Theoretical Exergy Analysis of HFO-1234yf and HFO-1234ze as an Alternative Replacement of HFC-134a in Simple Vapour Compression Refrigeration System

Naushad A. Ansari, Bipin Yadav, Jitendra Kumar

Abstract— An Exergy method for theoretical analysis of a traditional vapour-compression refrigeration system equipped with liquid vapour heat exchanger (lvhe) for HFO-1234yf (2, 3, 3, 3-Tetrafluoropropene) and HFO-1234ze (trans-1, 3, 3, 3-tetrafluoroprop-1-ene), both ultra low Global Warming Potential(GWP) and zero Ozone Depletion Potential(ODP) refrigerants and comparison of the results with HFC-134a refrigerant as possible alternative replacements in Automotive air-conditioning and stationary refrigeration is presented. A mathematical computational model has been developed for calculating Coefficient of performance (COP), exergetic efficiency, exergy destruction and efficiency defects for HFO-1234yf, HFO-1234ze and HFC-134a.During the investigation, condenser temperature is kept at 313K and evaporator temperature is kept in the range from 223K to 273K .Results obtained indicate that HFO-1234yf and HFO-1234ze can be good replacement of R-134a. Among the system components, condenser shows highest efficiency defect value and liquid vapour heat exchanger shows the lowest.

Index Terms— COP, Efficiency, Exergy, GWP, HFC-134a, HFO-1234yf, HFO-1234ze, ODP

1. INTRODUCTION

There is a general consensus that the next generation of refrigerants needs to have zero ozone depletion and low global warming potential. This consensus is also supported by proposed legislation in various countries to enforce a shift to refrigerants with a reduced environmental impact and more energy efficient [1]. The Clean Air Act Amendments were passed by the U.S. Congress in 1990 following the Montreal Protocol in 1987. The main impetus was of course the ozone depleting potential of the chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) commonly used in refrigeration leading to the phasing out of CFC12 [2]. This results in successful development and adoption of HFC134a in domestic refrigerators and mobile air conditioners, having similar vapour pressure and performance as that of CFC12. However, next serious global environmental problem is concerning the refrigerant. It is the global warming problem. In 1997, United Nations Framework Convention on Climate Change (UNFCCC), held in Kyoto, proposed 'Kyoto Protocol' to control emission of greenhouse gases including HFC's [3]. The HFC-134a was identified as having a high global warming potential (GWP) of 1,430 and hence needs to be replaced by more environmentally friendly refrigerant.

To meet its global warming obligations and emissions reduction targets, a new legislation was passed by the EU requiring both automotive Original equipment

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manufacturers (OEMs) and suppliers to adopt an alternative refrigerant with a GWP of 150 or less by the year 2012. The European Union's F-gas Regulation No 842/2006 became law on 4 July 2006 and many of the requirements came into force on 4th July 2007. The F-Gas regulations will phase out the use of HFC-134a in automotive air conditioning systems for all new models beginning in 2011 [4]. In anticipation, extensive research is being carried out to develop new low global warming potential fluids to support the refrigeration and air-conditioning industry, for example HFO-1234yf [5],[6]. HFO-1234yf, which has a 100 year GWP of 4 as compared to that of CO2 [7] could be used as a "near drop-in replacement" for HFC134a, which means that the automobile manufacturers would not required to make significant alterations in the assembly lines or in vehicle system designs to accommodate the product.

Brown [8] gives an overview of the feasibility of HFOs as replacement refrigerants. The researches on HFO are mostly focused on measuring or reckoning their thermodynamic properties [9], [10], [11], [12], [13]. Thermodynamic and transport properties of HFO-1234yf and HFO-1234ze fluids are available in REFPROP [14]. Leck [15] evaluated the performance of HFO-1234yf theoretically and showed that it had 2-9% less capacity and 2-7% less COP than HFC-134a. Also HFO-1234yf had similar lubricant miscibility and polymer compatibility as that of HFC-134a.

Leck [16] theoretically analyzed the performance of R-1234yf and other alternative refrigerants in air conditioning and stationary heating, and concluded that R-1234yf was having 57% less capacity and 7% higher COP than R-410a. Yana Motta et al. [17] experimentally established that performance of HFO-1234yf was similar to R-134a in a representative vending machine. Additionally, HFO-1234ze when tested in the vending machine with a 75% larger displacement compressor had slightly more capacity and less efficiency. Minor et al. [18] performed optimization of beverage cooler using HFO-1234yf and found that performance is comparable to

HFC-134a.

