of a solar assisted vapor compression refrigeration system. The simulation will be carried out based on the specified system constraints such as the working conditions of the system. Each component parameters will be simulated and then combined to give the overall system. Further, the coefficient of performance of the

system will be computed, the condensing and evaporating temperatures will be varied so as to observe the effects on the system properties and performance.

#### LITERATURE REVIEW

Reduction of energy consumption for refrigeration, however, cannot be relied solely on the improvement of efficiency. As cooling demand increases with the intensity of solar radiation, solar refrigeration has been considered as a logical solution. Therefore, a variety of solar refrigeration technologies have been developed and many of them are now available in the market at much cheaper prices than ever. This development has prompted scientists and engineers to make more research efforts on energy consumption and performance analysis of vapor compression refrigeration systems. Mehmet (2011) investigated a solar electric-vapor compression refrigeration (SE-VCR) system. In the study, the hourly variations of various parameters such as coefficient of the performance, condenser capacity and compressor power consumption were calculated. In addition, the minimum photovoltaic panel surface area was determined to meet the compressor power demand according to the hourly average solar radiation data. For evaporating temperature of 0 °C, the maximum compressor power consumption was obtained as 2.53 kW at 15:00 PM on August 23. The required photovoltaic panel surface area was found to be around 31.26 m<sup>2</sup>. It was determined that the SE-VCR system could be used for home/office-cooling purposes during the day in the southern region of Turkey. Thangavel and Somansundaram (2013) studied on Part load performance analysis of vapour compression refrigeration system with hydrocarbon refrigerants. In this work, various input parameters like compressor input power, discharge temperature, heat rejected in the condenser, refrigeration effect and coefficient of

performance were analyzed and presented at various loads and 2,4,6,8,10,12,14 kg of water were used in the evaporator. As compared to other loads, 10 kg of water gives economic mode to operate the system. Mishra (2014) investigated the methods of improving thermodynamic performance of vapour compression system using twelve eco-friendly refrigerants in primary circuit and nanofluid (water-nano particles based) in secondary circuit. The author pointed out that the COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. Domanski and Didion (1994) studied Evaluation of suction-line/liquid-line heat exchange in the refrigeration cycle. The author discovered that adding extra internal heat exchanger in a single-stage cycles prior to expansion process sub cools the liquid refrigerant which consequently improves performance of the system. Memet (2014) investigated the performance analysis of a vapor compression refrigeration cycle working with R134a and RE170. The motivation of this comparison was based on the efforts done to solve the problem of high GWP of R134a, since RE170 shows a significantly lower one. The study was developed on the analysis of the effect of evaporation pressure on some of important factors which should be considered in the selection of a new refrigerant: evaporation pressure, pressure ratio, Coefficient of Performance, power per ton of refrigeration, volumetric cooling capacity. The evaporation temperature varied in the range  $(-20, +10)^{\circ}\text{C}$  and the condensation temperature is kept constant, at  $45^{\circ}\text{C}$ . Since cycle performance can be improved by superheating and sub cooling inclusion, the two processes were considered in the cycle. Comparative results showed that RE170 could replace R134a, due to its low evaporation pressure and pressure ratio and also to its better COP and similar volumetric cooling capacity

Vincenzo and Giuseppe (2011), have analyzed and compared the performance of a vapour compression refrigerating unit operating with R22, and with three new HFC fluids, substituting the former according to Regulation No 2037/2000. Here the plant working efficiency was first tested with R22 and then with three new HFC fluids; R417a, R422a and R422d. It is analyzed that the performance with the new tested fluids did not result as efficient as when using R22.

Akhilesh and Kaushik (2008) elucidated on a detailed exergy analysis of an actual vapour compression refrigeration (VCR) cycle. A computational model was developed for computing coefficient of performance (COP), exergy destruction, exergetic efficiency and efficiency defects for R502, R404A and R507A. The investigation was done for evaporator and condenser temperatures in the range of  $-50^{\circ}\text{C}$  to  $0^{\circ}\text{C}$  and  $40^{\circ}\text{C}$  to  $55^{\circ}\text{C}$ , respectively. The results indicated that R507A is a better substitute to R502 than R404A. The efficiency defect in condenser is highest, and lowest in liquid vapour heat exchanger for the refrigerants considered.

