Thermodynamic Performance Evaluation of Multi-Evaporators single Compressor and single Expansion Valve and Liquid Vapour Heat Exchanger in Vapour Compression Refrigeration systems using Thirteen Ecofriendly Refrigerants for Reducing Global Warming and Ozone Depletion

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Abstract
The methods for improving first law and second law efficiency have been considered in this paper by using liquid vapour heat exchanger is investigated in this paper. Detailed energy and exergy analysis of multi-evaporators at different temperatures with single compressor and single expansion valve using liquid vapour heat exchanger vapour compression refrigeration systems have been done in terms of performance parameter for R507a, R125, R134a, R290, R600, R600a, R1234ze, R1234yf, R410a, R407c, R707, R404a and R152a refrigerants. The numerical computations have been carried out for both systems. It was observed that first law and second law efficiency improved by 20% using liquid vapour heat exchanger in the vapour compression refrigeration systems. It was also observed that performance of both systems using R717 is higher but R600 and R152a nearly matching same values under the accuracy of 5% can be used in the above system .But difficulties using R152a, R600, R290 and R600a have flammable problems therefore safety measures are required using these refrigerants. Therefore R134a refrigerant is recommended for practical and commercial applications although it has slightly less thermal performance than R152a which is not widely used refrigerant for domestic and industrial applications

1. Introduction

Technology of refrigeration is absorbs heat at low temperature sink and provides temperature below the surrounding by rejecting heat to the surrounding at higher temperature. The refrigeration system of two type such as air refrigeration system and vapour refrigeration system. Vapour refrigeration systems can be classified as vapour absorption system and vapour compression system. The vapour absorption system of two types such as NH3-H20 system and LIBR systems working on single effect, half effect, double effect and Tripple effect. The simple vapour compression system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures. Therefore there is need of multi evaporator vapour compression refrigeration system. The use suction heat exchanger or liquid vapour regenerative heat exchanger in vapor compression system is justified because superheating in liquid suction exchanger is preferable to superheating in evaporator itself

The systems under vapour compression technology consume huge amount of electricity, this problem can be solved by improving performance of system. Performance of systems based on vapour compression refrigeration technology can be improved by following:

The performance of refrigerator is evaluated in term of first law efficiency which is known as coefficient of performance (COP) which is the ratio of refrigeration effect to the net work input given to the system. The COP of vapour compression refrigeration system can be improved either by increasing refrigeration effect or by reducing work input given to the system. It is well known that throttling process in VCR is an irreversible expansion process. Expansion process is one of the main factors responsible for exergy loss in cycle performance because of entering the portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator. This problem can be eliminated by adopting multi-stage expansion with flash chamber where the flash vapours is removed after each stage of expansion as a consequence there will be increase in cooling capacity and reduce the size of the evaporator.

Work input can also be reduced by replacing multi-stage compression or compound compression with single stage compression.

Refrigeration effect can also be increased by passing the refrigerant through subcooler after condenser to evaporator.

Vapour compression refrigeration system based applications make use of refrigerants which are responsible for greenhouse gases, global warming and ozone layer depletion. Montreal protocol was signed on the issue of substances that are responsible for depleting Ozone layer and discovered how much consumption and production of

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ozone depletion substances took place during certain time period for both developed and developing countries. Another protocol named as Kyoto aimed to control emission of green house gases in 1997[1]. The relationship between ozone depletion potential and global warming potential is the major concern in the field of GRT (green refrigeration technology) so Kyoto proposed new refrigerants having lower value of ODP and GWP. Internationally a program being pursued to phase out refrigerants having high chlorine content for the sake of global environmental problems [2].Due to presence of high chlorine content ,high global warming potential and ozone depletion potential after 90's CFC and HCFC refrigerants have been restricted. Thus, HFC refrigerants are used nowadays, showing much lower global warming potential value, but still high with respect to non-fluorine refrigerants. Lots of research work has been done for replacing "old" refrigerants with "new" refrigerants [3-8].

2. Literature Review

Reddy et al. [9] performed numerical analysis of vapour compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A, and discussed the effect of evaporator temperature, degree of subcooling at condenser outlet, superheating of evaporator

outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature on COP and exergetic efficiency. They reported that evaporator and condenser temperature have significant effect on both COP and exergetic efficiency and also found that R134a has the better performance while R407C has poor performance in all respect.