Reaser et al. [19] investigated and compared the thermophysical properties of HFO-1234yf to those of HFC-134a and R410a to determine the drop-in replacement potential of HFO-1234yf and concluded that properties were similar to that of HFC-134a and not similar to that of R410a. Zang et al. [20] developed the non-azeotropic mixtures composed of HFOs (HFO-1234yf, HFO-1234ze(e), HFO-1234ze(z) and HFO-1234zf) as a replacement of HFC-134a and CFC-114 in air-conditioning and high temperature heat pump systems. It investigated theoretical cycle performance and found that COP of mixture of HFO-1234zf/HC-290 (60%/40% in mass) was 1.5% higher than that of HFC-134a, thus a good substitute in air conditioning system.

Leighton et al. [21] theoretically showed that HFO-1234yf had 9% lower COP and 6% less capacity than HFC-134a and also showed HFO-1234ze had 8% higher COP and 21% lower capacity than HFC-134a. Abdelaziz et al. [22] evaluated experimentally and compared the performance of HFC-134a to HFO-1234yf and HFO-1234ze, and concluded that HFO-1234yf had 2.7% higher energy consumption than HFC-134a, indicating that HFO-1234yf is a suitable drop-in replacement of HFC-134a in domestic refrigerators. While HFO-1234ze had 16% lower energy consumption than HFC-134a, hence to replace HFC-134a with HFO-1234ze lower capacity refrigerators were required, thus HFO-1234ze might not be suitable for drop-in replacement.

Esbri, et al. [23] experimentally analysed HFO-1234yf as a drop-in replacement for HFC-134a in a vapour compression system and summarized as, the cooling capacity of HFO-1234yf is about 9% lower than that of HFC-134a, which diminishes with the use of internal heat exchanger. Volumetric efficiency was about 5% less than that obtained with HFC-134a. Jung, et al. [24] evaluated the performance of HFO-1234yf and HFO-1234yf/HFC-134a mixture in three compositions and drawn the results that COP, capacity and discharge temperature of HFO-1234yf and mixture of refrigerants are similar to those of HFC-134a, with decrement in flammability as the content of HFC-134a increases.

First, literature survey emphasizes that HFO-1234yf and HFO-1234ze can be a promising alternative to HFC-134a.Secondly, it has been observed that in most of the studies referred above, the analysis of the systems is based on first law of thermodynamics i.e. estimating coefficient of performance. In this study a more comprehensive exergy approach is followed, based on both first and second laws of thermodynamics. It is a powerful tool in the design and performance evaluation of the systems, and allows an explicit presentation of thermodynamic processes by quantifying the effect of irreversibility occurring during the processes. Exergy balance applied to processes tells us how much of the exergy input to the system has been consumed (irreversibly lost) by the system. This analysis takes into account all the losses appearing in the refrigeration system, for calculating exergetic efficiency. The various parameters calculated are COP, exergetic efficiency, exergy destruction and efficiency defects. Effects of degree of sub-cooling, liquid vapour heat exchanger effectiveness and dead state temperature are also

computed and discussed. Table 1 shows the thermophysical properties of refrigerants [25], [26].

TABLE 1: THERMOPHYSICAL PROPERTIES OF REFRIGERANTS.

Properties	HFO-1234yf	HFO-1234ze	HFC-134a
Boiling Point, T_b	-29°C	-19°C	-26°C
Critical Point, T_c	94.7°C	109.4°C	101°C
Pvap, MPa (25°C)	0.682	0.500	0.665
Pvap, MPa (80°C)	2.519	2.007	2.635
Liquid Density, kg/m3 (25°C)	1092	1162	1207
Vapour Density, kg/m3 (25°C)	37.94	26.76	32.34

2. EXERGY ANALYSIS

The vapour compression refrigeration cycle with liquid vapour heat exchanger including superheating, sub-cooling is shown in figure 1(a) and (b).
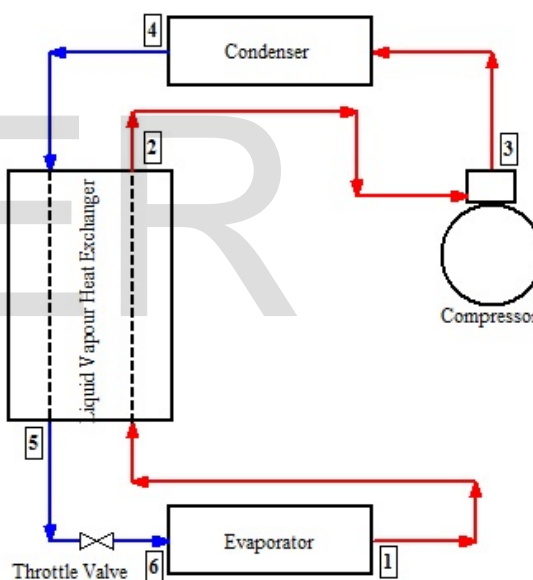