Wang et al. (2012) studied a solar-assisted cascade refrigeration cycle system. The system consists of electricity-

driven vapor compression refrigeration system and solar-driven vapor absorption refrigeration system. The vapor compression refrigeration system is connected in series with vapor absorption refrigeration system. Refrigerant and solution reservoirs are designed to store potential to keep the system operating continuously without sunlight. The results indicated that the system obtains pretty higher COP as compared with the conventional vapor compression refrigeration system. COP of the new-type vapor compression refrigeration system increases as sunlight becomes intense. Dalkilic and Wongwises (2010), have studied the performance of a vapour Compression refrigeration system with refrigerant mixtures based on R134a, R152a, R32, R290, R1270, R600 and R600a was done for various ratios and their results were compared with R12, R22 and R134a as possible alternative replacements. The results showed that all of the alternative refrigerants investigated in the analysis have a slightly lower COP than R12, R22, and R134a for the condensation temperature of  $50^{\circ}\text{C}$  and evaporating temperatures ranging between  $-30^{\circ}\text{C}$  and  $10^{\circ}\text{C}$ . Refrigerant blends of R290/R600a (40/60 by wt. %) instead of R12 and R290/R1270 (20/80 by wt. %) instead of R22 are found to be replacement refrigerants among other alternatives. Praveen and Simhadri (2018) experimentally investigated the performance of HFC-134a- HC-600a and hydro carbon blends (propane/isobutane) using solar driven vapour compression refrigeration system. The author made it known that an attempt has been made to conduct the experimental investigation of HC and HFC blends to replace the R134a to reduce the global warming potential. The various parameters such as cop, mass flow rate, compressor work net refrigeration effect were calculated. The results showed that the of COP of R134a is better than R290/600a but the global warming potential of R290/600a is lower than that of R134a, hence, it is more environmental friendly than R134a. Further, the solar driven system minimize the energy crisis and maintain room cooling during day and night. The author concluded that solar refrigeration can be expected to play a significant role in meeting the needs of people in the rural areas of developing countries for refrigeration. In spite of the extensive number of studies on the simulation performance evaluation of vapor compression refrigeration system, little has been done yet on the simulation of the vapour compression refrigeration system using solar energy source both theoretically and experimentally. Thus, the present study deals with the numerical simulation and performance assessment of a solar assisted vapour compression refrigeration system (VCRS).

#### NUMERICAL ANALYSIS

The numerical simulation model of a vapour compression refrigeration system utilised the fundamental equations and many thermodynamic relations. It is simulated on the MATLAB platform.

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The following assumptions are made for analysis of the system.

1. Clearance ratio of the compressor is 5%
2. Evaporator temperature ranges from -17.2°C to 32.8°C
3. Condenser temperature ranges from 45.3°C to 95.3°C
4. Losses are neglected in the system

### Fundamental Governing equations

The following fundamental governing equations for the major components of the Vapour Compression Refrigeration System are in here listed below:

#### Compressor

$$W_{comp} = m_1 c_p (T_2 - T_1)$$

$$m_1 = m_2$$

Where  $W_{comp}$  = Power input into the compressor  
 $c_p$  = Specific heat of refrigerant  
 at constant pressure

$m_1$  and  $m_2$  are mass flow rates

$T_1$  and  $T_2$  are temperatures at the compressor inlet and exit respectively.

#### Condenser

$$Q_c = m_2 c_p (T_3 - T_2)$$

$$m_2 = m_3$$

Where  $Q_c$  = rate of heat removal at the condenser  
 $c_p$  = Specific heat of refrigerant at  
 constant pressure

$m_2$  and  $m_3$  mass flow rates

$T_2$  and  $T_3$  are temperatures at the condenser inlet and exit respectively.

#### Capillary

$$T_4 = T_3$$

$$m_4 = m_3$$

Where  $m_3$  and  $m_4$  mass flow rates  
 $T_3$  and  $T_4$  are temperatures at the capillary inlet and exit respectively.

