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Exergetic Analysis of Refrigerants R-134a, R-600a and R-1234yf in a Vapour Compression Refrigeration System

JAGDISH NARAYAN GUPTA[1] AND SUNIL KUMAR GUPTA[2]

[1]Mechanical Engineering Department
Pusa Institute of Technology
Pusa, New Delhi- 110012
[2]Mechanical Engineering Department
Aryabhatt Institute of Technology,
G.T. Karnal Road, Delhi-110033.
E-mail: [1]jngupta75@yahoo.com, [2]sngupta71@gmail.com

Abstract—*This paper analyse the performance comparison of an HFC(R-134a), an HC(R-600a) and an HFO(R-1234yf) refrigerant in a vapour compression refrigeration system. Performance based on energy and exergy has been presented for the three refrigerants. It is concluded that however R-134a is the best choice in terms of thermodynamic aspect but due to ecological concern this refrigerant has to be essentially replaced with environment friendly refrigerants. R-1234yf shows better exergetic performance and more eco-freindly therefore it has been found suitable alternative to replace R-134a .*

Keywords: *HFC, HC, HFO, COP, Exergy Destruction, Exergy Efficiency.*

1. INTRODUCTION

Refrigeration and air-conditioning deals with the techniques to control the environments of the living and non-living subjects and thus provide them comforts to enable them to perform better and have longer lives.

Fast growing technological and social developments all over the world has given rise to use of refrigeration and air-conditioning on a large scale. Now-a-days refrigeration and air-conditioning is used almost everywhere – in homes, workplaces, hotels, shopping malls, hospitals, transport vehicles,etc.

Refrigeration and air conditioning systems have a major impact on energy demand which approximates to one third of total energy consumption in the world. Major contribution of refrigeration, air-conditioning and heat-pumping load is met out by the vapour compression systems. Conventionally these systems were operated on halogenated compounds such as CFCs and HCFCs because of their favourable thermo-physical and thermodynamic properties. However, these compounds contain chlorine which is responsible for ozone layer depletion. In addition to the ozone layer depletion, CFCs also contribute to global warming by greenhouse effect. Over the last two decades, immense improvement in refrigeration technology has resulted in increased energy efficiency.

Recent studies in search for more efficient vapour compression refrigeration system, have concentrated their aim to develop new technologies to obtain a better performance and the use of new refrigerants, pure or mixtures, fulfilling both energetic and environmental aspects.

Literature Survey :

Exergy investigation used to find that decrease of irreversibility rate in a plant component gives a more noteworthy decrease in the irreversibility rate of the plant as a whole, hence, to limit the exergy losses, the performance of condenser and evaporator should be optimised [1]. Changes of system parameter were investigated which influence exergy losses and evaluated the variety of the exergy efficiency and exergy flow identified with the substitutions of R-12, R-22 and R-502[2]. The exergy efficiency is incredibly influenced by changes in the evaporator and condenser temperature. The more noteworthy bit of exergy destruction occurs in the compressor. The highest exergy efficiencies are acquired with R1234ze and R134a [3]. It was proposed to improve exergy efficiency by increasing reference state temperature, subcooling up to 5^0, staging in compression, care for the compressor and sealing or choosing suitable refrigerant. Exergy efficiency can be enhanced by sub-cooling up to 5^0C and lowering the temperature difference of the evaporating and condensing temperature [4]. Exergy investigation of two-stage VCR system to assess ideal inter stage temperature (pressure) for refrigerants HCFC22, R410A and R717 demonstrated that the efficiency defect in condenser was higher in contrast with alternate parts [5]. Exergy examination connected to evaluate the performance of various air conditioning systems with the results that the air cooling and dehumidification is the procedure most in charge of the exergy loss and that the exergy efficiency of the overall systems is somewhat low[6]. Mosaffa et.al investigated and decided ideal benefits of working parameters of the system that augment the coefficient of performance (COP) and exergy efficiency[7]. The exergy efficiency is greatly affected by changes in the evaporator and condenser temperature.

The ambient temperature has substantial effect on the energy and exergy parameters[8]. Results of a computational model for evaluating COP, ED, exergetic efficiency, ED ratio and optimum evaporator temperature for R-22, R-407C and R-410A indicated that none of the alternate refrigerants will provide same performance as obtained in case of R-22. However, R-410A was found to be a better alternate as compared to R-407C, with high COP and low EDR [9]. The energy and exergy efficiency of two possible alternatives for R22, R438A and a new refrigerant mixture M1 (R32/R125/R600A) were found lesser than that of R22. However, R438A was found to be a better option since its COP as well as exergy efficiency worked out to be higher than that of M1 [10].