Fig. 1(a): Vapour compression refrigeration cycle with liquid vapour heat exchanger (lvhe)
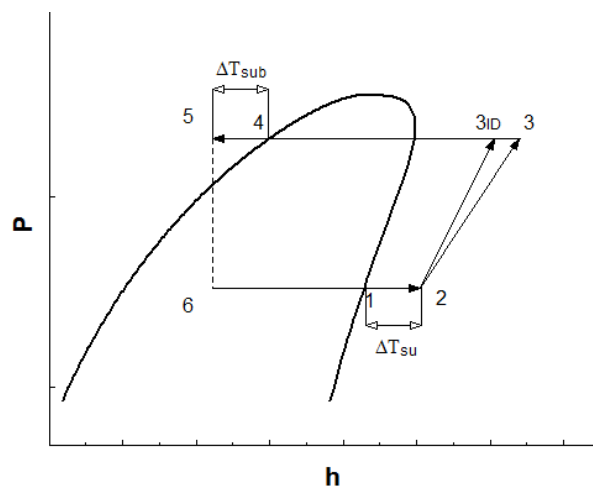
Fig. 1(b): pressure – enthalpy diagram of vapour compression refrigeration cycle with lvhe

From the first law of thermodynamics, coefficient of performance (COP) is the measure of performance of the cycle, which is defined as refrigeration effect (desired effect) produced per unit of work required. It is given by

$$COP = \frac{\dot{Q}_e}{\dot{W}_{comp}} \qquad (1)$$

COP = Coefficient of Performance
$\dot{Q}_e$ = Rate of heat transfer in evaporator (kW)
$\dot{W}_{comp}$ = Compressor work rate (kW)

The second law of thermodynamics infers the concept of exergy, a powerful tool for analysing both the quantity and quality of energy utilization. It is defined as the maximum amount of work obtainable when the stream of matter is brought from its initial state to the dead state by the processes during which the stream may interact only with the environment. The exergy balance is similar to an energy balance but has the fundamental difference that, while the energy balance is a statement of a law of conservation of energy, the exergy may be looked upon as a statement of law of degradation of energy [28].

Exergy balance for a control region undergoing a steady-state process is expressed as

$$\dot{E}_i + \dot{E}_j^Q = \dot{E}_e + \dot{W}_j + \dot{ED}_J \qquad (2)$$

$$\dot{E}_i = \sum_{IN} \dot{m}\,\epsilon$$

$$\dot{E}_e = \sum_{OUT} \dot{m}\,\epsilon$$

$$\dot{E}_j^Q = \sum \left[\dot{Q}_j \frac{T - T_o}{T}\right]$$

$$\epsilon = (h - T_o s) - (h_o - T_o s_o)$$

$\dot{E}_i$ = exergy rate at the inlet of control region (kW)
$\dot{E}_e$ = exergy rate at the exit of control region (kW)
$\dot{E}_j^Q$ = thermal exergy flow rate in the jth component (kW)
$\dot{W}_j$ = work rate of jth component of the system (kW)
$\dot{ED}_J$ = exergy destruction rate in jth component (kW)
$\dot{Q}_j$ = rate of heat transfer in jth component (kW)
ϵ = specific exergy (kJ/kg)
h = specific enthalpy (kJ/kg)
s = specific entropy (kJ/kg-K)
T_o = ambient state temperature (K)

where the first term on left hand and right hand side of (2) represent physical exergy (neglecting kinetic, potential and chemical exergy component) of stream of matter entering and leaving the control region respectively. The second term on left hand side and right hand side is thermal exergy flow, which gives exergy transfer rate corresponding to the heat transfer rate $\dot{Q}$ when the temperature at the control surface where heat transfer is occurring is T and exergy associated with work transfer to and from the control region. $\dot{ED}$ represents rate of exergy destruction [28].

2.1. Exergy destruction(ED)

2.1.1. Evaporator
$$\dot{ED}_e = \dot{E}_6 + \dot{Q}_e\left(1 - \frac{T_o}{T_r}\right) - \dot{E}_1 = \dot{m}_r[(h_6 - h_1) - T_o(s_6 - s_1)] + \dot{Q}_e\left(1 - \frac{T_o}{T_r}\right) \qquad (3)$$

$\dot{m}_r$ = mass flow rate of refrigerant (kg/s)
T_r = Temperature of space to be cooled (K)

