Asian Journal of Applied Science and Technology (AJAST)
(Peer Reviewed Quarterly International Journal) Volume 2, Issue 4, Pages 36-46, Oct-Dec 2018

R1234YF: An Eco-Friendly Drop In Replacement of R12 and R134A

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Article Received: 20 May 2018 *Article Accepted: 24 September 2018* *Article Published: 02 October 2018*

ABSTRACT

This article presents exergy analysis of a vapour compression refrigeration system with refrigerants R-12, R134a and R1234yf. A computational model based on exergy analysis is presented for the investigation of the effects of degree of subcooling, evaporating temperatures, dead state temperatures, exergetic efficiency and exergy destruction ratio of the vapour compression refrigeration cycle. Exergetic efficiency of system using R1234yf is close to that of R12 system. It is concluded that -25˚C is the optimum evaporator temperature for all three refrigerants at which exergetic efficiency is maximum, which proves that R1234yf is a good drop in replacement.

Keywords: GWP, Exergetic efficiency, EDR, ODP, R1234yf.

1. INTRODUCTION

In this era every nation in the world looking for sustainable development. Now a days researchers doing investigation on low GWP refrigerants and devices like solar air heaters and solar water heaters. Refrigerants are vital working fluids used in refrigeration systems. The characteristics of the refrigerants play a major role in performance of refrigeration system. Now a days the major concern of researcher is towards eco-friendly refrigerants for sustainable development. Researchers found that some of the refrigerants cause ozone layer depletion and global warming, which is a serious threat to our environment R12 refrigerant was widely used for domestic refrigeration which has been replaced by R134a, which is a HFC having zero ozone depletion potential (ODP). But, R134a causes global warming with a global warming potential (GWP) of 1300. This means that the emission of 1 kg of R134a is equivalent to 1300 kg of CO_2. R134a is stable in atmosphere for long time and has atmospheric life time of 13 years. Many investigations have been conducted research about substitutes of CFC12 and CFC22. Prasad and Chen [5] have conducted simulation of vapour compression cycle using R134a and R12 and investigated that the HFC 134a system is only slightly inferior to the CFC12 systems due to a higher (about 3%) exergy loss with HFC 134a.

Arora and Kaushik [6] have conducted theoretical investigation of vapour compression refrigeration system with R502, R404A and R507A. The results revealed that R507A was better substitute to R502 than R404A. Abdelaziz et al. [7] have conducted experimental investigation in domestic refrigerators of R1234yf and R1234ze as drop in replacement for R134a. They concluded that R-134a and R-1234yf have similar energy consumptions and capacities in both refrigerators tested, thus R-1234yf would make a good drop-in replacement for R-134a in domestic refrigeration**.** Esbri et al. [8-9] have presented experimental analysis of R1234yf as a drop in replacement of R134a in a vapour compression system and concluded that cooling capacity obtained with R1234yf in a R134a vapour compression system is about 9% lower than that obtained with R134a in the studied range. Navarro et al. [10] have conducted experimental investigation of an open piston compressor working with R-1234yf, R-134a and

R-290 and from this study they concluded that R-1234yf, improves its efficiencies compared to R-134a for pressure ratios higher than 8. From this study, they suggested that R-1234yf and R-290 can be good replacements for R-134a.

Bisht and Pratihar [11] have carried out theoretical analysis of vapour compression refrigeration system using R12, R134a and R1234yf as working fluid and concluded that with the use of liquid vapour heat exchanger R1234yf has highest value of relative capacity change index (RCI) of all the three refrigerants R1234yf is good drop in replacement and it has also advantage of lower GWP value than R12 and R134a. Mole´s et.al [12] carried out theoretical investigation performance evaluation of different single stage vapour compression refrigeration configurations using R1234yf and R1234ze as working fluids introducing an internal heat exchanger produces an increment on on the cooling capacity. Alptug Yataganbaba et.al [13] have conducted exergy analysis of R1234yf and R1234ze as R134a replacements in a two evaporator vapour compression refrigeration system they concluded that even though the values of performance parameters for HFO-1234yf was smaller than that of HFC-134a, but the difference was small, so it can be a good alternative to HFC-134a because of its environmentally friendly properties. Pratihar et.al [14-15] have conducted intensive research on compression–absorption refrigeration system that would be used in different chilling applications. There are several researchers that have conducted numerical study of low temperature systems [16-19] and other thermodynamic systems[20-23].

