Energy-Exergy Performance Comparison of an Ideal Vapor Compression Refrigeration Cycle using Alternatives Refrigerants of R134a for Low Potential of Global Warming

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Abstract- **This work presents a theoretical study on the application of low global warming refrigerants as alternative refrigerant to R 134a in a refrigeration system. The refrigerants investigated are R1234yf, R1234ze, R245fa and R227ea. The performance characteristics of the refrigeration system were predicted using mathematical models running by using EES program under different condenser and evaporator temperatures. The results show that at any working condition the R1234ze give identical performance to R134a and can be used as the best low global warming alternative refrigerant. So the compressor work with R1234ze should be designed with displacement volume more than that of R134a to overcame the reduction in mass flow rate.**
Keywords: refrigeration; Alternative refrigerant; R1234yf; R1234ze; R245fa; R227ea

I. Introduction

Refrigerator is a device which is used to produce lower temperature as compared to surrounding while undergoing in a cycle. Lower temperature are produced by various refrigerants. The performance of the refrigeration system mainly depends on the types of refrigerants, but this refrigerant have several environmental factors which put restraints on its, that are extremely hazardous to environment, causes (ODP) ozone layer depletion (i.e CFCs) and (GWP) global warning potential (i.e HFCs and HCs). United Nations Framework Convention on Climate Change (UNFCCC, 1997), held in Kyoto, proposed „Kyoto Protocol‟ to control emission of greenhouse gases including HFC‟s. The most infamous greenhouse gas is carbon dioxide (CO2), which once released remains in the atmosphere for 500 years, so there is a constant build up as time progresses. The main cause of CO2 emission is in the generation of electricity at power stations. The link between ozone and climate change must be addressed more fully. There is increasing evidence that changes in climate, ground temperature, levels of greenhouse gases and water vapor in the atmosphere will influence the recovery of the ozone layer. HCFCs have largely replaced CFCs in both developed, developing countries, and their replacement with HFCs is now underway. Although HCFCs deplete the ozone less and HFCs not at all, both still have large global-warming potential. The next generation of ozone policies must focus on replacing these substances with more climate friendly substances. R134a is a HFC refrigerant, R134a has been widely used in household refrigerators and in automotive air conditioning; R134a has a GWP of 1300, which means that the emission of 1 kg of R134a is equivalent to 1300 kg of CO2. According to a recent study, the phasing out of substances under the Protocol led to more reductions in greenhouse gases than what is foreseen under the Kyoto Protocol. If further measures are to materialise accelerated phase out of HFCs additional climate benefits could be reaped, possibly as much as taking out again the entire reduction potential of Kyoto[1]. Many studies are adopted focused on the alternative to R134a , Vijay et al[2] performed a theoretical study for refrigeration system, they did a comparison steady between R12 , R134a and R1234yf ,the result show that the system with R123yf has higher percentage increase in COP. And the work of compressor for system with R134a is higher than system with R1234yf.also R1234yf is best low global warming alternative refrigerant. Mahmood Mastani et.al [3] used R134a and R600a to perform exergy analysis for a refrigerator, they found that the maximum value of destructed exergy is from compressor. Bolaji et al. [4] use R12, R134a and R152a to check the exergetic performance of refrigerator. The results showed that the R152a has COP nearly close to that of R12 and R134a gives the highest efficiency defects. Selladurai et al [5] check the performance of domestic refrigerator by using R134a and R290/R600a mixture, they found that the mixture of R290/R600a obtained COP and exegetic efficiency more than R134a. As compare the compressor with other components, it is give maximum irreversibility. Mishra[6] employ numerical computations model to study the effect of nano particles in refrigerant on system performance. The results show that the use of Copper Nano particles will improve the system efficiency by 25% when mixing with the R-1234yf and 18% with R1234ze, so the system with R1234ze can be used instead of R134a in high temperature. Gaurav et al [7] did an experimental study for automotive air conditioning system using R1234yf instead of R134a, they found that cooling time for system with R1234yf is to be lesser than of R134a by range between 4% to 6%. And can be used as suitable alternative refrigerant for R134a.Shobhit et.al [8] did a comparison study to replace R134a with HFO-1234yf. They found that COP of HFC-134a is 11.81-4.24% more than HFO-1234yf. Hence HFO-1234yf can be a good drop in replacement of HFC-134a at higher values of evaporator temperature. The current study focused on alternative refrigerant for R134a with low global warming that named R1234yf, R1234ze, R245fa and R227ea. Table (1) show the thermodynamic properties for this refrigerant with R134a.