Selladurai and Saravana kumar [10] compared the performance between R134a and R290/R600a mixture on a domestic refrigerator which is originally designed to work with R134a and found that R290/R600a hydrocarbon mixture showed higher COP and exergetic efficiency than R134a. In their analysis highest irreversibility obtained in the compressor compare to condenser, expansion valve and evaporator. **Nikolaidis and Probert [11]** studied analytically that change in evaporator and condenser temperatures of two stage vapour compression refrigeration plant using R22 add considerable effect on plant irreversibility. They suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator. **Kumar et al. [12]** did energy and exergy analysis of vapour compression refrigeration system by the use of exergy-enthalpy diagram. They did first law analysis (energy analysis) for calculating the coefficient of performance and exergy analysis (second law analysis) for evaluation of various losses occurred in different components of vapour compression cycle using R11 and R12 as refrigerants. **Mastani Joybari et al.[13]** performed experimental investigation on a domestic refrigerator originally manufactured to use of 145g of R134a.They concluded that exergetic defect occurred in compressor was highest as compare to other components and through their analysis it has been found that instead of 145g of R134a if 60g of R600a is used in the considered system gave same performance which ultimately result into economical advantages and reduce the risk of flammability of hydrocarbon refrigerants. **Anand and Tyagi [14]** did detailed exergy analysis of 2 ton of refrigeration capacity window air conditioning test rig with R22 as working fluid and reached to the conclusions , that irreversibility in system components will be highest when the system is 100% charged and lowest when 25% charged and irreversibility in compressor is highest among system components. **Arora and Kaushik [7]** developed numerical model of actual vapour compression refrigeration system with liquid vapour heat exchanger and did energy and exergy analysis on the same in the specific temperature range of evaporator and condenser and concluded that R502 is the best refrigerant compared to R404A and R507A and compressor is the worst component and liquid vapour heat exchanger is best component of the system in case of exergy transfer. **Ahamed et al. [17]** had performed experimental investigation of domestic refrigerator with hydrocarbons (isobutene and butane) by energy and exergy analysis. They reached to the results that energy efficiency ratio of hydrocarbons comparable with R134a but exergy efficiency and sustainability index of hydrocarbons much higher than that of R134a at considered evaporator temperature. It was also found that compressors shows highest system defect (69%) among components of considered in the system. **Ahamed et al. [15]** emphasized on use of hydrocarbons and mixture compressor shows much higher exergy destruction as compared to rest of components in the vapour compression refrigeration system and this exergy destruction can be minimized by using of nanofluid and nanolubricants in compressor. **Bolaji et al. [18]** had done experimentally comparative analysis of R32, R152a and R134a refrigerants in vapour compression refrigerator and concluded that R32 shows lowest performance whereas R134a and R152a showing nearly same performance but best performance was obtained of system using R152a. **Yumrutas et al. [19]** carried out exergy analysis based investigation of effect of condensing and evaporating temperature on vapour compression refrigeration cycle in terms of pressure losses, COP, second law efficiency and exergy losses. Variation in temperature of condenser as well as have negligible effect on exergy losses of compressor and expansion valve, also first law efficiency and exergy efficiency increase but total exergy losses of system decrease with increase in evaporator and condenser temperature. **Padilla et**