R1234yf is a new refrigerant which has lower global warming potential than R134a. R1234yf has global warming potential (GWP) of 4, so it satisfy MAC Directive (GWP below 150) passed in July 2006 [24].
The main characteristics of R12 and its alternatives are given in Table 1.

Table 1 Characteristics of R12 and its alternative refrigerants [25]

Characteristics	R12	R134a	R1234yf
Chemical Formula	CF_2Cl_2	CF_3CH_2F	$C_3F_4H_2$
Molecular weight (g/mol)	120.92	102.03	114.04
Boiling point (˚C)	-29.75	-26.07	-29.03
Ozone Depletion Potential (ODP)	1	0	0
Global warming Potential (GWP)	10,900	1430	4
Safety Group	$\mathbf{A_1}$	$\mathbf{A_1}$	$\mathbf{A_2}$

2. EXERGY ANALYSIS OF VAPOUR COMPRESSION REFRIGERATION SYSTEM [26-28]

The vapour compression system used in present analysis has been shown in figure 2.1

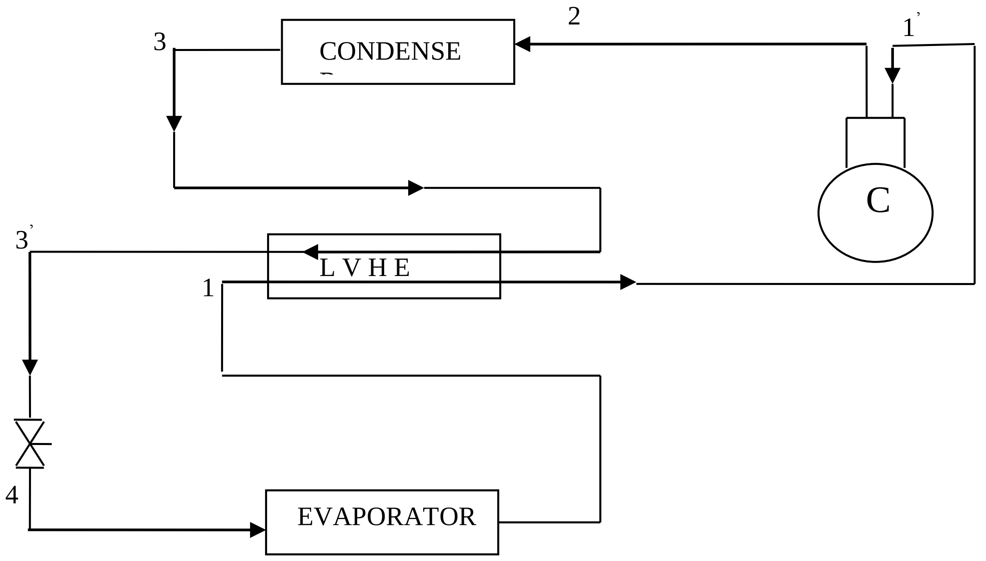

Fig. 2.1: Schematic diagram of vapour compression system with LVHE

Assumptions

Following assumptions have been taken in the analysis:

1. The system is at steady state condition. All processes are steady flow processes.
2. Negligible changes in kinetic and potential energy in analysis of all the components of system.
3. There is no heat in-leak to the system.
4. Pressure losses in pipelines are neglected

Computational code has been developed in EES software [29] for carrying out the exergy analysis of the system.

Exergy balance equation for compressor

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest,1-5} = 0 \quad (2.1)$$

$$\dot{E}x_{dest,1-5} = \dot{E}x_{in} - \dot{E}x_{out} \quad (2.2)$$

Exergy destruction in compressor:

$$\dot{E}x_{dest\ compressor} = \dot{m}(T_0(S_5 - S_1)) \quad (2.3)$$

Compressor exergetic efficiency given by ratio of reversible work to actual work

$$\eta_{ex,comp} = \frac{\dot{w}_{comp\ reversible}}{\dot{w}_{comp}} \quad (2.4)$$