#### Evaporator

$$Q_e = m_4 c_p (T_1 - T_4)$$

$$m_4 = m_3$$

Where  $Q_e$  = rate of heat removal at the evaporator  
 $c_p$  = Specific heat of refrigerant at  
 constant pressure

$m_4$  and  $m_3$  = mass flow rates

$T_4$  = Inlet temperature of refrigerant

$T_1$  = outlet temperature of refrigerant

$$\text{C.O.P} = \frac{Q_e}{W_{comp}}$$

While the solar photovoltaic properties of interest are calculated as follows:

PV power production

$$W_{pv} = \eta_{sol-pow} \cdot Q_s$$

Solar radiation production

$$Q_s = I \cdot A$$

Where  $A$ (m<sup>2</sup>) is the solar cell or panel surface area  $I$  (kW/m<sup>2</sup>) is solar radiation or the direct irradiation of solar beam and

$\eta_{sol-pow}$  is the efficiency of the solar panel. In the solar-electricity system, compressor power consumption ( $W$ ) is aimed to be covered by the electricity ( $W_{pv}$ ) produced from solar (i.e. photovoltaic) panels. On the other hand, sufficient photovoltaic panels depending on their properties should be provided to meet the whole energy demand of the system. The necessary total photovoltaic panel area of the system should be determined to cover daily power consumption of the compressor. Therefore, daily total power consumption of the compressor  $W_T$  (kWh/day), daily total solar radiation  $I_T$  (kWh/m<sup>2</sup>day) and the photovoltaic area  $A$ (m<sup>2</sup>) are related by the following

$$A = \frac{W_T}{\eta_{sol-pow} \cdot I_T}$$

In this work average solar irradiation of Nigeria as 5.5kwhr/m<sup>2</sup>/day (Ojosu, 1990) efficiency of the solar panel as 20% and the number of hours of use of the refrigeration system to be 12 hours per day were used. Due to the limited number of studies regarding the experimental study of Solar assisted vapor compression refrigeration system, Praveen and Simhadri (2018)'s experimental database will be used in the validation process of the proposed model.

**The following thermodynamics relations were also used in this work:**

- 1) Refrigeration Effect  $RE = h_1 - h_4$
- 2) Work done by the compressor,  $W_c = h_2 - h_1$

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3) Coefficient of Performance of the system  $COP = (h1 - h4) / (h2 - h1)$

Where,

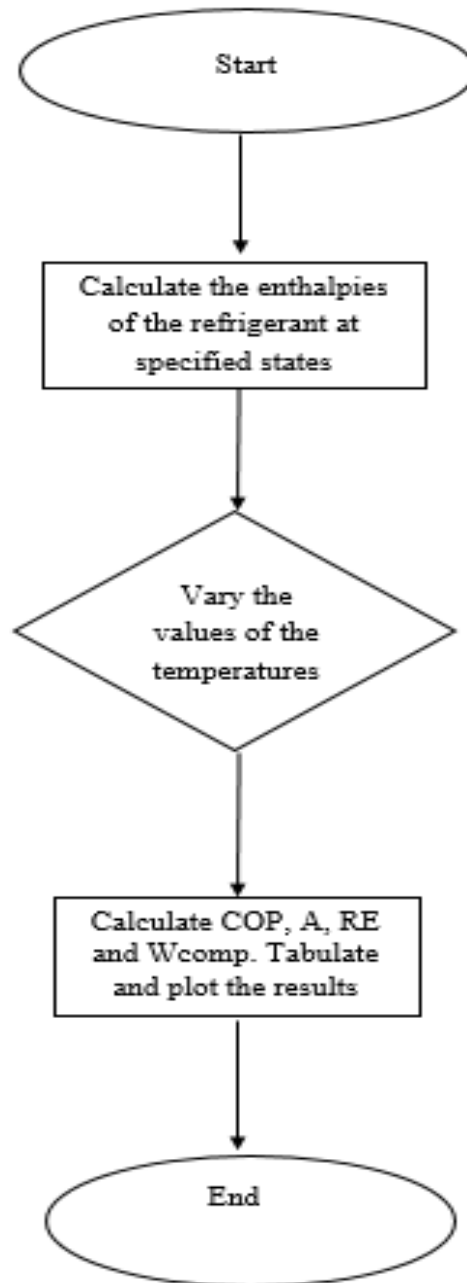
h1= enthalpy of refrigerant at the outlet of evaporator

h2= enthalpy of refrigerant at the inlet of condenser

h3= enthalpy of refrigerant at the outlet of condenser

h4= enthalpy of refrigerant at the inlet of evaporator

The program is coded using MATLAB with Coolprop and Python Software. Based on mathematical calculations, graphs are generated in the graphical user interface. It displays the performance characteristic curves for refrigeration effect, work done by the compressor, coefficient of performance, and panel surface area against evaporator temperature/ condenser temperature.