II. Thermodynamic System Analysis:-

For this study all refrigeration cycle components will analysis by using simple model with these assumptions[9]:-

- Steady state steady flow cycle.
- Negligible kinetic and potential energy changes across each component ($\Delta KE = 0, \Delta Z = 0$). And
- No heat transfer (gain or losses) and no pressure drop in the connecting pipe lines. The steady flow energy equation is applied to each of the four components.

2.1 Energy Analysis:-

The vapour compression cycle consist from: compressor, evaporator, condenser, and expansion valve. In an ideal refrigerator cycle there are four thermodynamic process Fig (1):

Isentropic Compression in Compressor (Process 1-2):
The amount of specific work done by compressor per unit mass of the refrigerant can be express regarding the change in enthalpy between State**1** and State **2**.

$$w_c = h_2 - h_1 \quad (1)$$

Isobaric Heat rejection in Condenser (Process 2-3)
For the condenser the energy equation can be write as the enthalpies of refrigerant at the entrance and exit:

$$q_C = h_2 - h_3 \quad (2)$$

Isentropic Throttling in Capillary tube (Process 3-4)
For the capillary tube, the energy equation can be write as:

$$h_3 = h_4 \quad (3)$$

Isobaric heat addition in evaporator (Process 4-1)
The amount of specific heat absorbed by evaporator can be find by evaluating the refrigerant enthalpies at the inlet and outlet.

$$q_E = h_1 - h_4 \quad (4)$$

To get an indicted about the vapour compression cycle performance the coefficient of performance should be adopted ,which is the proportion of refrigerating effect to the work done by compressor, which used to give an

$$COP = \frac{\text{Heat absorbed by evaporator}}{\text{Compressor Work}}$$

$$COP = \frac{h1 - h4}{h2 - h1} \quad (5)$$

2.2 Exergetic Analysis:

The method of exergy analysis get over many of the thermodynamic first law restrictions. Exergy analysis can give the energy quality quantify during heat transfer. The main objective of exergy technique is to give meaningful efficiencies, the causes and real ingredients of exergy losses. For the main components, the equations of exergy rate can be write as follows [10]:-

-For Compressor

$$\dot{m}_r\, ex_{in} + w_{in} = \dot{m}_r\, ex_{out} + Ex_{dcom}$$

$$Ex_{dcom} = \dot{m}_r\, (ex_{in} - ex_{out}) + w_{in}$$

$$Ex_{dcom} = \dot{m}_r\, (h_1 - h_2 - T_o(s_1 - s_2)) + \dot{m}_r (h_2 - h_1)$$

$$Ex_{dcom} = \dot{m}_r T_o (s_2 - s_1) \quad (6)$$

-For Condenser

$$\dot{m}_r\, ex_{in} = \dot{m}_r\, ex_{out} + Q_c \left(1 - \frac{To}{Tc}\right) + Ex_{dcon}$$

$$Ex_{dcon} = \dot{m}_r\, (ex_{in} - ex_{out}) - Q_c \left(1 - \frac{To}{Tc}\right)$$

$$Ex_{dcon} = \dot{m}_r\, (h_2 - h_3 - T_o(s_2 - s_3)) - Q_c \left(1 - \frac{To}{Tc}\right) \quad (7)$$

-For capillary Tube

$$\dot{m}_r\, ex_{in} = \dot{m}_r\, ex_{out} + Ex_{dexp}$$

$$Ex_{dexp} = \dot{m}_r\, (ex_{in} - ex_{out})$$

$$Ex_{dexp} = \dot{m}_r\, (h_3 - h_4 - T_o(s_3 - s_4)) \quad (8)$$

- For Evaporator

$$\dot{m}_r\, ex_{in} + Q_e \left(1 - \frac{To}{Te}\right) = \dot{m}_r\, ex_{out} - Ex_{devp}$$

$$Ex_{devp} = \dot{m}_r\, (ex_{out} - ex_{in}) - Q_e \left(1 - \frac{To}{Te}\right)$$

$$Ex_{devp} = \dot{m}_r\, (h_1 - h_4 - T_o(s_1 - s_4)) - Q_e \left(1 - \frac{To}{Te}\right) \quad (9)$$