Energy balance equation for condenser

$$\dot{m}\, h_3 + \dot{Q}_C = \dot{m}\, h_5 \quad (2.5)$$

$$\dot{Q}_C = \dot{m}\, h_5 - \dot{m}\, h_3 \quad (2.6)$$

Exergy balance in condenser

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest,5-3} = 0 \quad (2.7)$$

$$\dot{E}x_{dest,5-3} = \dot{E}x_5 - \dot{E}x_3 - \dot{Q}_c\left(1 - \frac{T_c}{T_0}\right) \quad (2.8)$$

Exergy destruction in condenser:

$$\dot{E}x_{dest\ condenser} = = \dot{m}(h_5 - T_0 \times S_5) - \dot{m}(h_3 - T_0 \times S_3) \quad (2.9)$$

Expansion Valve:

Energy balance equation for expansion valve

$$\dot{m}\,h_{33} = \dot{m}\,h_4 \quad (2.10)$$

Expansion valve is essentially an isenthalpic device.

$$h_{33} = h_4 \quad (2.11)$$

Exergy balance in expansion valve

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest,33-4} = 0 \quad (2.12)$$

$$\dot{E}x_{dest,33-4} = \dot{E}x_{33} - \dot{E}x_4 \quad (2.13)$$

$$\dot{E}x_{dest,33-4} = \dot{m}[h_{33} - h_4 - T_0(s_{33} - s_4)] \quad (2.14)$$

Exergetic efficiency of throttle valve expressed as the ratio of the exergy recovered to the exergy expended.

$$\eta_{ex,exp\ valve} = 1 - \frac{\dot{E}x_{dest,33-4}}{\dot{E}x_{33} - \dot{E}x_4} \quad (2.15)$$

$$\eta_{ex,exp\ valve} = 1 - \frac{\dot{E}x_{33} - \dot{E}x_4}{\dot{E}x_{33} - \dot{E}x_4} \quad (2.16)$$

There is no exergy recovered in an expansion valve, and thus exergy efficiency is zero.

Energy balance equation for evaporator

$$\dot{m}\,h_4 + \dot{Q}_{rc} = \dot{m}\,h_{11} \quad (2.17)$$

$$\dot{Q}_{rc} = \dot{m}\,h_{11} - \dot{m}\,h_4 \quad (2.18)$$

Exergy balance in evaporator

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest,4-11} = 0 \quad (2.19)$$

$$\dot{E}x_{dest,4-11} = \dot{E}x_4 - \dot{E}x_{11} - \left[-\dot{Q}_{RC}\left(1 - \frac{T_r}{T_0}\right)\right] \quad (2.20)$$

Exergy balance in liquid vapour heat exchanger

$$\dot{E}x_{in} - \dot{E}x_{out} - \dot{E}x_{dest\ lvhe} = 0 \quad (2.21)$$

$$\dot{E}x_{dest\ lvhe} = \dot{E}x_3 - \dot{E}x_{33} + \dot{E}x_{11} - \dot{E}x_t \quad (2.22)$$

$$Ex_{dest\ lvhe} = \dot{m}((h_3 - h_{33} + h_{11} - h_1) - T_0(s_3 - s_{33} + s_1 - s_{11}) \quad (2.23)$$

Total exergy destruction in the system is the sum of exergy destruction in different components of the system and is given by following equation:

$$\sum \dot{Ed}_1 = ex_{dest\ comp} + ex_{dest\ evap} + ex_{dest\ cond} + ex_{dest\ throttle\ valve} + ex_{dest\ lvhe} \quad (2.24)$$

Thermal exergy loss

The thermal exergy loss in a component is given by

$$\sum \dot{EL}_1 = Q_I\left(1 - \frac{T_0}{T_I}\right) \quad (2.25)$$

Where $\dot{Q}_1$ is the heat rejected by the Ith component and T_I is the temperature at the boundary of the Ith component. Thermal exergy loss rate is related to external irreversibility which takes place because of temperature difference between the control volume and the immediate surroundings.