The exergy destruction rate of the compressor obtained with HFO-1234yf is lower than that calculated for R-134a[11]. Using HFO-1234yf as the air conditioning refrigerant lead to higher exergy efficiency compared to HFC-134a. Also, maximum entropy generation and exergy destruction occured in the compressor .[12].

It was found that modified vapour compression refrigeration system based on energy and exergy analysis gave better results than separate systems[13].

dropin alternative to R134a considering the energy consumption and the cooling capacity of the refrigerating facility taking into account the corresponding safety requirements for an A2L refrigerant [14].

Exergy analysis of a refrigerator with R134a showed that the compressor had the highest amount of exergy destruction followed by the condenser, capillary tube, evaporator and superheating coil. The amount of charge required for R600a is 50 g, 66% lower than R134a [15].

To the authors' knowledge, there is no specific work reported on the performance comparison of R600a and R1234yf as an alternative to R134a in domestic refrigerators. The main objective of this paper is to investigate R1234yf as a potential alternative to R134a.

2. PERFORMANCE ANALYSIS

The vapour compression cycle which is used in vapour compression refrigeration system is now-a-days used for all purpose refrigeration. It is used for all industrial purposes from a small domestic refrigerator to a big air conditioning plant.

In a vapour compression cycle, total heat input comprise of heat abstracted from the evaporator and the compressor work input. For a complete cycle total heat added should be rejected in the condenser. Therefore,

$Q_R=Q_E+W_C$

Where Q_E is the heat abstracted from the evaporator and Q_R is the heat rejected in the condenser. W_C is the work done on the compressor during a cycle.

Evaporator:

Heat abstracted in the evaporator is given by following equation,

$$\dot{Q}_E = \dot{m}_r (h_4 - h_1) \quad (1)$$

where $\dot{m}_r$ = mass flow rate of refrigerant

h_1 = enthalpy of refrigerant at exit of the evaporator

h_4 = enthalpy of refrigerant at entrance to the evaporator

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Compressor:

The isentropic (theoretical) Work input to the compressor is given by following equation,

$$\dot{W}_{C_s} = \dot{m}_r (h_{2s} - h_1) \quad (2)$$

and actual work input to the compressor is given by following equation,

$$\dot{W}_C = \frac{\dot{W}_{Cs}}{\eta_s}$$

W

where η_s is the isentropic efficiency of the compressor.

Condenser:

Heat rejected to atmosphere by the condenser is given by following equation,

$$\dot{Q}_R = \dot{m}_r (h_3 - h_2) \quad (3)$$

where h_3 is the liquid enthalpy of refrigerant at condenser pressure.

COP gives the measure of performance of refrigeration cycle as:

$$COP = \frac{Q_E}{W_C} \quad \textbf{(4)}$$

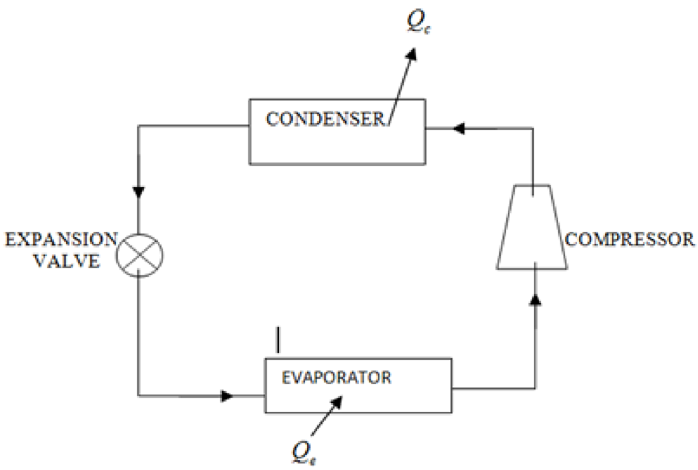

Figure 1(a): Simple Vapour-Compression Refrigeration Cycle (Schematic Diagram)