So the second law exergetic efficiency for refrigerator is the ratio of total output exergy to input exergy:-

$$\eta_{exergetic} = \frac{\text{Exergy output}}{\text{Exergy input}}$$

$$Ex_{DT} = EX_{in} - EX_{out}$$

$$Ex_{out} = EX_{in} - EX_{DT}$$

$$\eta_{exergetic} = 1 - \frac{EX_{DT}}{Wc} \quad (10)$$

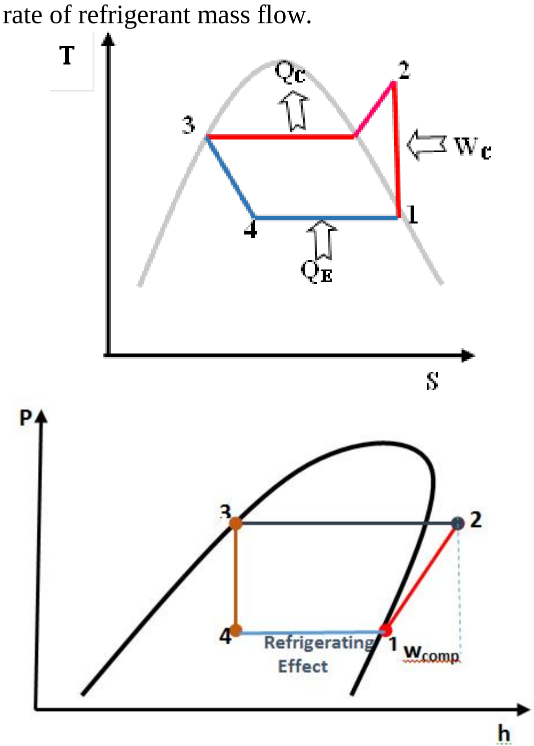
Where:-

ex_{in} , ex_{out} is the exergy input and output respectively.

Ex_{dcop} , Ex_{dcon}, Ex_{dexp} ,Ex_{devp} is the destructed exergy in compressor, condenser, expansion valve and the evaporator respectively.

Qc, Qe= condenser heat rejected and evaporator heat absorbed .

mr= rate of refrigerant mass flow.



Fig(1) Complete of Vapor compression Cycle on T-S &P-h Diagram Thermodynamic system Methodology

In this work, all The equations related to both energy and exergy analysis and other properties of selected refrigerant are performed using Engineering Equation Solver Professional (EES)version 8.4, which is a powerful mathematical program developed by Dr. Sanford Klein of the University of Wisconsin (1992-2013). EES has a built-in thermodynamic and transport property relations, graphical skills, numerical integration, and various other useful mathematical functions, EES can fast solve scores of transcendental equations.

III. Result and Discussion:

3.1 Effect of Evaporating Temperature on System Performance:

In this part to study the effect of evaporating temperature on system performance the evaporating temperature is varied from -15 ℃ to 15 ℃ with 5 ℃ steps of increment at constant condensation temperature of 50℃

3.1.1 Compressor work:

From Fig(2) the increasing of evaporating temperature will decrease the compressor work for all studied refrigerants , because of at constant condensing temperature the compression ratio of compressor will decease as the temperature of evaporating increasing Fig(3), and this will lead to decrease the required refrigerant mass flow rate then compressor work . Also from Fig (2) the R245fa have the highest compressor work and pressure ratio from other studied refrigerant.