Flow chart for the MATLAB programming

### RESULTS AND DISCUSSION

The results are in here presented in both graphical and tabular forms. Based on the numerical simulation model. The following tables and graphs established the performance of the system.

1) Varying the evaporator temperature for different values of compressor work, COP, panel area and refrigerating effect.

2) Varying the Condenser temperature for different compressor work, COP, panel area and refrigerating effect.

Table 1

Evaporator Temperature $T_e$ (K)	$W_{comp}$ (KJ/kg)	COP
255.8000	43.3295	2.8622
261.3556	39.9375	3.1902
266.9111	36.5958	3.5728
272.4667	33.3130	4.0234
278.0222	30.0979	4.5601
283.5778	26.9604	5.2071
289.1333	23.9114	5.9986
294.6889	20.9630	6.9829
300.2444	18.1294	8.2306
305.8000	15.4273	9.8474

Table 2

Evaporator Temperature $T_e$ (K)	Refrigerating effect (RE)(KJ/Kg)	Area (m <sup>2</sup> )
255.8000	127.4085	12.7625
261.3556	124.0165	11.7634
266.9111	130.7502	10.7791
272.4667	134.0330	9.8122
278.0222	137.2481	8.8652
283.5778	140.3856	7.9411
289.1333	143.4347	7.0430
294.6889	146.3831	6.1745
300.2444	149.2166	5.3399
305.8000	151.9188	4.5440