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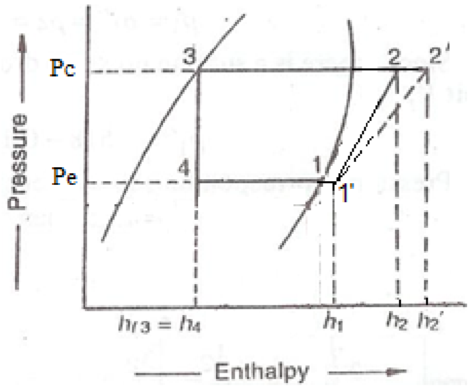


Figure 1 (b): P-h diagram of Vapour Compression Refrigeration Cycle

Usually, exergy balance for a control volume in a steady state process is expressed as [16]

$$\dot{E}x_d = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} + \sum\left[\dot{Q}\left(1-\frac{T_0}{T}\right)\right]_{in} - \sum\left[\dot{Q}\left(1-\frac{T_0}{T}\right)\right]_{out} + \sum \dot{W}_{in} - \sum \dot{W}_{out} \quad (5)$$

Where $\dot{E}x_d$ is the exergy flow destruction and the first two terms on the right are stream exergy flows, the next two terms are heat transfer exergy flows and the last two terms are work exergy flows.

According to the exergy balance, the exergy destruction for system components can be expressed as follows in terms of per unit mass of mixture refrigerant at the compressor inlet.

For compressor:

$$ex_{d,com} = W_c + \left[(h_1 - h_2) - T_0(s_1 - s_2)\right] = T_0(s_2 - s_1) \quad (6)$$

Since the heat transferred from the refrigerant in the condensation unit is rejected to the ambient, the exergy of the heat is assumed to be useless. Thus for the condensation unit:

$$ex_{d,con} = \left[(h_2 - h_3) - T_0(s_2 - s_3)\right] \quad (7)$$

For the evaporator:

$$ex_{d,evap} = \left[(h_4 - h_1) - T_0(s_4 - s_1)\right] + Q_E\left(1 - {T_0}/{T_r}\right) \quad (8)$$

Where T_r is the air temperature in the cold room, and the value is set to 20^{0}C .

For capillary tube:

$$ex_{d,ct} = (h_3 - h_4) - T_0(s_3 - s_4) = T_0(s_4 - s_3) \quad (9)$$

The total exergy destruction equation for the VCR system is given by

$$ex_{d,t} = ex_{d,com} + ex_{d,con} + ex_{d,evap} + ex_{d,ct} \quad (10)$$

The exergetic efficiency of the VCR system is given by

$$\eta_{ex} = 1 - ex_{d,t} / W_c \quad (11)$$

The component exergy destruction rate can be compared to total exergy destruction rate within the system, $\dot{E}_{D,tot}$, giving the exergy destruction ratio [17] :

$$y_D^* = \frac{\dot{E}_D}{\dot{E}_{D,tot}} \qquad (12)$$

Table 1-Main thermodynamic,safety and environmental properties(ASHRAE 2013,D.Sanchez ,2017[14])

Fluid	Chemical Formula	Pcr (MPa)	Tcr (°C)	MW (kg.kmol^{-1})	NBP (°C)	Vsat,v(NBP) ($m^3.kg^{-1}$)	Safety Group	GWP (100 years)
HFC 134a	C2H2F4	4.059	101.06	102.03	-26.07	0.0693	A1	1301
HFO 1234yf	C3H2F4	3.382	94.70	114.04	-29.45	0.0567	A2L	<1
HC 600a	C4H10	3.629	134.66	58.12	-11.75	0.2349	A3	4

Assumptions:

Q_E = 3.5167 kW

Isentropic efficiency of Comprressor = 75%

Evaporator Coil Temp T_e= -10°C to +5°C

Condenser Temp T_c= 40°C, 50°C, 60°C

Cold Room Temperature =20°C

Ambient or environment temperature =30°C

Refrigerant : R-134a, R-600a, R1234yf

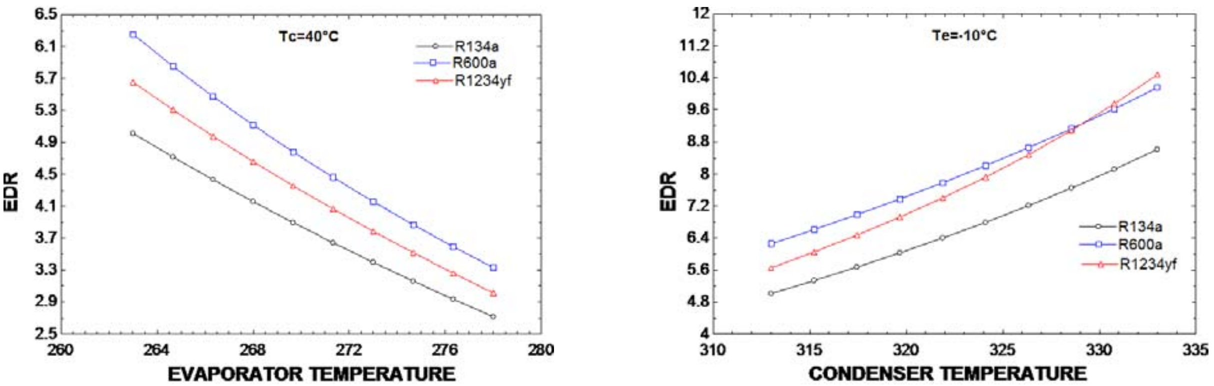
Neglecting pressure losses in evaporator and condenser.

superheating in evaporator =2degree

Neglecting subcooling in condenser.

3. RESULTS AND DISCUSSION

Figure -2 depicts Exergy Destruction Ratio (EDR) is the highest in case of R-600a and it is lowest for R-134a at selected range of evaporator temperature (keeping Tc=constant).



(a) **(b)**

Figure-2 (a & b): Exergy Destruction Ratio

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Reference to Figure-3,total exergy destruction (ED_{total}) in the system is found to be lowest for R-134a whereas it is the highest in case of R-600a at condenser temperature of 40°C and 50°C. It is seen that exergy destruction reduces as the evaporator temperature increases and it increases as the condenser temperature increases. Total exergy destruction in case of R-1234yf is lower than R-600a at condenser temperature 40°C and 50°C while it increases a little over R-600a at 55.4°C condenser temperature.

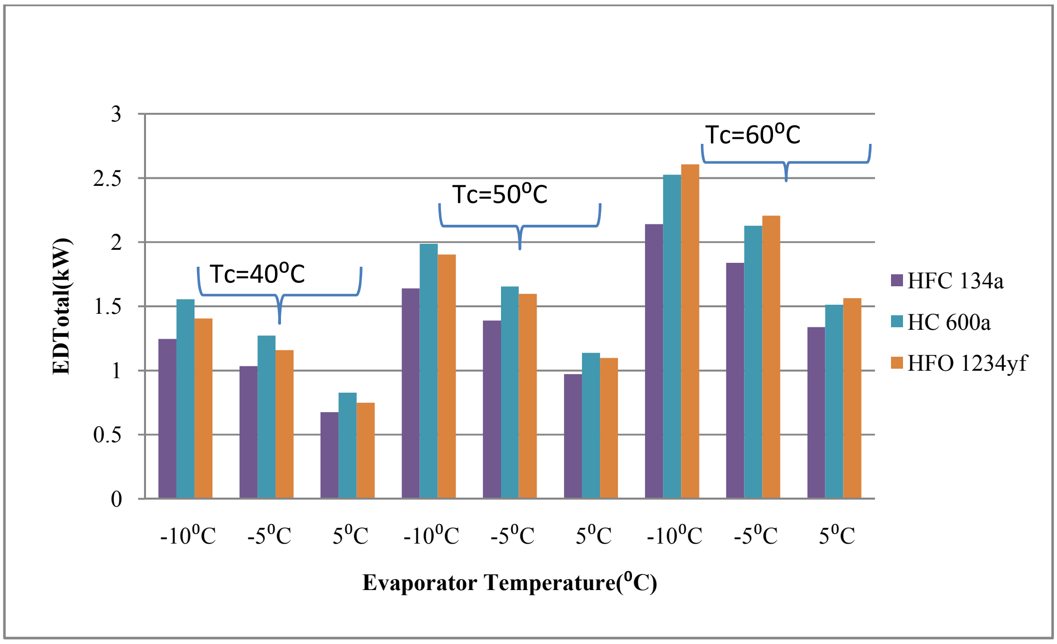
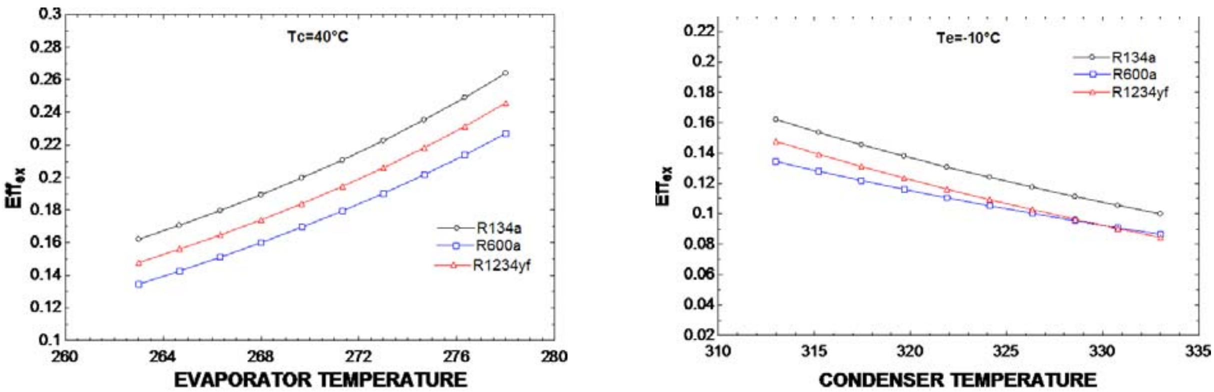