al. [20] exergy analysis of domestic vapour compression refrigeration system with R12 and R413A was done. They concluded that performance in terms of power consumption, irreversibility and exergy efficiency of R413A is better than R12, so R12 can be replaced with R413A in domestic vapour compression refrigeration system. **Getu and Bansal [21]** had optimized the design and operating parameters of like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system. A regression analysis was also done to obtain optimum thermodynamic parameters of same system. **Spatz and Motta [22]** had mainly focused on replacement of R12 with R410a through experimental investigation of medium temperature vapour compression refrigeration cycles. In terms of thermodynamic analysis, comparison of heat transfer and pressure drop characteristics, R410a gives best performance among R12, R404a and R290a. **Mohanraj et al. [23]** concluded through experimental investigation of domestic refrigerator they arrived on conclusions that under different environmental temperatures COP of system using mixture of R290 and R600a in the ratio of 45.2: 54.8 by weight showing up to 3.6% greater than same system using R134a, also discharge temperature of compressor with mixture of R290 and R600a is lower in the range of 8.5-13.4K than same compressor with R134a. **Han et al. [24]** Under different working conditions experimental results revealed that there could be replacement of R407C in vapour compression refrigeration system having rotor compressor with mixture of R32/R125/R161 showing higher COP, less pressure ratio and slightly high discharge compressor temperature without any modification in the same system. **Halimic et al. [25] had** compared performance of R401A, R290 and R134A with R12 by using in vapour compression refrigeration system, which is originally designed for R12.Due to similar performance of R134a in comparison with R12, R134A can be replaced in the same system without any medication in the system components. But in reference to green house impact R290 presented best results. **Xuan and Chen [26]** presented in this manuscript about the replacement of R502 by mixture of HFC-161 in vapour compression refrigeration system and conducted experimental study it was found that mixture of HFC-161 gives same and higher performance than R404A at lower and higher evaporative temperature respectively on the vapour compression refrigeration system designed for R404A. **Cabello et al. [27]** had studied about the effect of operating parameters on first law efficiency (COP), work input and cooling capacity of single-stage vapour compression refrigeration system. There is great influence on energetic parameters due change in suction pressure, condensing and evaporating temperatures. **Cabello et al. [28] discussed the** effect of condensing pressure, evaporating pressure and degree of superheating was experimentally investigated on single stage vapour compression refrigeration system using R22, R134a and R407C.It was observed that mass flow rate is greatly affected by change in suction conditions of compressor in results on refrigeration capacity because refrigeration capacity depended on mass flow rate through evaporator. It was also found that for higher compression ratio R22 gives lower COP than R407C. **Stanciu et al. [29]**did numerical and graphical investigation on one stage vapour compression refrigeration system for studied refrigerants (R22, R134a, R717, R507a, R404a) in terms of COP, compressor work, exergy efficiency and refrigeration effect. Effect of subcooling, superheating and compression ratio are also studied on the same system using considered refrigerants and also presented system optimization when working with specific refrigerant in the vapour compression.

Based on the literature it was observed that researchers have gone through detailed first law analysis in terms of coefficient of performance and second law analysis in term of exergetic efficiency of simple vapour compression refrigeration system with single evaporator. Researchers did not go through the irreversibility analysis.

This paper maily deal with the thermodynamic analysis of simple VCR with liquid vapour heat exchanger using thirteen eco friendly refrigerants

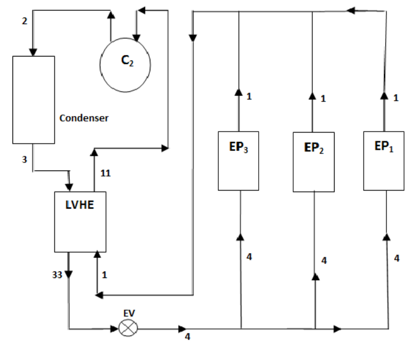

Fig: 1(a). Schematic diagram of actual multi evaporator with single compressor and single expansion valve and LVHE

To improve thermal performance of vapour compression refrigeration systems both multiple evaporator system by using liquid vapour heat exchanger for improving: First law efficiency (COP) , second law efficiency (Exergetic efficiency) and Reduction of system defect in components of system in terms of exergy destruction ratio which results into reduction of work input The multiple evaporators at the same temperature with single compressor and single expansion valve and liquid vapour heat exchanger vapour compression refrigeration system.

2.1 Mass of refrigerant flowing through each evaporator

$$m_1 = \frac{Q_1}{h_1 - h_4} \qquad (1)$$

$$m_2 = \frac{Q_2}{h_1 - h_4} \qquad (2)$$

$$m_3 = \frac{Q_3}{h_1 - h_4} \qquad (3)$$

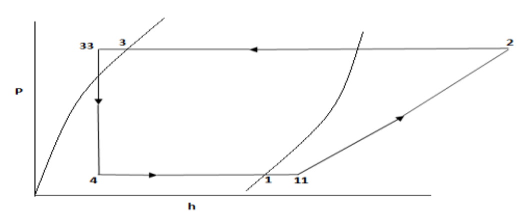

Fig: 1(b). Pressure enthalpy diagram of actual multi evaporator with single compressor, and single expansion valve and LVHE