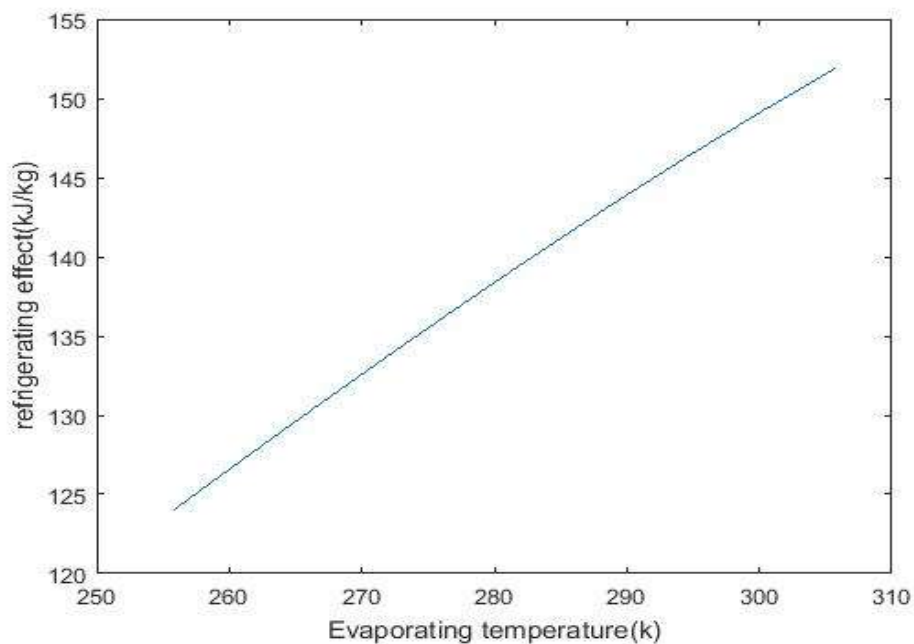
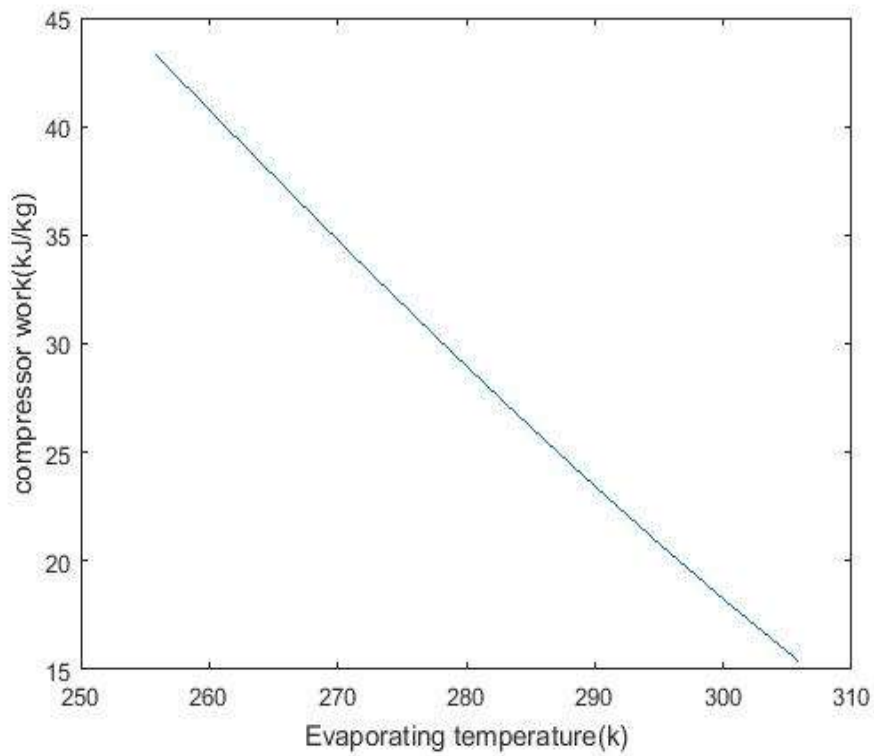
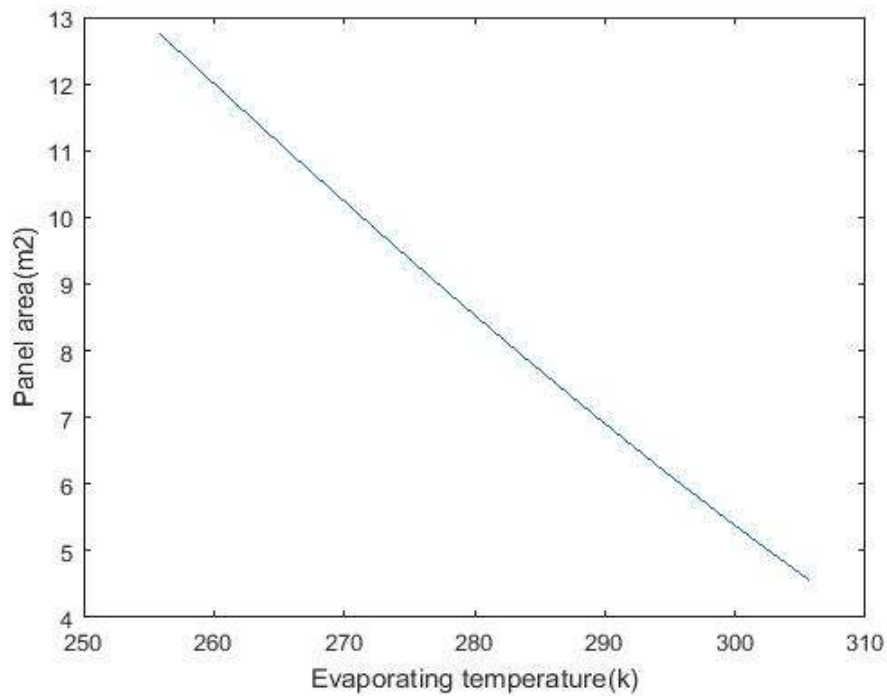