Figure 3: Total Exergy Destruction at various evaporator and condenser temperatures

Exergetic efficiency in case of R-134a is found to be highest among all refrigerants considered whereas it is the lowest for R-600a at condenser temperature of 40°C and 50°C(Figure-4).

It is seen that exergy efficiency increases with increase in the evaporator temperature and decreases with the increase in condenser temperature.



(a)
Figure 4 : (a) Effect of Evaporator Temperature on Exergetic Efficiency

(b)
Figure.4(b) Effect of Condenser Temperature on Exergetic Efficiency

As indicated by Figure-5, the Compressor work required to run the system in case of R-600a is the highest at condenser temperature of 40°C and 50°C, and it is lowest in case of HFC 134a refrigerant. The compressor work for R-1234yf is highest

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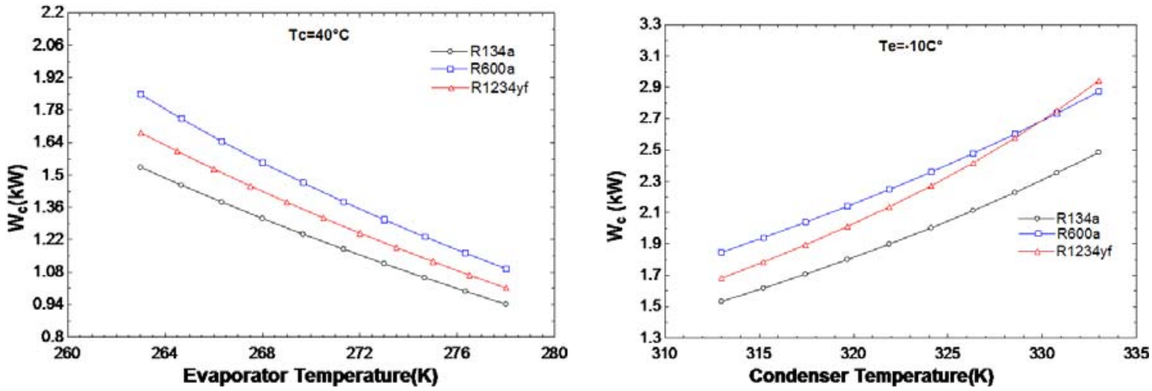
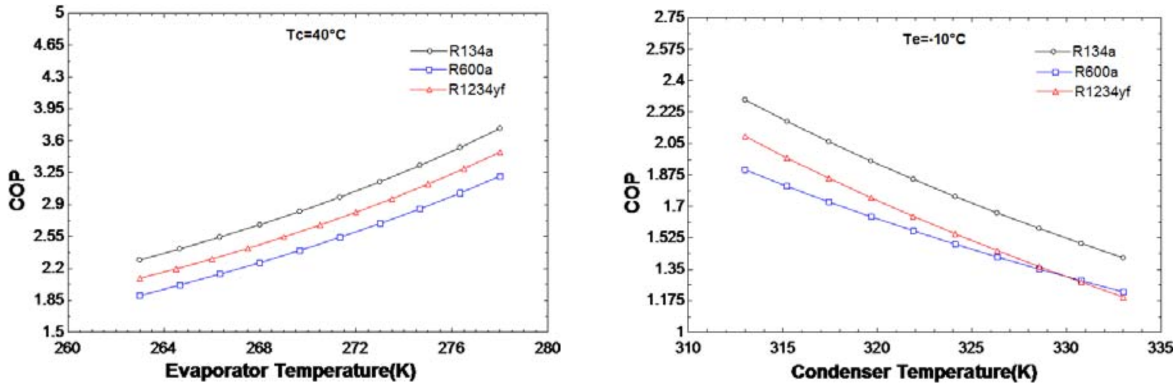
beyond 55.4^{o}C(328.6K) at various evaporator temperatures. It is also seen that compressor work decreases at elevated evaporator temperatures but increases as the condenser temperature increases.