Efficiency defect is electrical power supplied to the compressor in the present case and is given by

$$\delta_i = \frac{\sum \dot{Ed}_1 + \sum \dot{EL}_I}{w_c} \quad (2.26)$$

Exergetic efficiency: In general case exergetic efficiency is defined as the ratio of exergy recovered to the exergy supplied.

$$\eta_{ex} = \frac{\text{Exergy recovered}}{\text{Exergy supplied}}$$

$$\eta_{ex} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy supplied}} \quad (2.27)$$

When we apply exergy rate balance in the system then, we get

$$\dot{EF} = \dot{EP} + \sum \dot{ED}_1 + \sum \dot{EL}_1 \quad (2.28)$$

$\dot{EF}$ = the exergy rate at which fuel is supplied, in actual vapour compression system it is equal to compressor work input w_c.

EP= the exergy rate of product, in case of vapour compression refrigeration system, the product is the exergy of the heat abstracted in to the evaporator from the space to be cooled at temperature T_r,

$$\dot{EP} = \dot{Q}_{rc}\left|\left(1 - \frac{T_0}{T_r}\right)\right| \quad (2.29)$$

$$\eta_{ex} = \frac{\dot{EP}}{\dot{EF}} \quad (2.30)$$

$$\eta_{ex} = \frac{\dot{Q}_e\left|\left(1 - \frac{T_0}{T_r}\right)\right|}{w_c} \quad (2.31)$$

Both the equation of exergetic efficiency will give the same result

Exergy destruction ratio (EDR)

$$EDR = \frac{1}{\eta_{ex}} - 1 \quad (2.32)$$

$$\eta_{ex} = \frac{1}{1 + EDR} \quad (2.33)$$

3. RESULT AND DISCUSSIONS

Computational model developed for carrying out the exergy analysis of the system using Engineering Equation Solver software [29] was solved to get the desired results.