2.1.2. Compressor
$$\dot{ED}_{comp} = \dot{E}_2 + \dot{W}_{comp} - \dot{E}_3 = \dot{m}_r[T_o(s_3 - s_2)] \qquad (4)$$

2.1.3. Condenser
$$\dot{ED}_c = \dot{E}_3 - \dot{E}_4 = \dot{m}_r[(h_3 - h_4) - T_o(s_3 - s_4)] \qquad (5)$$

2.1.4. Liquid vapour heat exchanger (lvhe)
$$\dot{ED}_{lvhe} = (\dot{E}_4 - \dot{E}_5) + (\dot{E}_1 - \dot{E}_2) = \dot{m}_r[(h_4 - h_5) + (h_1 - h_2) - T_o[(s_4 - s_5) + (s_1 - s_2)]] \qquad (6)$$

2.1.4. Throttle Valve
$$\dot{ED}_t = \dot{E}_5 - \dot{E}_6 = \dot{m}_r[T_o(s_5 - s_6)] \qquad (7)$$

2.2. Total exergy destruction

It is the sum of exergy destruction in different components of the system.

$$\dot{ED}_{total} = \dot{ED}_e + \dot{ED}_{comp} + \dot{ED}_c + \dot{ED}_{lvhe} + \dot{ED}_t \qquad (8)$$

Second law of thermodynamics provides the means of assigning a quality index to energy. The concept of exergy provides a useful measure of energy quality. Second law efficiency or exergetic efficiency is defined as the ratio of minimum exergy required to do a given task to the actual exergy consumed in performing the same task by (9)[29].

2.3. Exergetic efficiency ($\eta_{exergetic}$)

$$\eta_{exergetic} = \frac{\text{minimum exergy required to do given task}}{\text{actual exergy consumed}} \qquad (9)$$

For vapour compression refrigeration system, desired task is heat abstraction in to the evaporator from the space to be cooled at temperature Tr and minimum exergy required is the thermal exergy flow between evaporator and space to be cooled, i.e.

$$\dot{E}_e^Q = \dot{Q}_e\left|\left(1 - \frac{T_o}{T_r}\right)\right| \qquad (10)$$

and actual exergy consumed is actual compressor work input, $\dot{W}_{comp}$.

Hence, exergetic efficiency is given by

$$\eta_{exergetic} = \frac{\dot{Q}_e\left|\left(1 - \frac{T_o}{T_r}\right)\right|}{\dot{W}_{comp}} = \frac{COP_{vcr}}{COP_{rev}} \qquad (11)$$

where COPrev is coefficient of performance of reversible refrigerator operating between temperature T_o and T_r and COP_{VCR} is coefficient of performance of actual vapour compression cycle.

2.4. Exergy destruction ratio (EDR)

EDR is defined as the ratio of total exergy destruction in the system to minimum exergy required in doing a given task and is given by (12).

$$\text{EDR} = \frac{\dot{\text{ED}}_{\text{total}}}{\dot{E}_e^Q} = \frac{\text{COP}_{\text{vcr}}}{\text{COP}_{\text{rev}}} - 1 \qquad (12)$$

EDR in terms of exergetic efficiency can be written as (13).

$$\text{EDR} = \frac{1}{\eta_{\text{exergetic}}} - 1 \qquad (13)$$

2.5. Efficiency defect (δ_j)

That fraction of the input which is lost through irreversibilities in the different components is called efficiency defect. It gives a direct casual relationship between component irreversibilities and their effect on the efficiency of the plant [28]. It is ratio between the rate of exergy destruction in j-th component to the actual exergy consumed (i.e. actual compressor work) and is given by (14).

$$\delta_j = \frac{\dot{\text{ED}}_j}{\dot{W}_{\text{comp}}} \qquad (14)$$

3. RESULTS AND DISCUSSION

A mathematical computational model is developed for performing the energy and exergy analysis of the system using EES software [30]

The input data assumed for the calculation of results shown in fig. 2-6 are:

1. Mass flow rate of refrigerant ($\dot{m}_r$): $1 \, \text{kg/s}$
2. Isentropic efficiency of compressor(η_{comp}): 75%
3. Effectiveness of liquid vapour heat exchanger($\varepsilon_{\text{lvhe}}$): 0.8
4. Degree of sub-cooling of liquid refrigerant in lvhe(ΔT_{sub}): 5K
5. Difference between space and evaporator temperature($T_r - T_e$): 15K
6. Evaporator temperature(T_e): 223K to 273K
7. Condenser temperature(T_c): 313K
8. Ambient state temperature(T_o): 298K
9. It is assumed that pressure drop in evaporator; condenser and liquid vapour heat exchanger is negligible.
10. Effectiveness of liquid vapour heat exchanger is varied from 0 to 1, while discussing its effect on the system performance.
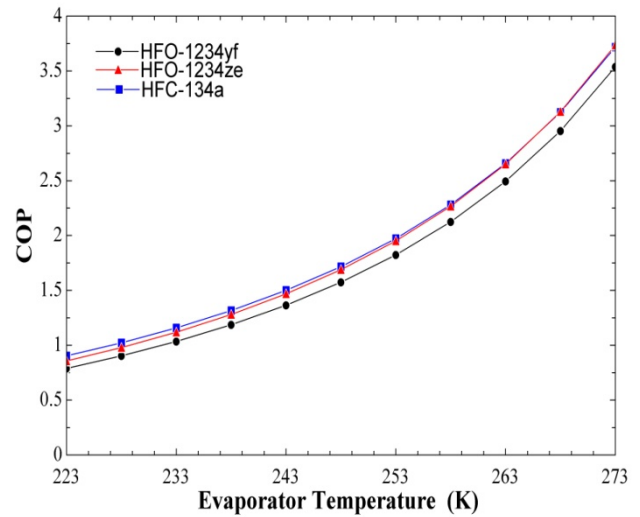

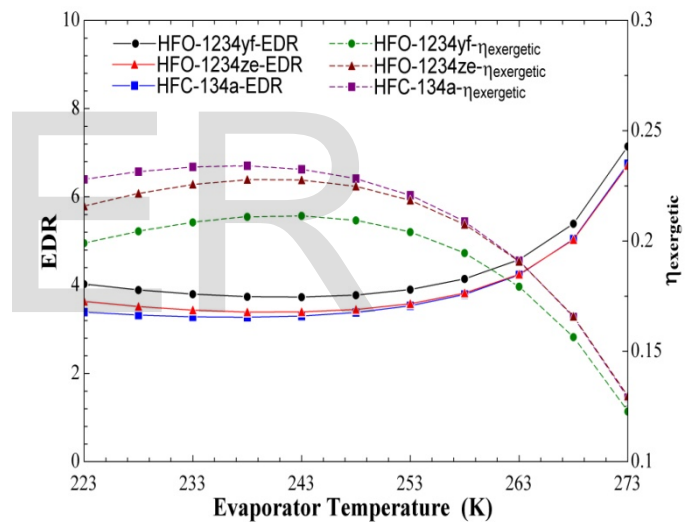Fig.2. Variation of COP with evaporator temperature.

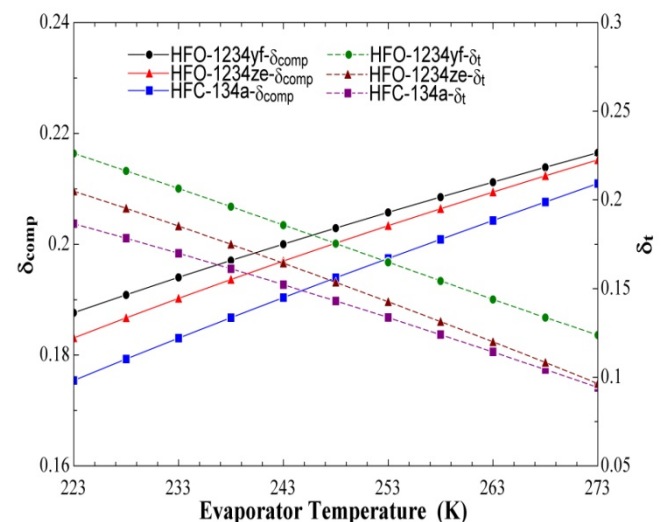Fig.3. Variation of exergetic efficiency and EDR with evaporator temperature.

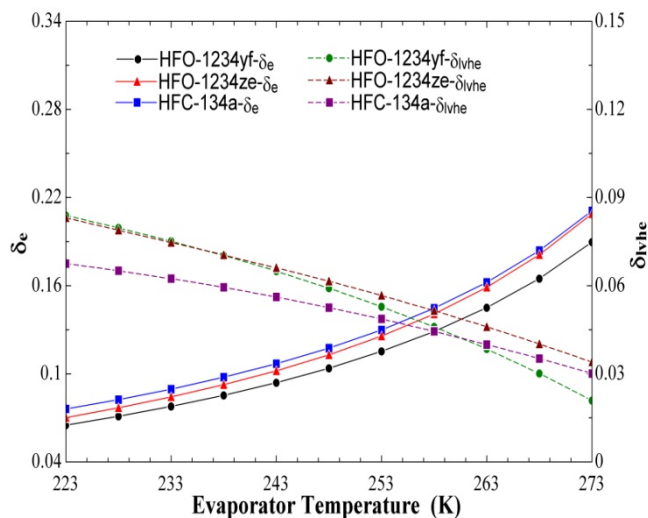Fig.4. Variation of efficiency defect in compressor (δcomp) and throttle valve (δt) with evaporator temperature.