2.2 Work required to run the compressor

$$W_{comp} = (m_1 + m_2 + m_3)(h_2 - h_1) \qquad (4)$$

According to the first law of thermodynamics, coefficient of performance () defined as the ratio of the net refrigeration effect produced per unit of work input. It is given as

2.3 Coefficient of performance

$$\beta = \frac{Q_1+Q_2+Q_3}{W_{comp}} \quad (5)$$

Second law analysis (exergy analysis) According to second law thermodynamic loss of work input required to drive the system due to irreversibility occur in various states (f1 and f2) for a steady flow system is given as components of the system. Irreversibility in each component by neglecting the kinetic energy an potential energy of the system as per Eqs. (6)– (13) specified below

$$\Phi_{e1} = \chi_4 - \chi_1 + Q_1\left(1-\frac{T_0}{T_1}\right)$$
$$= m_1(h_4 - T_0 s_4) - m_1(h_1 - T_0 s_1) + Q_1\left(1-\frac{T_0}{T_1}\right)$$
(6)

$$\Phi_{e2} = \chi_4 - \chi_1 + Q_2\left(1-\frac{T_0}{T_1}\right)$$
$$= m_2(h_4 - T_0 s_4) - m_2(h_1 - T_0 s_1) + Q_2\left(1-\frac{T_0}{T_1}\right)$$
(7)

$$\Phi_{e3} = \chi_4 - \chi_1 + Q_3\left(1-\frac{T_0}{T_1}\right)$$
$$= m_3(h_4 - T_0 s_4) - m_3(h_1 - T_0 s_1) + Q_3\left(1-\frac{T_0}{T_1}\right)$$
(8)

Compressor

$\Phi_{comp} = \chi_{11} - \chi_2 + W_{comp} = m((h_{11}- h_2) - T_o (s_{11}- s_2)) + m (h_2 - h_{11}) = m T_o (s_2 - s_{11})$ (9)

Condenser

$\Phi_c = \chi_2 - \chi_3 = m((h_2- h_3) - T_o (s_2- s_3)$ (10)

Expansion Valve

$\Phi_{ev} = \chi_{33} - \chi_4 = m((h_{33}- h_4) - T_o (s_{33}- s_4))$
$= m(T_o (s_4-s_{33})$ (11)

Liquid vapour heat exchanger

$\Phi_{lvhe} = (\chi_1 - \chi_{11}) + (\chi_{x3} - \chi_{x33}) = m((h_1-T_o s_1)-(h_{11}-T_o s_{11}))$
$+ m((h_3-T_o s_3)-(h_{33}-T_o s_{33}))$ (12)

3.1 Total destruction

$\Phi_{total} = \Phi_e + \Phi_{comp} + \Phi_c + \Phi_{ev} + \Phi_{lvhe}$ (13)

3.2 Second law efficiency

It is defined as the ratio of exergy in product in the work required to drive the system

$$\text{Exergy output} = (Q_1 + Q_2 + Q_3)\left|\left(1-\frac{T_0}{T_1}\right)\right|$$
(14)

$$\eta_{ex} = \frac{Exergy\ Output}{Exergy\ Input} = (Q_1 + Q_2 + Q_3)\left|\left(1-\frac{T_0}{T_1}\right)\right| \Big/ W_{comp}$$

EDR is the ratio of total irreversibility in the system to the exergy product

$$EDR = \frac{\Phi_{total}}{(Q_1+Q_2+Q_3)\left|\left(1-\frac{T_0}{T_1}\right)\right|} \quad (16)$$

3. Results and Discussions

Using Engineering Equation Solver software [9] a numerical model is developed for tfirst law and second law analysis of the multi evaporators VCR for enhancing thermal performances. The performance parameters are calculated by assuming following specifications: Adiabatic efficiency of compressor (ζ_{comp}):75% Condenser temperature (T_c): 313K. Dead state temperature (T_0): 298K. Variation of evaporator's temperature (T_e):223K to273K. Dead state enthalpy (h_0) and entropy (s_0) of the refrigerants have been calculated corresponding to the dead state temperature (T_0) of 298K. Degree of superheating of vapour refrigerant in liquid vapour heat exchanger before compression (ΔT_{sh}): 10K. Effectiveness of the liquid vapour heat exchanger is 100%. Degree of sub cooling of liquid refrigerant in the liquid vapor heat exchanger (ΔT_{sc}): 10K. Loads on the evaporators EP1, EP2 and EP3 are 35KW, 70KW and 105KW respectively.