3.1 EFFECT OF EFFECTIVENESS OF LIQUID VAPOUR HEAT EXCHANGER ON THE EXERGETIC EFFICIENCY AND EDR OF THE SYSTEM

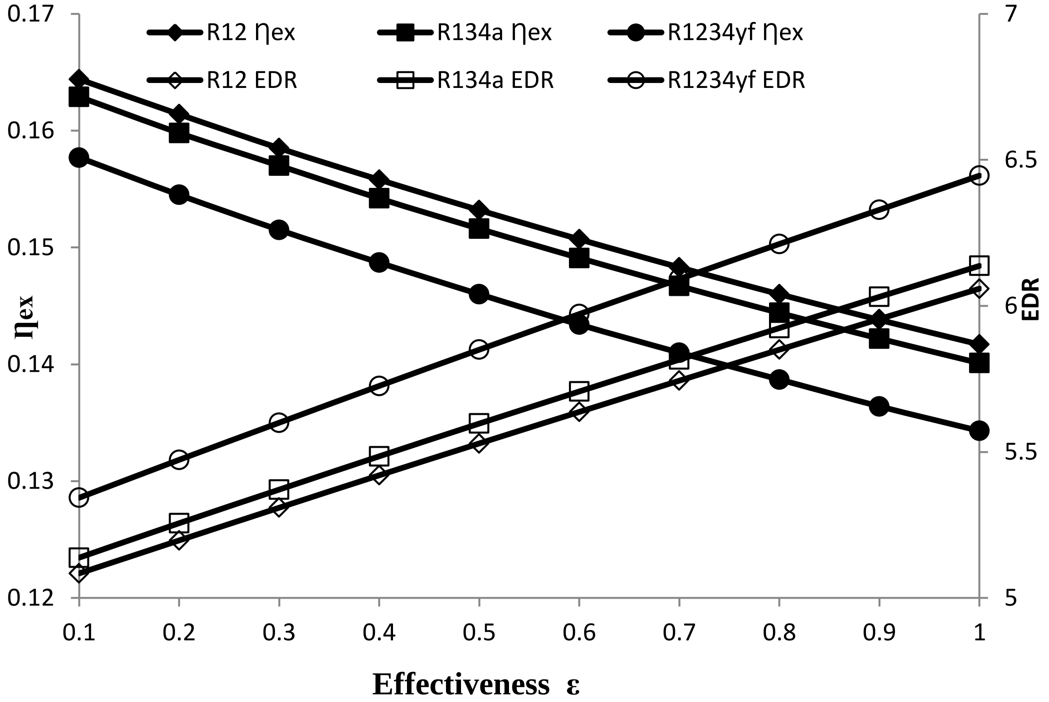

Fig. 3.1 Variation in ηex and EDR with effectiveness (ε) of LVHE

Fig.3.1 shows the variation of exergetic efficiency of the system with effectiveness of liquid vapour heat exchanger. For all three refrigerants, the value of exergetic efficiency decreases with increase in effectiveness of the liquid vapour heat exchanger. When effectiveness of liquid vapour heat exchanger is 0.1, the exergetic efficiency is the highest for all three refrigerants. When value of effectiveness is 1 the value of exergetic efficiency for system is the lowest. The percentage decrease in exergetic efficiency of system with refrigerants R12, R134a and R1234yf are 13.8%, 13.99% and 14.82 % respectively. When effectiveness of liquid vapour heat exchanger is 0.1 the value of exergy destruction ratio for system with refrigerants R12, R134a and R1234yf are the lowest. When value of effectiveness is 1 of exergy destruction ratio for all refrigerants is the highest.

This trend of results can be explained from the fact that with the increase in effectiveness of liquid-vapour heat exchanger, first there is increase in degree of subcooling, consequently specific refrigerating effect increases causing cooling capacity to increase. Second, there is superheating of suction vapour, which causes isentropic compression to happen along the isentropes having reduced slope, and thus increase in compressor work is observed. The positive effect of increase in cooling capacity is heavily negated by increase in compressor work.

 Online ISSN: 2456-883X

The cooling effect $Q_{rc}\left(1-\frac{T_0}{T_r}\right)$ also has slightly increased in its value, because $\left(1-\frac{T_0}{T_r}\right)$ has no effect of effectiveness, and remain constant. The exergetic efficiency by ratio of cooling effect divides by compressor work of the system. The denominator term has large increase in value than the numerator term $Q_e\left(1-\frac{T_0}{T_r}\right)$ when the effectiveness of the LVHE increases, therefore exergetic efficiency of system decreases. At the same time since EDR is inversely proportional to exergetic efficiency, value of EDR increases with the increase in effectiveness of liquid vapour heat exchanger.