Fig. 2. Graph of Refrigerating effect against Evaporation temperature



**Fig.3.** Graph of Compressor work against Evaporation temperature



**Fig.4.** Graph of Panel area against Evaporation temperature

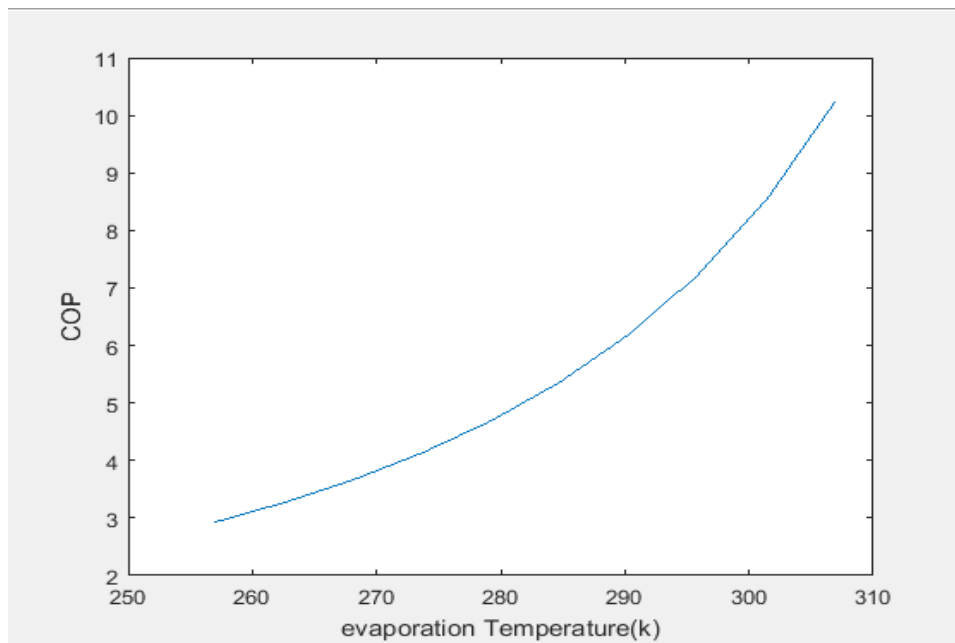


Fig.5. Graph of COP against Evaporation temperature

Table 3

Condenser Temperature Tc(K)	Refrigerating effect (RE)(KJ/Kg)	Area (m <sup>2</sup> )
318.3000	124.0165	12.7625
323.8556	115.4679	12.7625
329.4111	106.7108	12.7625
334.9667	97.7105	12.7625
340.5222	88.4195	12.7625
346.0778	78.7701	12.7625
351.6333	68.6586	12.7625
357.1889	57.9087	12.7625
362.7444	46.1724	12.7625
368.3000	32.5284	12.7625