(a) (b)

Figure 5 : (a) Effect of varying Evaporator Temperature on Compressor Work **Figure 5 (b) Effect of varying Condenser Temperature on Compressor Work**

As shown in figure-6, COP in case of R-134a is found to be the highest at all condenser and evaporator temperatures whereas COP for R-600a is found to be the lowest for condenser temperature upto 55.4^{o}C. R1234yf has slightly lower COP than R600a at higher condensing temperature (328.6K and above) as shown in Figure-6(d,e,f). It is seen that COP at higher evaporating temperature is more and it is less for the higher condensing temperature.



(a) (b)

Figure 6 : (a) Effect of varying Evaporator Temperature on COP **Figure 6(b) Effect of varying Condenser Temperature on COP**

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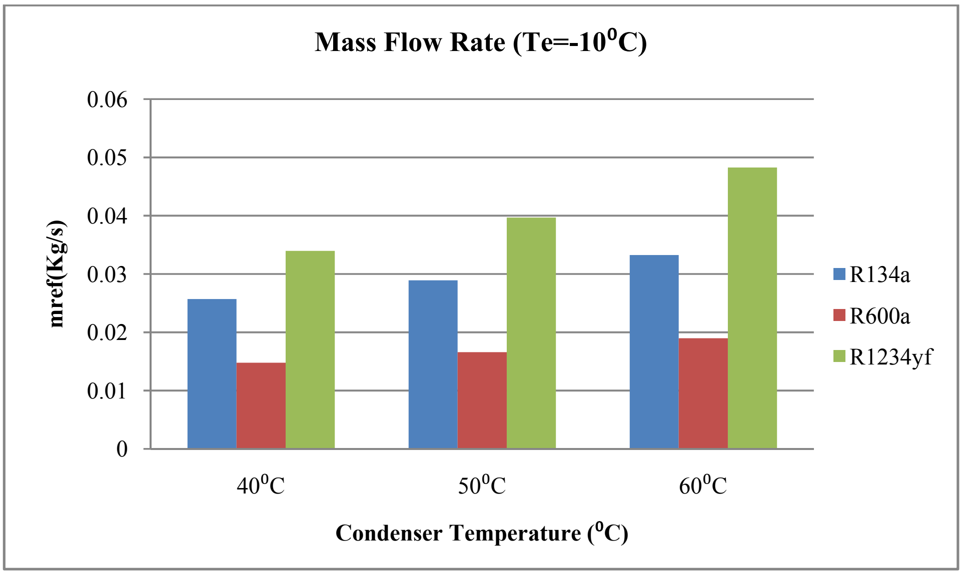

Figure 7 : Mass Flow Rate vs Condenser Temperature

For same refrigerating effect(Q_{evap}), mass of refrigerant R-600a circulated (m_r) is almost 60% as compared to R-134a and it is about 40% to that of R-1234yf (Figure-.7). Therefore to get the same refrigerating effect, amount of charge required with R600a will be 40% less than that required for R-134a and about 60% less than R-1234yf.