3.2 EFFECT OF EVAPORATOR TEMPERATURE ON EXERGETIC EFFICIENCY AND EDR OF THE SYSTEM

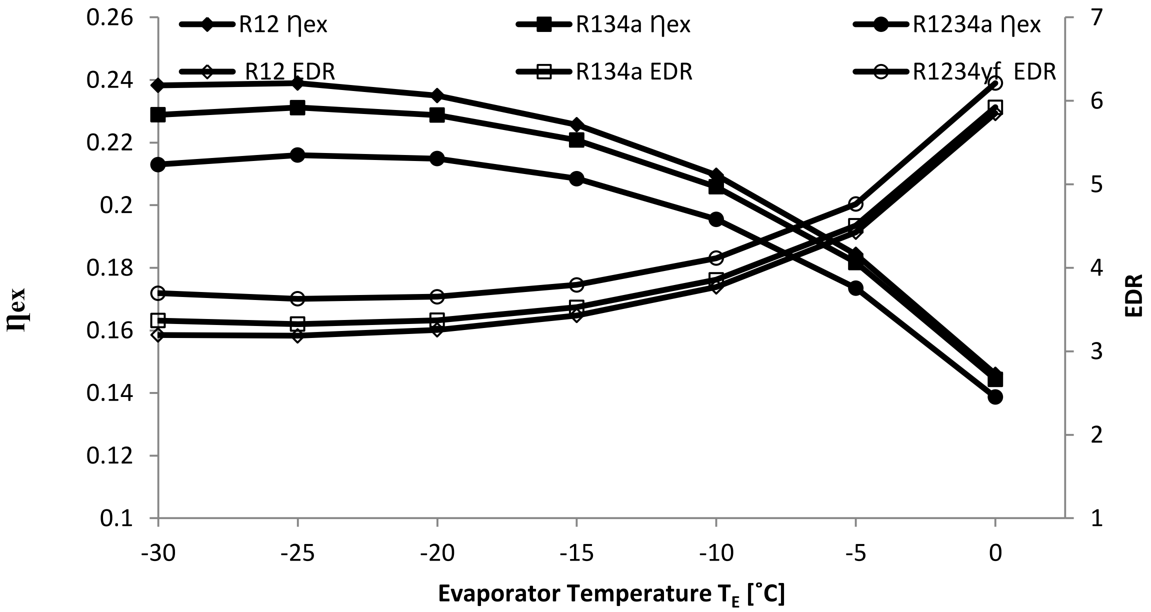

Fig. 3.2 Variation in ηex and EDR with evaporator temperature

Fig. 3.2 shows the effect of evaporator temperature on exergetic efficiency and EDR. The condenser temperature is fixed to 35˚C. The evaporator temperature is varied from -30˚C to 0˚C. There is rise and fall of exergetic efficiency with increase in evaporator temperature. The rise and fall are based on two parameters; first is exergy of cooling effect, i.e. $\dot{Q}_{rc}\left(1-\frac{T_0}{T_R}\right)$ and the compressor work. With increase in evaporator temperature $\dot{Q}_{rc}$ increases, however the term $\left(1-\frac{T_0}{T_R}\right)$ reduces since T_R approachesT_0. The compressor work decreases with increase in evaporator temperature, so both $\dot{Q}_{rc}$ and compressor work have positive effect on exergetic efficiency where as term $\left(1-\frac{T_0}{T_R}\right)$ has negative effect on increase of exergetic efficiency. At condenser temperature 35˚C $\dot{Q}_{rc}$and compressor, work is dominant over $\left(1-\frac{T_0}{T_R}\right)$ and there is rise in exergetic efficiency at evaporator temperature equal to -25˚C, after -25˚C there is again fall in exergetic efficiency. At this condenser temperature 35˚C and optimum evaporator temperature is -25˚C, at which exergetic efficiency is maximum.

3.3 EFFECT OF DEAD STATE TEMPERATURE ON EXERGETIC EFFICIENCY AND EDR OF THE SYSTEM

Fig.3.3 show the variation in exergetic efficiency and EDR with dead state temperature, which is varied from 25˚C to 50˚C.For all refrigerants with increase in dead state temperature the exergetic efficiency increases and has the highest value at 50˚C.The EDR value for all refrigerants decreases with increase in dead state temperature. R12 have highest value of exergetic efficiency among all the three refrigerants at 50˚C. The variation of exergetic efficiency and EDR is explained with help of two parameters first one is exergy of cooling effect, i.e. $\dot{Q}_{rc}\left(1-\frac{T_0}{T_r}\right)$ and second one is compressor work.

With increase in dead state temperature, term $\left(1-\frac{T_0}{T_r}\right)$ increases while cooling capacity and compressor work remain constant and thus exergetic efficiency increases therefore EDR decreases. This is justified, as exergetic efficiency is inversely proportional to EDR. For a fixed condenser temperature, the increase in dead state temperature causes the irreversibility (due to finite temperature difference) to decrease and hence EDR decreases and exergetic efficiency increases. Both R12 and R134a show the identical trends and their variations for EDR and exergetic efficiency are nearly overlapping. R1234yf has lowest value of exergetic efficiency and highest value of EDR among the three refrigerants.