Fig.7. Variation of exergetic efficiency and EDR with ambient state temperature (Te=273K, Tc=313K).

Fig.5. Variation of efficiency defect in evaporator (δe) and liquid vapour heat exchanger (δlvhe) with evaporator temperature.
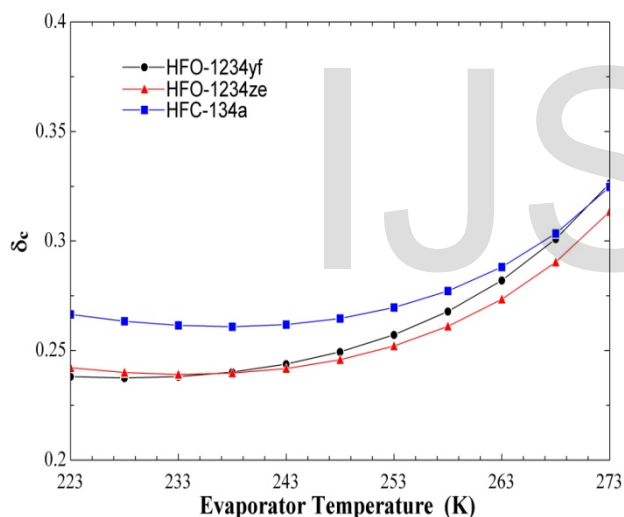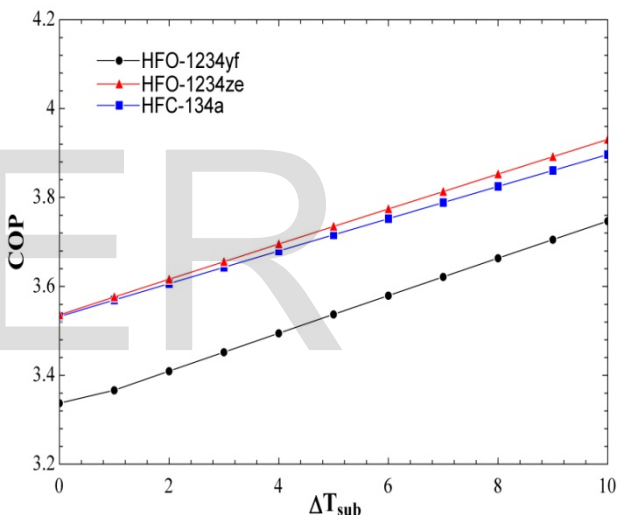

Fig.8. Effect of degree of sub-cooling on COP (Te=273K, Tc=313K).

Fig.6. Efficiency defect in condenser (δc) with evaporator temperature.

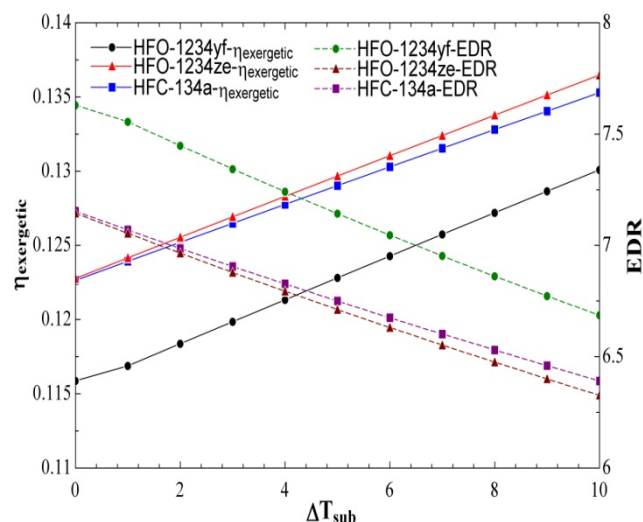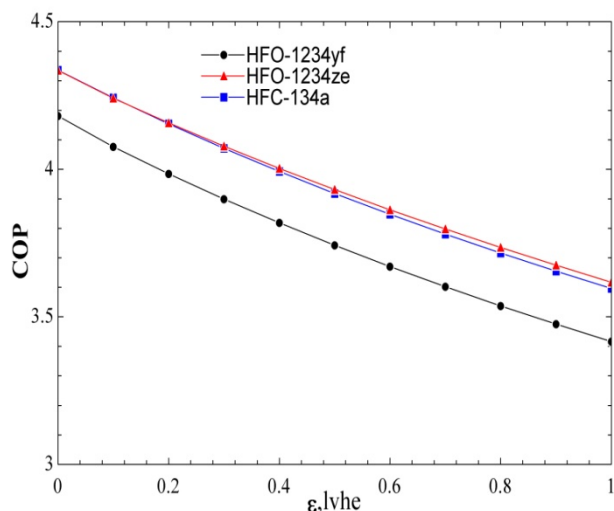Fig.9. Effect of degree of sub-cooling (ΔTsub) on exergetic efficiency and EDR (Te=273K, Tc=313K).