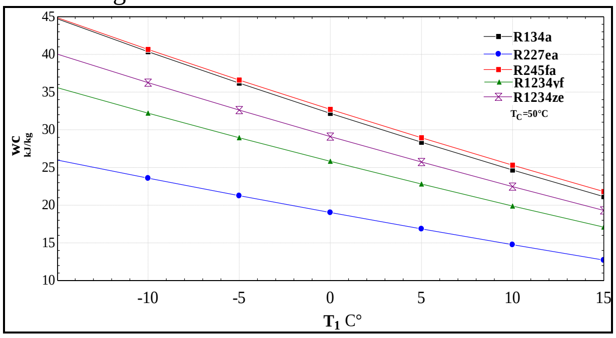


Fig (2) Compressor Work Vs Evaporating temperature

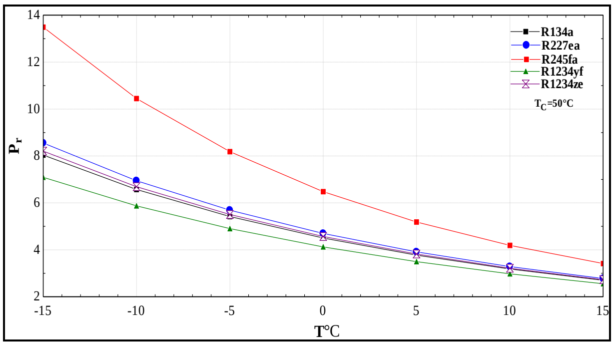


Fig (3) Compressor Pressure ratio Vs Evaporating temperature

3.1.1 Evaporator Capacity:

From Fig (4) as the evaporating temperature increased the evaporator capacity increased also due to the increases in latent heat of vaporization Fig(5). And the refrigerant R245fa give evaporator capacity more than of R134a at all evaporating temperature because it have the highest latent heat of vaporization from all studied refrigerant

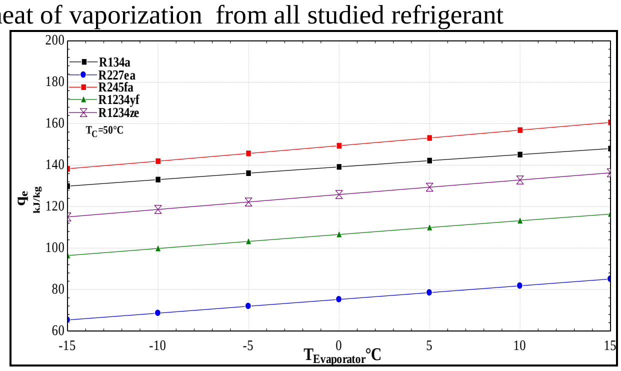


Fig (4) Evaporator capacity Vs Evaporating temperature

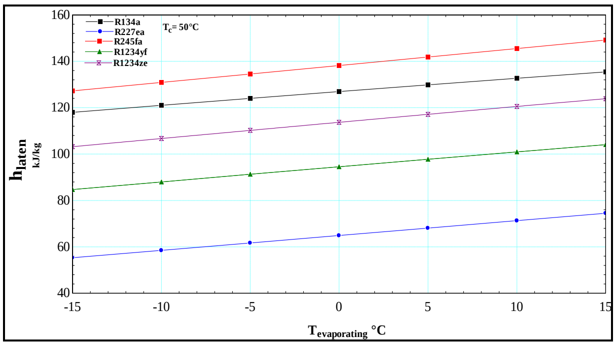


Fig (5) Latent heat of vaporization Vs Evaporating temperature

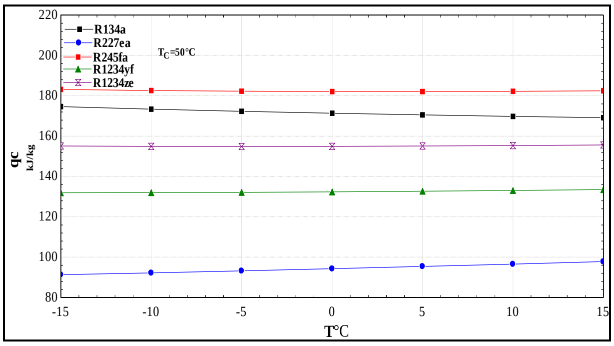


Fig (6) Condenser heat rejected Vs Evaporating temperature

3.1.2 Condenser Capacity:

From Fig(6) as the evaporating temperature increased the heat rejected by condenser is decrease but with little effect ,due to the increasing in evaporating temperature will incresed the refrigerant mass flow rate that delivered by compressor which overcome the reducation in specific heat rejected by condenser Fig(7).

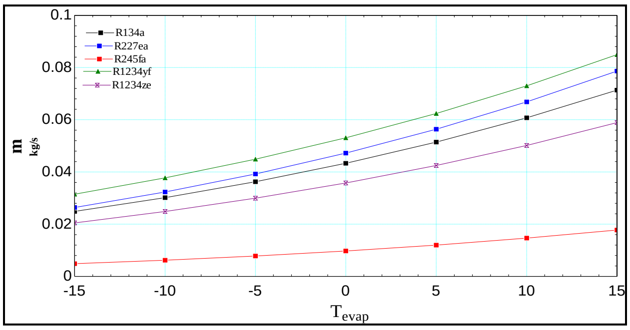


Fig (7) Refrigerant mass flow rate Vs Evaporating temperature

3.1.3 Coefficient of performance:

From Fig(8) the Coefficent of performance increased as the evaporation temperature increaseing for all tested refrigerant ,since COP is the ratio of refrigerating effect to compressor work .The evaporating temperature effect on compressor work and refrigerating effect paragraph are clarified the COP increasing with evaporating temperature, so the refrigerant R245fa give highest overall COP from all studied refrigerants.