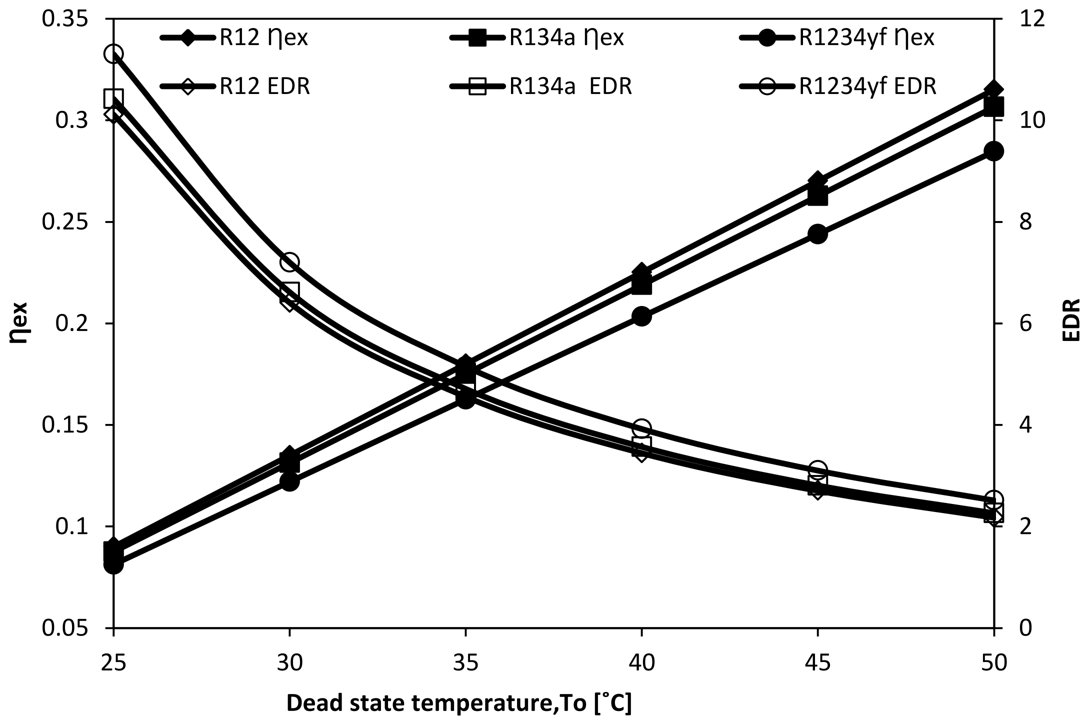

Fig.3.3 Variation in value of exergetic efficiency with dead state temperature

4. CONCLUSION

From this numerical study the following conclusions are drawn:

- The total exergy destruction at both condenser temperatures 50 and 35˚C, at evaporator temperature 0˚C is the maximum in system using R134a. In the descending order of total exergy destruction these refrigerants can be arranged as R134a, R1234yf and R12.
- The increase in dead state temperature has positive effect on the exergetic efficiency of system increases and EDR decreases. R12 shows higher value of exergetic efficiency than R134a and R1234yf
- Exergetic analysis result concluded that R1234yf is good drop in replacement and it has also advantage of lower GWP value than R12 and R134a. R1234yf is the only refrigerants of all the refrigerants used in present work that satisfy MAC directive (2006/40/EG) because of its GWP value less than 150.

REFERENCES

[1] Bisht, V. S., Patil, A. K., & Gupta, A. (2018). Review and performance evaluation of roughened solar air heaters. Renewable and Sustainable Energy Reviews, 81, 954-977.https://doi.org/10.1016/j.rser.2017.08.036

[2] Ankit Kumar, Vijay Singh Bisht, Maneesh Khati, and Satish Kumar(2017).Numerical Study of a Roughened Solar Air Heater using Matlab, IJIACE,4.

[3] Prabhakar Bhandari, Lokesh Varshney, Vijay Singh Bisht (2018). Numerical analysis of Hybrid Solar Water Heating System Using Wire Screen Packed Solar Air Heater. 1st International Conference on New Frontiers in Engineering, Science & Technology, vol 1, pp 415-1422.

[4] L Varshney, Prabhakar Bhandari, Vijay Singh Bisht(2014).Performance Evaluation of Hybrid Solar Water Heating System Using Wire Screen Packed Solar Air Heater. Int. Journal of Engineering Research andApplication (IJERA) 311-316.

[5]Prasad and Chen.1999. Simulation of vapour compression cycle using R134a and R12. International communication of heat and mass transfer. 1933:00037-8.

[6]Arora, A. and Kaushik, S.C.2008.Theoreticalanalysis of a vapour compression refrigeration system with R502, R404 and R507A. International journal of refrigeration. 31: 998 – 1005.

[7]Abdelaziz. O., Karber. M and Vineyard. A. 2012. Experimental Performance of R-1234yf and R-1234ze as Drop-in Replacements for R-134a in Domestic Refrigerators. International refrigeration and air conditioning conference. School of Mechanical Engineering, U.S. 2241 Purdue University ,.

[8]Esbrı, J., Mendoza-Miranda, J. M., Mota-Babilonia, A., Barragan-Cervera, A. and Belman-Flores, J.M. 2012.Experimental analysis of R1234yf as a drop-in replacement for R134a in vapour compression system. International journal of refrigeration. 36 :870 - 880.