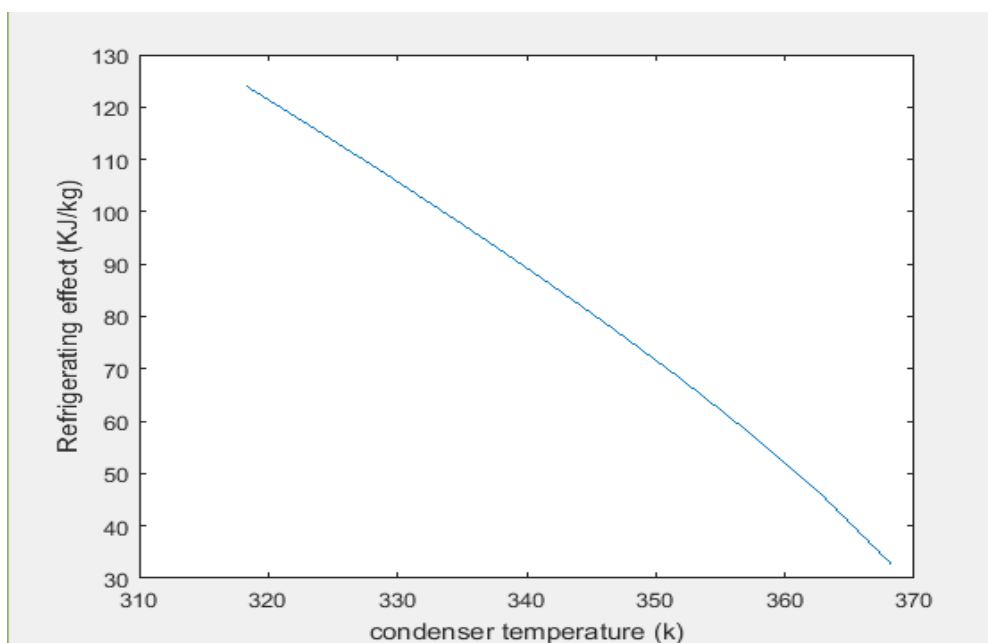
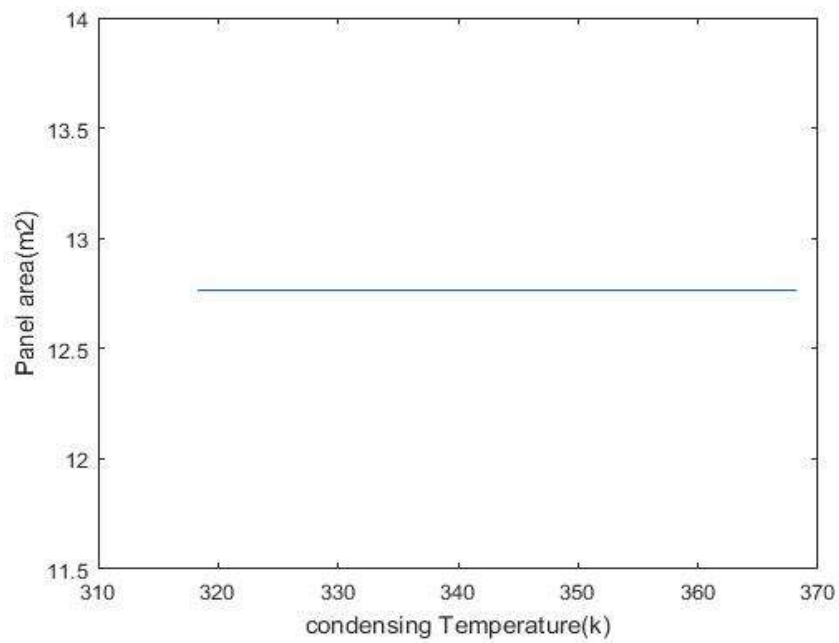