3.2 Effect of Condensation Temperature on System Performance:

To evaluate the effect of condensation temperature on system performance the condensing temperature is varied from 40 °C to 70 °C with 5 °C steps of increment at constant evaporation temperature of 5°C

3.2.1 Compressor work:

From Fig(9) for all studied refrigerants the compressor work will increase as the condensing temperature increased ,due to the compressor compression ratio increasing as a result of condensing temperature increase Fig(10), and this will lead to increase the required refrigerant mass flow rate and on the other hand compressor work , also from Fig (9) the R245fa have the highest compressor work with 2% more than of R134a .

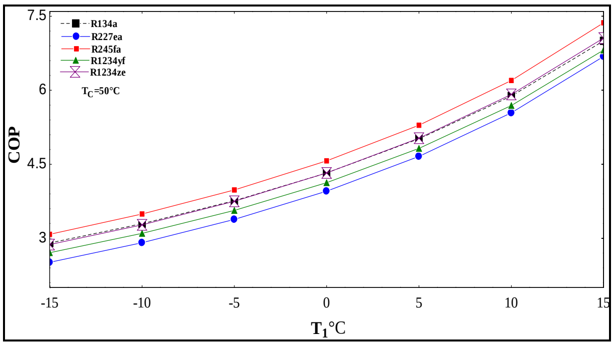


Fig (8) Evaporator heat absorbed Vs Condensing Temperature

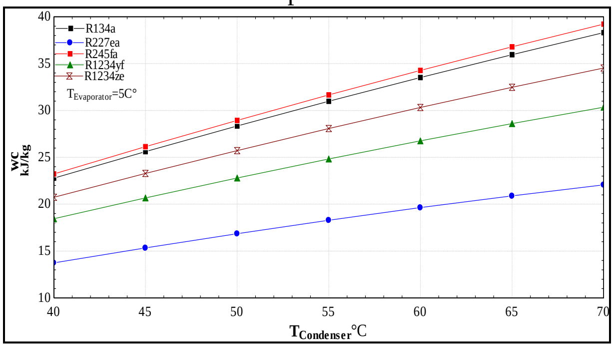


Fig (9) Compressor Work Vs Condensing Temperature

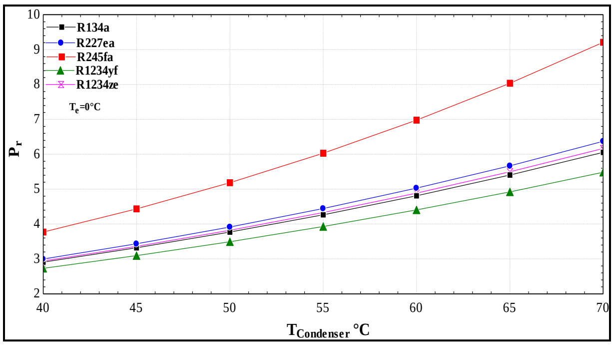


Fig (10) Compressor Work Vs Condensing Temperature

3.2.2 Condenser Heat rejected:

From Fig (11) as the condensing temperature increased the heat rejected by condenser will decrease for all studied refrigerants ,this due to the length of two phase region for all refrigerant will decreased as the condensing temperature increased ,this means that the heat rejected by this region will decrease ,since the heat rejected by condenser is occur in three rejoins gas region ,two phase and sub cooled so two phase region represent the biggest portion of condenser heat rejected.

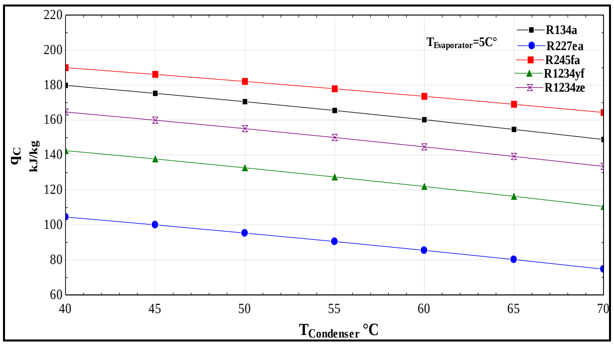


Fig (11) Condenser Heat rejected Vs Condensing Temperature

3.2.3 Evaporator Capacity:

From Fig (12) as the condensing temperature increased the evaporator capacity will decrease this due to the increasing in the portion of refrigerant vapor at the evaporator inlet Fig(13), and this will led to reduce the value of latent heat so evaporator capacity . And from fig (12) at all condensing temperature the refrigerant R245fa give the highest evaporator capacity with 9% increasing of R134a.