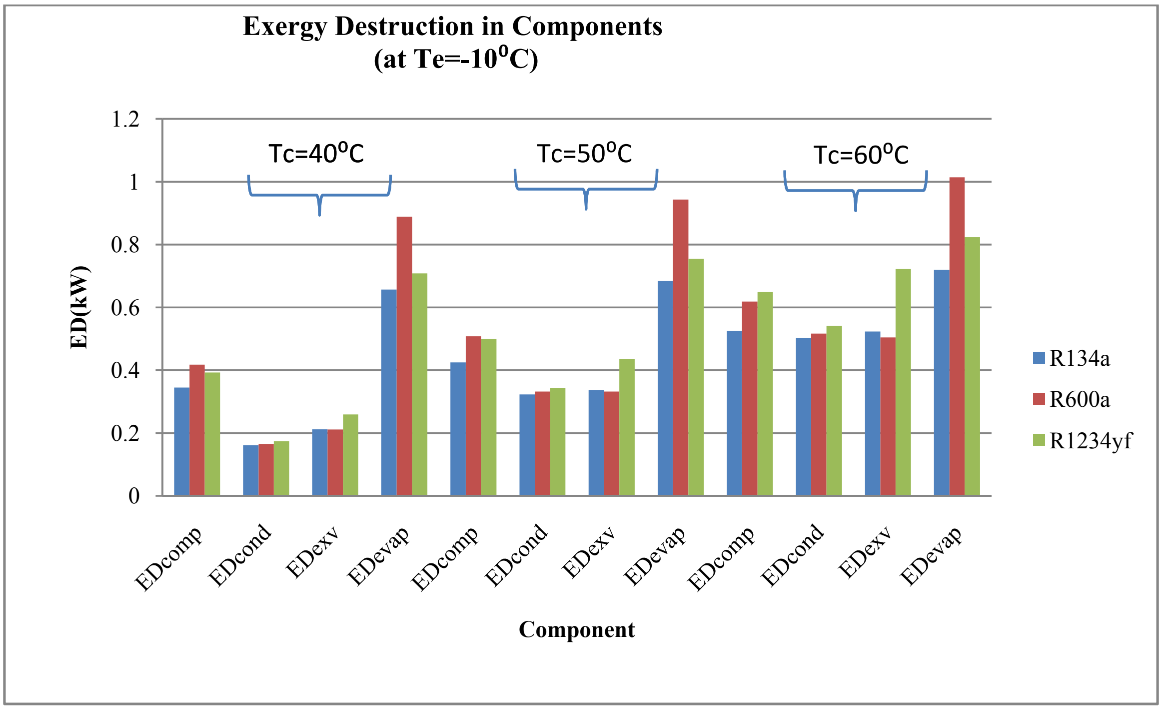

Figure 8 : Exergy destruction in components at various condenser temperature (Te=-10⁰C)

Figure-8 shows exergy destruction in components at various condensing temperature while evaporator temperature fixed at -10°C. Exergy destruction in evaporator is highest whereas exergy destruction in condenser is lowest It is seen that exergy destruction increases for all the refrigerants with increase in condensing temperature.

Figure-9 represents the validation of present work with the theoretical work of Jarall (2012) at evaporator temperature 5°C and condenser temperature of 40°C. The model of present work has been checked against the experimental results of the above mentioned work for COP of R-1234yf corresponding to dead-state temperature 25°C. The COP of R-1234yf for the present work is 7.79% higher, as compared to the experimental results of the above-mentioned researcher.