[9]Esbrı J. N., Mole.F. and Barragan-Cervera. A. 2013. Experimental analysis of the internal heat exchanger influence on a vapour compression system performance working with R1234yf as a drop-in replacement for R134a. Applied Thermal Engineering.59 :153-161.

[10]Navarro, E., Martınez-Galvan, J., Nohales, I.O, and Gonzalvez-Macia, J. 2012. Comparative experimental study of an open piston compressor working with R-1234yf, R-134a and R-290. International Journal of Refrigeration . 36:768 -775.

[11]Bisht, V. S., & Pratihar, A. K. (2014). Thermodynamic analysis of actual vapour compression system with R12 and its eco-friendly alternatives refrigerants. International Journal of Engineering Research and Applications, 4(1), 114-122.

[12]Molés, F., Esbrí, N.J., Peris, B., Babiloni, M.A., Cervera, B.Á., 2014. Theoretical energy performance evaluation of different single stage vapour compression refrigerationconfigurations using R1234yf and R1234ze (E) as working fluids. Int. J. Refrigeration 44, 141–150.

[13]Yataganbaba .A, Kilicarslan .A, Kurtbas .I. 2015. Exergy analysis of R1234yf and R1234ze as R134a replacements in a two evaporator vapour compression refrigeration system. International Journal of Refrigeration 60 (2 0 1 5) 26–37.

[14]Pratihar, A. K., Kaushik, S. C., & Agarwal, R. S. (2010). Simulation of an ammonia–water compression–absorption refrigeration system for water chilling application. international journal of refrigeration, 33(7), 1386-1394.

[15]Pratihar, A. K., Kaushik, S. C., & Agarwal, R. S. (2012). Performance evaluation of a small capacity compression–absorption refrigeration system. Applied Thermal Engineering, 42, 41-48.

[16]Rawat, K. S., Bisht, V. S., & Pratihar, A. K. (2015). Thermodynamic Analysis and Optimization of CO2 based Transcritical Cycle.

[17]Rawat, K. S., Kshetri, R., Khulve, H., & Pratihar, A. K. (2015). Parametric study of R744-R717 cascade refrigeration system. Science, 2.

[18]Rawat, K. S., & Pratihar, A. K. (2018, February). Numerical Investigation of Ice Slurry Flow in a Horizontal Pipe. In IOP Conference Series: Materials Science and Engineering (Vol. 310, No. 1, p. 012095). IOP Publishing.

[19]Rawat, K. S., & Pratihar, A. K. Thermodynamic Analysis and Optimization of N2O-NH3 Cascade System for Low Temperature Refrigeration.

[20] Kumar S., Bisht V.S. (2018) 2D Modelling and Simulation of Heat Transfer in Blast Furnace Hearth Using ANSYS. In: Singh R., Choudhury S., Gehlot A. (eds) Intelligent Communication, Control and Devices. Advances in Intelligent Systems and Computing, vol 624. Springer, Singapore

[21] Kumar, S., & Bisht, V. S. CFD Analysis of Solar Air Heater Roughened with S-shape Ribs with Gap and S-shape Protrusion Roughness.

[22]Bisht, N., & Bisht, V. S. CFD Analysis of Solar Air Heater Roughened With Crown Shape Roughness.

[23]Haldia, S., Bisht, V. S., & Kumar, S. CFD Study of Solar Air Heater Roughened With Broken Arc Shaped and Broken S Shaped Ribs.

[24]Honeywell. Factsheet.2013. www.1234facts.com solstice-yf- refrigerant.

[25]Tanaka, K. and Higashi, Y. 2009. 2009. Thermodynamic properties of HFO-1234yf. International journal of refrigeration . 33, 474 – 479.

[26]Dincer, I. and Rosen, M. 2013. Exergy, Environment and Sustainable Development, 2nd ed, Elsevier, 11-12.

[27]Dincer. I. and Kanoglu, M. 2010. Refrigeration Systems and Applications second edition Wiley publication.
[28]Yumrutas .R., Kunduz, M and Kanoglu, M. 2002. Exergy analysis of vapor compression refrigeration systems. Journal of Exergy. 2:266-272.
[29]Klein. S. A., Reindl, D.T. and Brownell, K. 2000. Refrigeration system performance using liquid-suction heat exchangers. International Journal of Refrigeration 23: 588-596.