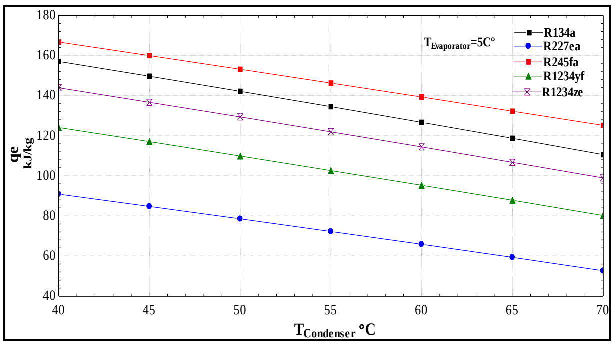


Fig (12) Evaporator capacity Vs Condensing Temperature

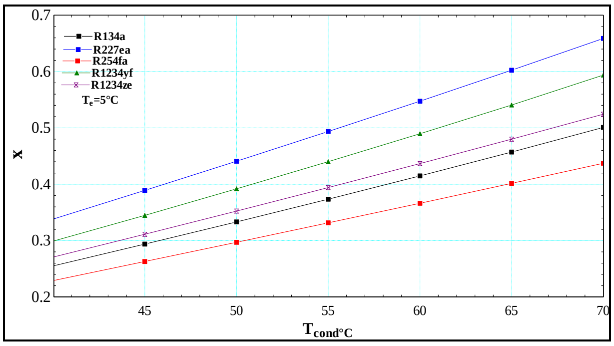


Fig (13) Refrigerant quality Vs Condensing Temperature

3.2.4 Coefficient of performance:

The coefficient of performance depend on refrigerating effect and compressor work , From Fig(14) for all studied refrigerants the coefficient of performance decreased as the condensing temperature increasing , because of the increasing in condensing temperature will increase the compressor work "the denominator" .and decrease the refrigerating effect "numerator" then decrease the value of COP. At any condensing temperature the R1234ze give identical performance to R134a, so R245fa give 6.8 % higher than of R134a.

3.2 Exergy Distraction and Exergy efficiency:

From Fig(15) All of the investigated refrigerants have low total exergy destruction than of R134a, so the major exergy destruction is from compressor. On the other hand the exergy efficiency will decrease as the condensing temperature increase fig (16) ,this due to the increasing in pressure ratio so compressor work. the refrigerant R1234ze give identical behavior to R134a while R227ea have the lowest exergy destruction and highest exergy efficiency.