Fig.6. Graph of Refrigerating effect against Condenser temperature

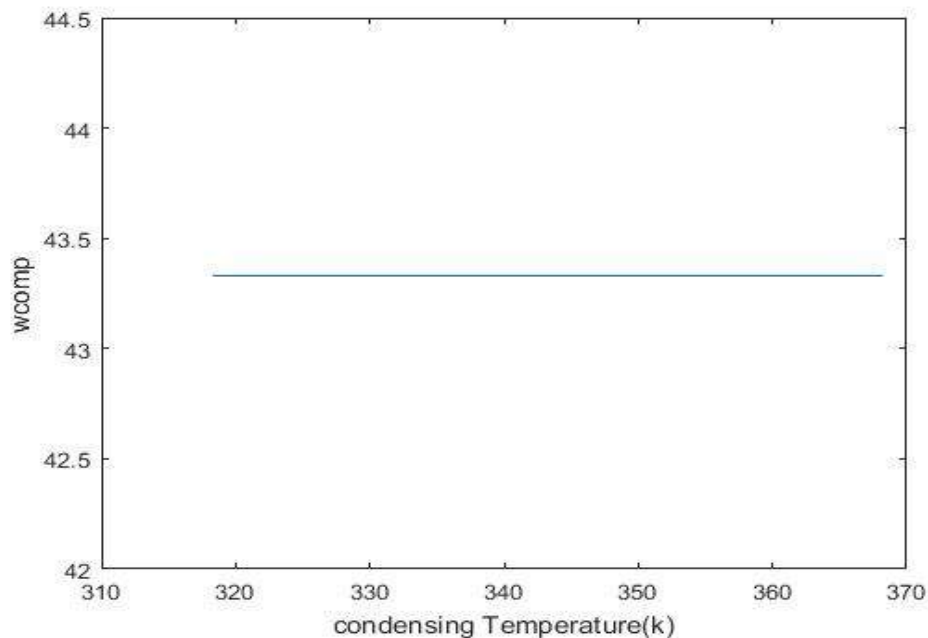




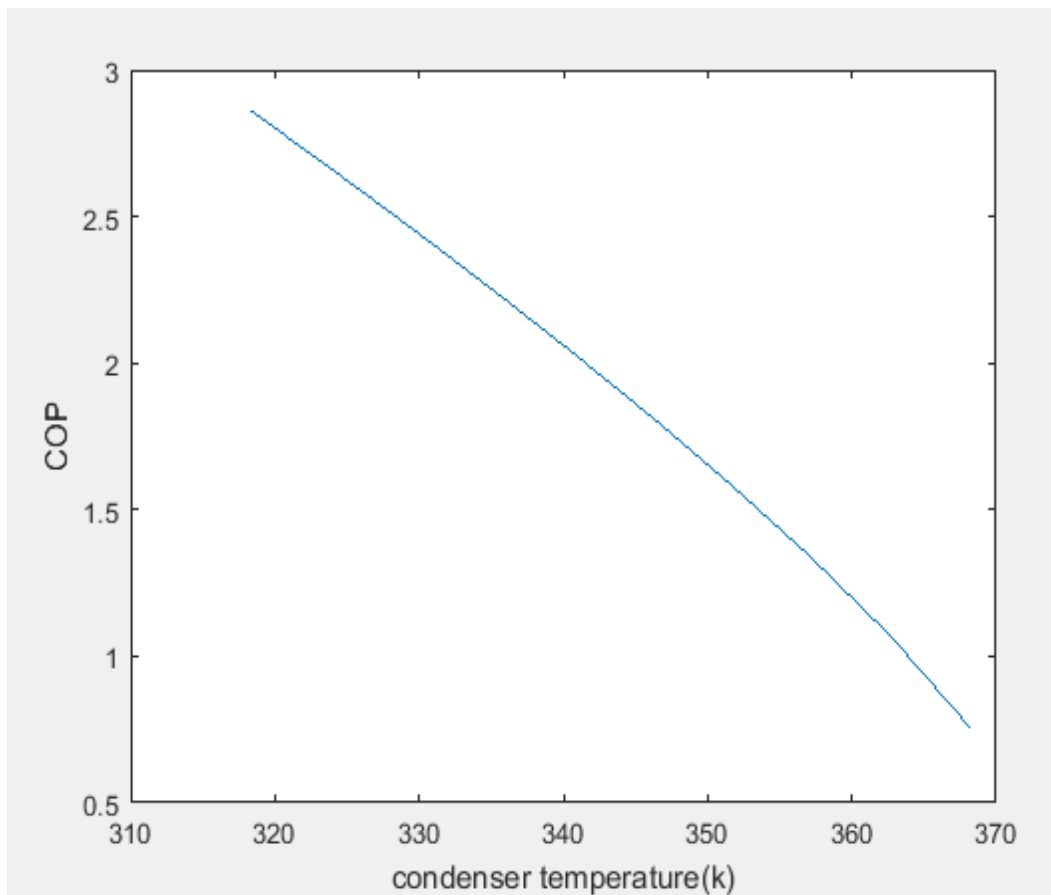
**Fig.7.** Graph of Panel area against Condenser temperature

Table 4

Condenser Temperature T <sub>c</sub> (K)	W <sub>comp</sub> (KJ/kg)	COP
318.3000	43.3295	2.8622
323.8556	43.3295	2.6649
329.4111	43.3295	2.4628
334.9667	43.3295	2.2551
340.5222	43.3295	2.0406
346.0778	43.3295	1.8179
351.6333	43.3295	1.5846
357.1889	43.3295	1.3365
362.7444	43.3295	1.0656
368.3000	43.3295	0.7507



**Fig.8.** Graph of Compressor work against Condenser temperature



**Fig.9.** Graph of COP against Condenser temperature

## CONCLUSION

In the analysis conducted in two cases, both the refrigerating effect and the COP of the system increase as the evaporation temperature is increased while the compressor work and the PV panel area decrease. Also, both the refrigerating effect and the COP of the system decrease as the condenser temperature is increased while the compressor work and the PV area remain constant. This present study also demonstrate the impact of different parameters which need to be optimised so as to increase the performance of the system.

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