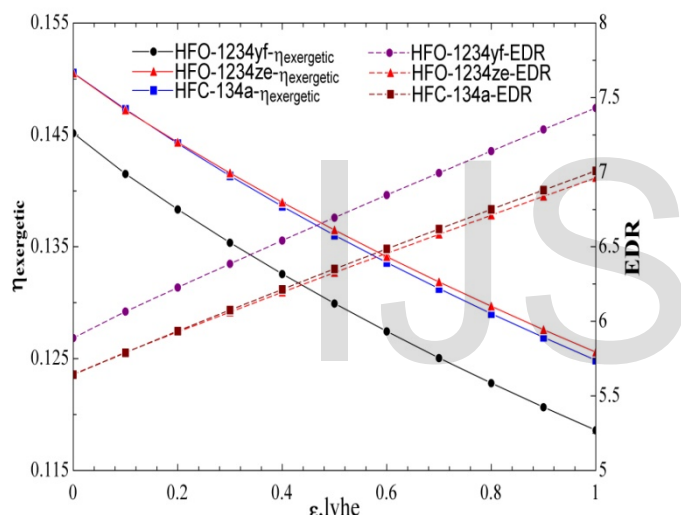Fig.10. Effectiveness of liquid vapour heat exchanger (ε, lvhe) vs. COP (Te=273K, Tc=313K).

Fig.11. Effectiveness of liquid vapour heat exchanger (ε, lvhe) vs. exergetic efficiency and EDR (Te=273K, Tc=313K).

Fig.2 shows variation of COP with evaporator temperature and it can be easily inferred that as the evaporator temperature is increases, pressure ratio decreases causing compressor work to reduce and specific refrigerating effect to increase and hence COP increases.HFC-134a shows highest COP among all the refrigerants, followed very closely by HFO-1234ze which shows almost same COP.HFO-1234yf shows lesser COP then HFC-134a. The COP of HFC-134a is 14.5-5% higher than HFO-1234yf, having minimum value at higher end of evaporator temperature, and 5.6% higher than HFO-1234ze which diminishes at high value of evaporator temperature.

Fig.3. represents the variation of exergy destruction ratio (EDR) and exergetic efficiency with evaporator temperature. Exergetic efficiency first rises and then falls, and this can be attributed to two parameters (refer (11)). First parameter is thermal exergy flow in the evaporator i.e. $\dot{Q}_e \left| \left(1 - \frac{T_o}{T_r} \right) \right|$, with increase in evaporator

temperature, refrigerating effect $\dot{Q}_e$ increases, however the term $\left| \left(1 - \frac{T_o}{T_r} \right) \right|$ reduces since Tr approaches To and second parameter is compressor work, which reduces with the increment in the evaporator temperature. The effect of $\dot{Q}_e$ and $\dot{W}_{comp}$ is to increase the exergetic efficiency as opposite to the decreasing effect of $\left| \left(1 - \frac{T_o}{T_r} \right) \right|$. The combined effect of these two parameters is to increase the exergetic efficiency till it reaches the maximum point and the evaporator temperature corresponding to this efficiency is optimum evaporator temperature, beyond which the combined effect is to decrease the exergetic efficiency. It has been observed that trend shown by curves of EDR is reverse of that shown by curves of exergetic efficiency and it can be validated by (13). Exergetic efficiency of HFC-134a is 14.4-5% higher than HFO-1234yf, having minimum difference at the higher end of evaporator temperature and 5.5% higher than HFO-1234ze at lower end of evaporator temperature, which is negligible at higher end, at condenser temperature of 313K. EDR of HFO-1234yf is higher than HFC-134a and this difference decreases in the range 5.8-18.8% as the evaporator temperature increases.