Fig.2 presents the variation of first law efficiency (coefficient of performance) with the evaporator temperature at 313K condenser temperature. The COP will increase with evaporator temperature this is due to the fact that COP is the ratio of the net refrigeration effect of the work required to drive the compressor, compressor work will go down due to reduction in pressure on the other hand refrigeration effect will also enhance, So COP will increase. It was observed that COP of the system using R134a and R1234ze nearly matching same values.R134a and R1234ze show better COP than R-1234yf.Although R134a having a high global warming potential (GWP) and responsible for global warming. The maximum difference observed between COPs of R134a and R1234yf is (2%-6%).

Effect of increase in evaporator temperature on second law efficiency has shown in Fig. 3. As clear from Fig.3 that exergetic efficiency increase with increase in evaporator temperature but it should be cleared that this increment up to an optimal value of evaporator temperature after that exergetic efficiency goes down with increase in evaporator temperature. R1234ze shows the lowest value of exergetic efficiency among considered refrigerants. The percentage increase in second law efficiency of R1234ze as compared with R1234yf at 243K, 248K, 253K, 258K, 263K, 268K and 273K evaporator temperature are 4.57%, 4.33%, 4.07%, 3.80%, 3.55%, 3.30% and 3.06% respectively. System defect provides the information about of amount of loss of work input (exergy) given to the system. As shown in Fig.4 that the highest system defect occurs in R1234yf.it was also observed that system defect in R1234ze only 1% higher than R134a, but with the increase in evaporator temperature this problem is eliminated. The maximum difference in system defect of R1234yf comparison with R134a is 3.7 % at 248K evaporator temperature. Fig.5 shows the effect of degree of sub cooling on COP. It is evident that sub cooling increases refrigeration capacity whereas there is no change in compressor work, hence COP increases. Both R134a and R1234ze presents maximum COP (3.18) by the 10K degree of sub cooling than R1234yf.Thus sub cooling responsible for the betterment for system performance. The effect of sub cooling on second law efficiency shown Fig.6 reveals that both R134a and R1234ze shows better exergetic efficiency than R1234yf It is observed from Fig.7 and Fig.8 that trends of COP and exergetic efficiency are almost same for selected refrigerants, both COP and exergetic efficiency will decrease with increase in condenser temperature. Both COP and exergetic efficiency of R134a and R1234ze are 3.7 % and 3.9% at 314K condenser temperature higher than R1234yf.