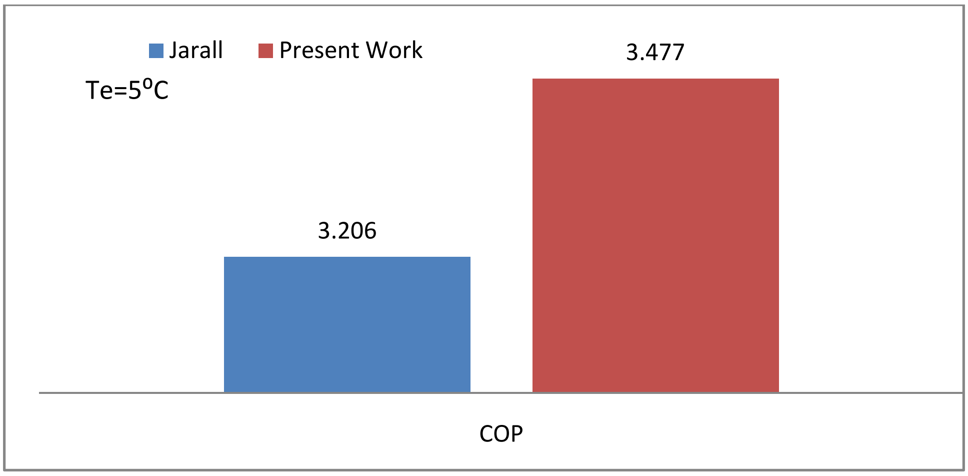

Figure 9 : (a)Validation of present work with Jarall(22) for R-1234yf

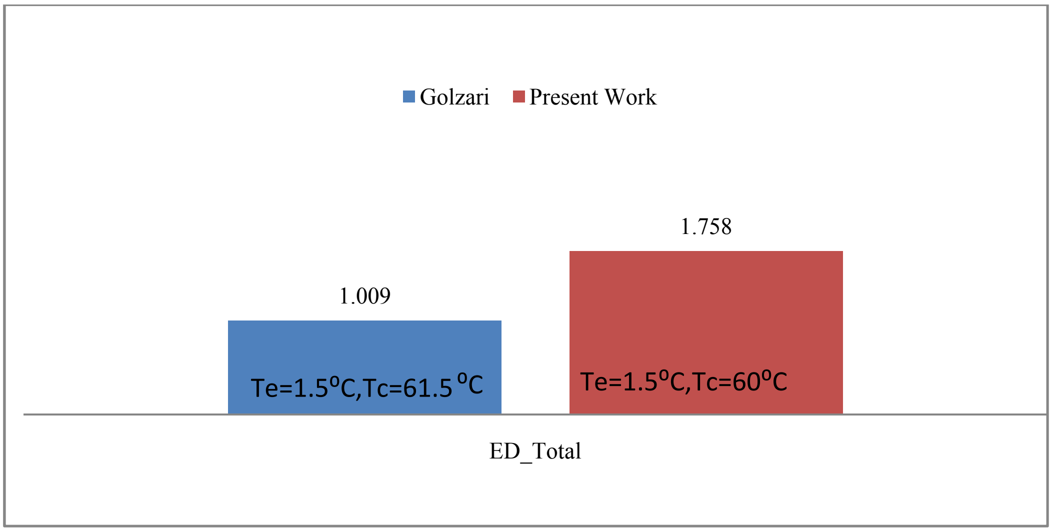

Figure 9 : (b)Validation of present work with Golzari [32] for R-1234yf

4. CONCLUSION

1. Exergy Destruction Ratio (EDR) is the highest in case of R-600a and it is lowest for R-134a (Tc=constant).
2. Total exergy destruction (ED_{total}) in the system is found to be lowest for R-134a whereas it is the highest in case of R-600a at condenser temperature of 40°C and 50°C. Exergy destruction reduces as the evaporator temperature increases and it increases as the condenser temperature increases. Total exergy destruction in case of R-1234yf is lower than R-600a at condenser temperature 40°C and 50°C while it increases a little over R-600a after 55.4°C condenser temperature.

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3. Exergetic efficiency in case of R-134a is found to be highest among all refrigerants considered whereas it is the lowest for R-600a at condenser temperature of 40°C and 50°C. Exergy efficiency increases with increase in the evaporator temperature and decreases with the increase in condenser temperature.
4. The Compressor work required to run the system in case of R-600a is the highest at condenser temperature of 40°C and 50°C, and it is lowest in case of HFC 134a refrigerant. The compressor work for R-1234yf is highest beyond 55.4°C(328.6K) at various evaporator temperatures. The compressor work decreases at elevated evaporator temperatures but increases as the condenser temperature increases.
5. COP in case of R-134a is found to be the highest at all condenser and evaporator temperatures whereas COP for R-600a is found to be the lowest for condenser temperature upto 55.4°C. R1234yf has slightly lower COP than R600a at higher condensing temperature (55.4°C and above). The COP at higher evaporating temperature is more and it is less for the higher condensing temperature.
6. Exergy destruction in evaporator is highest whereas exergy destruction in condenser is lowest. The exergy destruction increases for all the refrigerants with increase in condensing temperature.
7. For same refrigerating effect (Q_{evap}), mass of refrigerant R-600a circulated (m_r) is lesser by 60% and 40% than R-134a and R-1234yf respectively. In other words, to get the same refrigerating effect, amount of charge required with R600a will be 40% and 60% less than that required for R-134a and R-1234yf respectively. This will address the issue of flammability if R600a is used in small units.
8. The use of R-1234yf is however growing as there is minimal modifications except for the safety. In the meanwhile, since HFCs only solve the ozone depletion issue and the issue with respect to climate change remain, therefore, there is need to promote natural refrigerants with much better safety standards.

5. ACKNOWLEDGEMENTS

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