Fig. 4-6 represents variation of efficiency defect in compressor, throttle valve, condenser, evaporator and liquid vapour heat exchanger. Efficiency defect shows that what fraction of the input is lost through irreversibilities in different components of the system. Thus it assists in determining the worst component in a system. Liquid vapour heat exchanger showing minimum efficiency defect is the most efficient component of a system. In the descending order of efficiency defect the components are arranged as condenser, compressor, throttle valve, evaporator and liquid vapour heat exchanger. From the perspective of refrigerants it is observed that loss input energy due to irreversibility in compressor and throttle valve is maximum for HFO-1234yf and minimum for HFC-134a and the difference is decreasing as the evaporator temperature is increasing. In condenser and evaporator, HFC-134a gives maximum efficiency defect value. HFO-1234yf gives minimum value at lower end of evaporator temperature and HFO-1234ze gives minimum value at higher end of evaporator temperature for condenser. Total of efficiency defects in different components is observed to be minimum for HFC-134a followed by HFO-1234ze and HFO-1234yf in ascending order. HFO-1234yf shows 3.7-0.7% higher than HFC-134a having minimum value at higher evaporator temperature. Similarly HFO-1234ze shows 0.8% higher than that of HFC-134a at lower evaporator temperature and is almost same at higher evaporator temperature.

Fig. 7 shows the effect of ambient state temperature on exergetic efficiency and EDR. With increase in ambient state temperature, exergetic efficiency increases and EDR reduces, because of the increment in the term $\left| \left(1 - \frac{T_o}{T_r} \right) \right|$, while the term $\dot{Q}_e$ and $\dot{W}_{comp}$ remains constant as can be observed from (11) and (13). This can also be attributed to the reason that with increase in the ambient state temperature, the irreversibility due to finite temperature difference decreases and hence EDR reduces and exergetic efficiency increases. HFO-1234ze and HFC-134a

show the similar trends and their curves for exergetic efficiency and EDR are almost overlapping. HFO-1234yf shows lesser values for exergetic efficiency and higher values for EDR as compared to HFO-1234ze and HFC-134a for the ambient temperature range considered.

It is evident that sub-cooling increases the refrigerating effect whereas there is no change in compressor work, hence COP increases, as illustrated in fig. 8 and also increase in exergetic efficiency and decrease in EDR with increase in degree of sub-cooling is shown in fig. 9. It can be noticed from the figures that exergetic efficiency and COP obtained for HFO-1234ze is higher than that obtained for HFC-134a, and the trend shown by the curves is similar for both. HFO-1234yf gives lesser values of exergetic efficiency and COP. The total increase in exergetic efficiency for 10K of sub-cooling is 12.3% for HFO-1234yf, 10.3% for HFC-134a and 11.1% for HFO-1234ze at 313K condenser temperature.

Fig. 10-11 shows the effect of effectiveness of lvhe on COP, exergetic efficiency and EDR. With the increase in effectiveness of liquid vapour heat exchanger, COP and exergetic efficiency decreases whereas EDR increases for all the refrigerants concerned in the study. This can be explained as with the increase in effectiveness of lvhe, degree of sub-cooling increases and also superheating of suction vapour takes place which results in compression to take place along the isentropes having reduced slope and thus compression work increases. The positive effect of increase in refrigerating effect is belittled by increase in compressor work and hence COP of the system decreases. (12) - (13) demonstrates the effect of COP on exergetic efficiency and EDR. Exergetic efficiency of the system decreases by 18.3% for HFO-1234yf, 17% HFC-134a and 16.5% for HFO-1234ze. Similar trend is shown by the curves of COP.

4. CONCLUSION

During this extensive energy and exergy analysis of HFO-1234yf, HFO-1234ze and HFC-134a in a theoretical vapour compression cycle following conclusions are summarized below.

1. COP and exergetic efficiency of HFC-134a and HFO-1234ze is almost same having a difference of 5.6%, which decreases with the increase in evaporator temperature, whereas it is 14.5-5% higher than HFO-1234yf. Hence HFO-1234yf can be a good 'drop-in' replacement of HFC-134a at higher value of evaporator temperature and HFO-1234ze can be a good replacement after certain modification.

2. From the irreversibility or exergy destruction viewpoint, worst component is condenser followed by compressor, throttle valve, evaporator and liquid vapour heat exchanger, the most efficient component. Total efficiency defect is more for HFO-1234yf followed by HFO-1234ze and HFC-134a, but the difference is small.

3. Increase in ambient state temperature has a positive effect on exergetic efficiency and EDR, i.e. EDR reduces and exergetic efficiency increases.HFO-1234yf gives lesser values of exergetic efficiency whereas HFO-1234ze gives approximately similar values.

4. HFC-134a gives higher COP and exergetic efficiency than HFO-1234yf but lesser value than HFO-1234ze. However reverse trend is seen when effectiveness of heat exchanger is increased from 0 to 1.

Hence, it can be concluded that even though the values of performance parameters for HFO-1234yf are smaller than that of HFC-134a, but the difference is small, so it can a good alternative to HFC-134a because of its environmental friendly properties. HFO-1234ze can replace the conventional HFC-134a after having slight modification in the design as the performance parameters are almost similar.

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