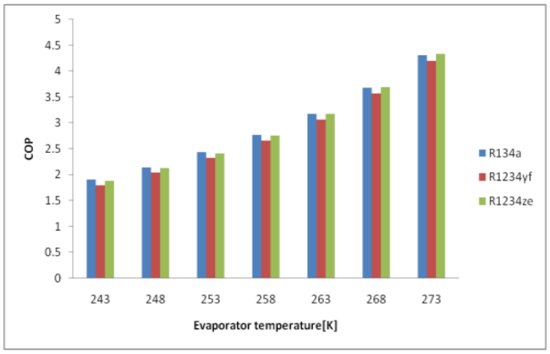

Fig: 2. Variation of COP with evaporators' temperatures

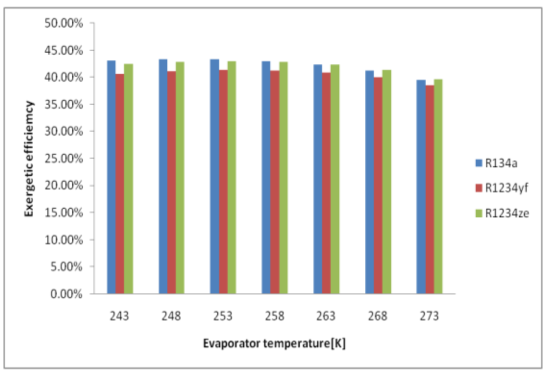

Fig: 3. Variation of exergetic efficiency with evaporators' temperatures

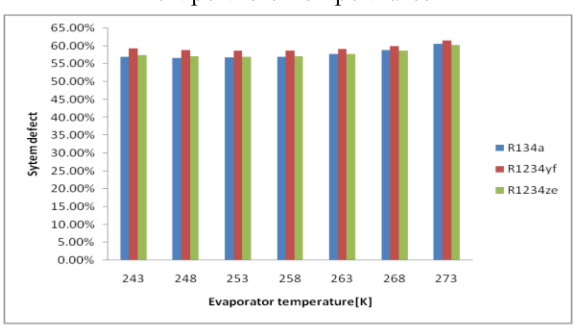

Fig: 4. Variation of system defect with evaporator temperatures

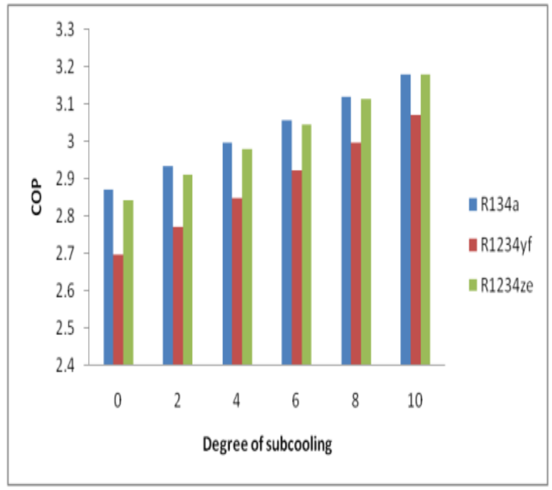

Fig: 5. Variation of COP with degree of sub cooling at condenser outlet

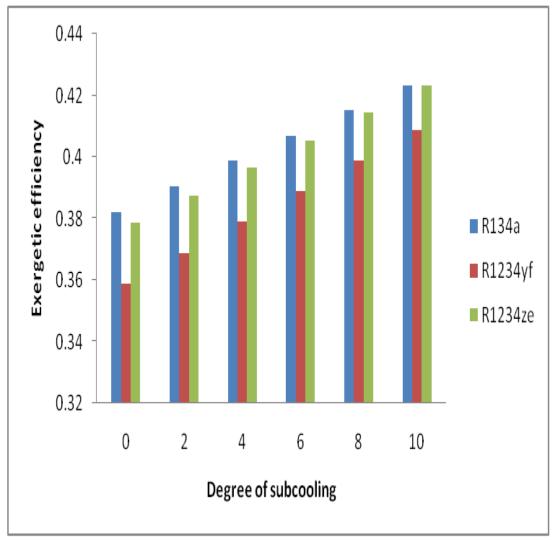

Fig: 6. Variation of exergetic efficiency with degree of sub cooling at condenser outlet

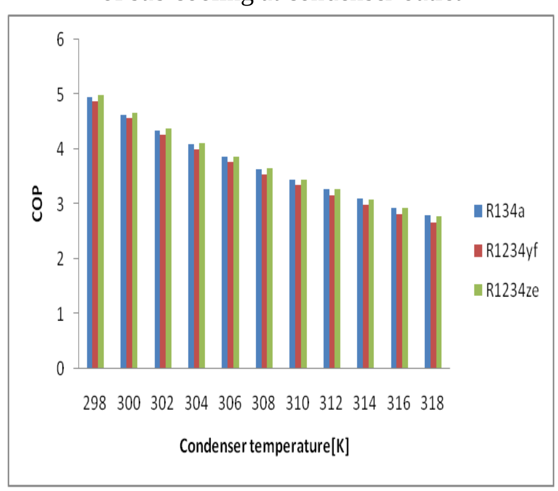

Fig: 7. Variation of COP with condenser temperature

4. Conclusions

In this paper, first law and second law analysis of an actual multi-evaporators vapour compression refrigeration system using ecofriendly refrigerants (R134a, R1234yf, and R1234ze) have been presented.