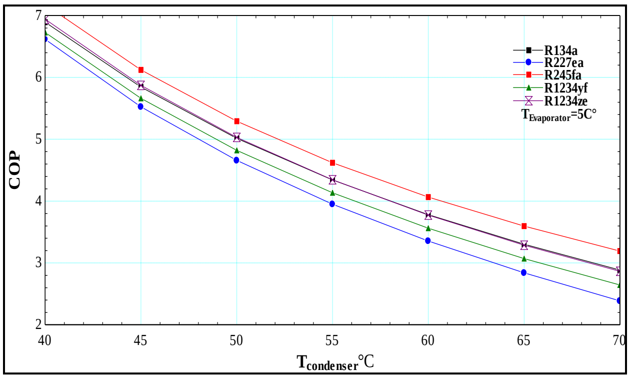


Fig (14) COP Vs Condensing Temperature

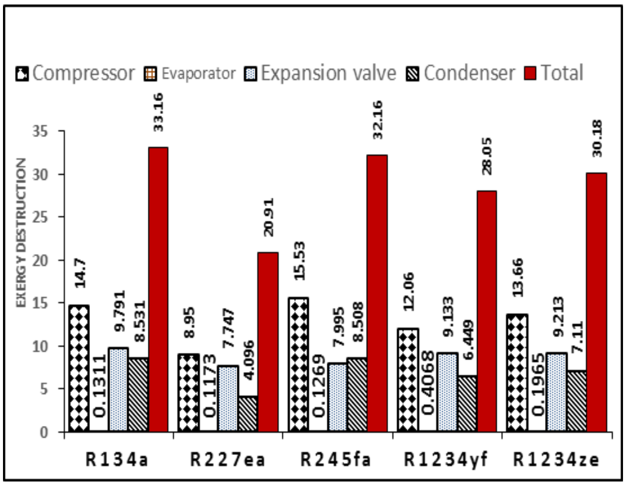


Fig (15) Exergy destruction Vs Condensing Temperature

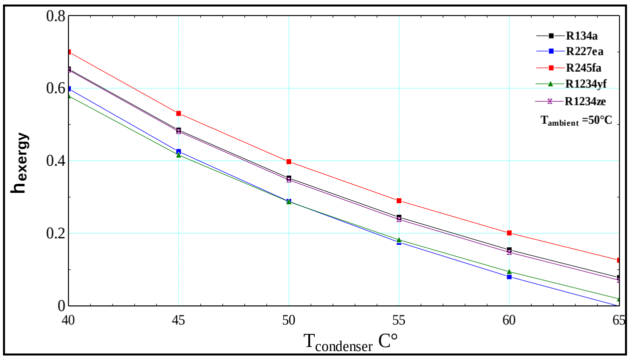


Fig (16) Exergy Efficiency Vs. Condensing Temperature

IV. Conclusions:

The preceding results of current study, the following conclusions can be drawn:-

1. The compressor work with R1234ze should be designed with displacement volume more than that of R134a to over cam the reduction in mass flow rate.
2. The compressor represents the major exergy destruction component in the refrigeration cycle.
3. The refrigerant R227ea have the lowest exergy destruction and highest exergy efficiency from all investigated refrigerants.
4. The system working with refrigerant R245fa give 6.8 % higher than that working with R134a but this portion cannot overcome the higher value of global warming potential and it cannot be used as alternative refrigerant to R134a.
5. At any working condition the R1234ze give identical performance to R134a and can be used as the best low global warming alternative refrigerant

V. References:

1. United Nations framework convention on climate change, United Nations 1992.
2. Vijay Singh Bisht , A.K. Pratihar, Thermodynamic Analysis of Actual Vapour Compression System with R12 and Its Eco-Friendly Alternatives Refrigerants Int. Journal of Engineering Research and Applications Vol. 4, Issue 4(Version 7), April 2014, pp.114-122
3. Mahmood Mastani Joybari, Mohammad Sadegh Hatamipour, Amir Rahimi Fatemeh GhadiriModarres,2013,Exergy analysis and optimization of R600a as a replacement of R134a in a domestic refrigerator system, International Journal of Refrigeration, Vol.20,pp.1-10.
4. B. O. Bolaji and Z. Huan, Thermodynamic analysis of hydrocarbon refrigerants in a sub cooling refrigeration system, Journal of Engg. Research ,vol. 1, no. June, pp. 317–333, 2013.
5. R.Saravanakumar, V.Selladurai, Exergy analysis of a domestic refrigerator using eco-friendly R290/R600a refrigerant mixture as an alternative to R134a. Journal of Thermal Analysis and Calorimetry,2014, Volume 115, Issue 1, pp 933-940.
6. R. S. Mishra ,Energy-Exergy Performance Comparison of Vapour Compression Refrigeration Systems using three NANO Materials Mixed in R718 as secondary Fluid and R1234yf and R1234ze Ecofriendly Refrigerants in the Primary Circuit, International Journal of Advance Research and Innovation, Volume 3, Issue 4 (2015)
7. Gaurav and Raj Kumar, Sustainability of Automobile Air Conditioning System Using Refrigerant R1234yf Instead of R134a, International Journal of Automotive Engineering, Vol. 5, Number 3, Sept 2015
8. Shobhit Mishra, M. Emran Khan ,Theoretical Exergy Analysis of Actual Vapour Compression System with HFO-1234yf and HFO- 1234ze as an Alternative Replacement of HFC-134a, Volume 5 Issue 4, April 2016
9. Refrigeration systems and applications second edition, Ibrahim Dincer, Mehmet Kanoglu, 2010 John Wiley & Sons, Ltd.
10. Exergy Analysis of Heating Refrigerating and Air Conditioning, Ibrahim Dincer and Marc A. Rosen. Elsevier Inc.2015.