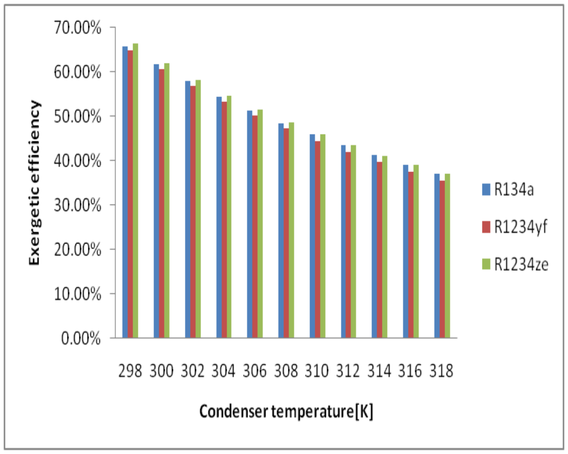

Fig: 8. Variation of exergetic efficiency with condenser temperature Conclusion

First law and second law efficiency for R134a and R1234ze are matching the same values, both are better than that for R123yf and showing 2–6% higher value of COP and second law efficiency in comparison to R123yf. Both energetic and exergetic efficiency increase with increase in degree of subcooling It was found that energetic and exergetic efficiency greatly affected by changes in evaporator and condenser temperature. R1234ze is the best among considered refrigerant since it has 238 times lower GWP values than R134a and R1234ze is ecofriendly has both ODP and GWP are lowest.

Table: 1. Multiple evaporator single compression single expansion valve vapour compression refrigeration system using eco friendly refrigerants with LVHE

Eco friendly Refrigerant	COP$_{WITH\ LVHE}$	EDR	Exergetic Efficiency
R290	3.052	1.462	0.4062
R404A	2.747	1.735	0.3656
R410A	2.931	1.564	0.390
R134A	3.104	1.421	0.4131
R152A	3.227	1.328	0.4295
R600	3.234	1.324	0.4303
R600A	3.122	1.407	0.4155
R407C	2.62	1.868	0.3487
R507A	2.80	1.683	0.3727
R1234YF	2.964	1.535	0.3945
R1234ZE	3.086	1.435	0.4107
R717	3.205	1.345	0.4265
R125	2.628	1.859	0.3497

Table: 2. Multiple evaporator single compression single expansion valve vapour compression refrigeration system using eco friendly refrigerants without LVHE

Refrigerant	COP$_{WITHOUT\ LVHE}$	EDR	Exergetic Efficiency
R290	2.97	1.53	0.3952
R404A	2.626	1.862	0.3495
R410A	2.858	1.63	0.3803
R134A	3.022	1.486	0.4022
R152A	3.177	1.365	0.4228
R600	3.161	1.377	0.4207
R600A	3.032	1.478	0.4035
R407C	2.541	1.958	0.3381
R507A	2.678	1.806	0.3564
R1234YF	2.854	1.633	0.3798
R1234ZE	2.991	1.512	0.3980
R717	3.21	1.341	0.4271
R125	2.473	2.039	0.3291

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5. Results and Discussions and Conclusions

In this paper, first law and second law analysis of vapour compression refrigeration systems using multiple evaporators and single compressor and single expansion valve with thirteen eco friendly refrigerants have been presented. The conclusions of the present analysis are summarized below:

1. The First law efficiency (COP) and Second law efficiency (Exergetic efficiency) of vapour compression refrigeration systems using liquid vapour heat exchanger and multiple evaporator and single compressor and single expansion valve is higher than without liquid vapour heat exchanger for above mentioned ecofriendly refrigerants.
2. The First law efficiency (COP) and Second law efficiency (Exergetic efficiency) of vapour compression refrigeration systems using R717 refrigerant is higher but is has toxic nature can be use by using safety measure for industrial applications.
3. COP and exergetic efficiency for R152a and R600 are nearly matching the same values.are better than that for R125 at 313K condenser temperature and showing higher value of COP and exergetic efficiency in comparison to R125.
4. For practical applications R-134a is recommended because it is easily available in the market has second law efficiency slightly lesser than R-152a which was not applicable for commercial applications.
5. The worst component from the viewpoint of irreversibility is expansion valve followed by condenser, compressor and evaporators, respectively. The most efficient component found to be subcooler. The R-152a has least efficiency defects for 313K condenser temperature.
6. The increase in dead state temperature has a positive effect on exergetic efficiency and EDR, i.e. EDR decreases and exergetic efficiency increases with increase in dead state temperature. Both R-152a and R-600 show the identical trends for exergetic efficiency are nearly overlapping. The exergetic efficiency for R-600 is higher than that of R-134a for the practical range of dead state temperature considered.

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