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Exergetic performance evaluation of modified vapour compression refrigeration systems

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Abstract

Comparative analysis of eight ultra-low GWP refrigerants (HFO, &HCFO) in the modified vapour compression refrigeration systems have been done on the basis of exergetic-energetic performances. The performance parameters such as COP, exergetic efficiency were investigated for different modified VCRS at different loads and temperature conditions. It was found that both energetic and exergetic efficiencies using R1234ze(Z) in modified systems found to be highest. and lowest by using R1234yf.

It was also found that the energetic and exergetic performances using R1233zd(E) is slightly higher than using R1224yd(Z). Similarly, the energetic and exergetic performances of R1336mzz(Z) is higher than R1225ye(z) and R1243zf and R1234ze(E) in multi evaporator vapour compression refrigeration systems.

1. Introduction

The Refrigeration technology based on the principle of rejection of heat to the surrounding at higher temperature and absorption of heat at low temperature [1] evaporator, expansion valve, condenser and compressor are the main four components of single stage vapour compression system. In the many refrigeration systems, different temperatures are required to be maintained at various point as in the hotels, large restaurants, institutions industrial plants and food markets where food products are received in large quantities and stored at different temperatures. Normally the fresh fruits, fresh vegetal, fresh cut meats, frozen products, dairy products, canned goods, bottled goods have all different conditions of temperature and humidity for storage. In such cases, each location are cooled by its own evaporator in order to obtain more satisfactory control of conditions.

Vapour compression refrigeration systems consume large amount of electricity. This difficulty can be removed by improve the performance parameters of system. Coefficient of performance and exergetic efficiency are main two parameters to calculate the performance of refrigeration systems. Coefficient of performance can be enhanced either by minimizing power consumption of compressor or increasing of refrigeration effect. Refrigeration effect can be increased by adoption of multi-stage throttling. On the other hand, power consumption of compressor can be enhanced by incorporation of multi-stage compression and flash chamber. Collective effect of these two factors improves overall performance of vapour compression system [1].

It is presented that exergy destruction (i.e. irreversibility) in system components take place due to large temperature

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difference between system and surrounding. In order to improve thermodynamic system performances, the exergy destruction (i.e. irreversibility) of each components should be computed/ measured in the cycle along with total exergy destruction in the whole system, because Exergy destruction (i.e. thermal losses are responsible for degradation of system's thermodynamic first and second law performances The Coefficient of performance (COP) is known as first law efficiency is commonly used to calculate thermal performance of vapour compression system However first law efficiency (COP) provides no information regarding thermodynamic losses in the vapour compression refrigeration system components. Using second law performances (i.e. exergy analysis) is can be quantify the exergy destruction (losses in the components and total losses is the sum of exergy destruction in each component in the vapour compression refrigeration systems. The Exergy destruction (i.e. losses) can be increased with increasing of temperature difference between systems and surrounding. Exergy is the accessible which is the useful energy from the system and loss of energy means loss of exergy in the system. Exergy destruction (i.e. losses) are useful to improve thermodynamic performances of system for better utilization of energy input given to thevapour compression refrigeration system which is advantageous by utilizing the green energy by this method for environmental conditions [2-4].

In past decades, refrigerants such as R11, R12, R22 etc. used in vapour compression refrigeration system responsible for increasing of global warming and ozone depletion potential. An international society named Montreal protocol discussed and signed on the refrigerants having higher global warming and ozone depletion potential values for all countries. In order to control the emission of greenhouse gases one more committee was formed named as Kytoprotocol [5]. After 90's a program was ran to phase out the higher GWP and ODP refrigerants (CFC and HCFC) for the purpose of environmental problems.

To replace "old" refrigerants with "new" refrigerants lots of researches carried out plenty of research [6-11].

Selladurai and Saravana kumar [12] evaluated thermodynamic performance parameters (i.e. COP, exergetic efficiency) with R290/R600 hydrocarbon mixture on a domestic refrigerator designed to work with R134a and found that the performance of same system is higher wit using hydrocarbon mixture (R290/R600a) as compared to R134a and found that the condenser, expansion valve and evaporator showing lower exergy destruction compared to compressor.

Reddy et al.[13]carried out a thermodynamic analysis of vapour compression refrigeration using R134a, R143a, R152a, R404A, R410A, R502 and R507A as refrigerants in system and computed the effect on coefficient of performance and second law efficiency along with the variation of superheating at evaporator outlet, and degree of sub-cooling at condenser outlet with using vapour liquid heat exchanger effectiveness and degree of sub-cooling condenser temperature and found that the COP and exergetic efficiency (both) significantly affected with change of evaporator and condenser temperatures, variation of super heating temperature, and also found that R134a shown highest and and R407C shown its lowest thermodynamic performances. Kumar et al. [14] evaluated energy and exergy performances of single stage vapour compression refrigeration system using R11 and R12 as working fluids.

Thermal performance evaluation in terms of COP, exergetic efficiency and exergy losses in different components (compressor, evaporator, expansion valve and condenser) was done. Cornelissen [15] proposed that non-renewable energy sources are useful for minimizing the irreversibility of the system for sustainable development of systems and observed that emissions of gases put adverse effect on environmental conditions. Nikolaidis and Probert [16] measured the effect of condenser and evaporator temperatures on two-stage vapour compression refrigeration system using R22 was studied and suggested that there is requirement to optimize the condenser and evaporator conditions.

Many investigators had carried out detailed energy analysis on different proportion of hydrocarbons as working fluid in vapour compression refrigeration systems. Fatouh and Kafafy [17] recommended to replace R134a with hydrocarbon mixtures such as propane, propane/isobutane/n-butane mixtures, butane, and various propane mass fractions in domestic refrigerator. Pure butane showed high operating pressures and low coefficient of performance among considered refrigerants. Wongwisesetal [18] carried out experimental investigation on automotive air-conditioners with isobutene, propane, butane and suggested to replace R134a with these hydrocarbon mixtures. They observed that mixture of propane 50%, butane 40%, and isobutene 10% was best hydrocarbon mixture to replace R134a.Jung et al. [19], Arcaklioglu [20], and Arcaklioglu et. al [21] suggested the use of pure hydrocarbon instead of their mixtures due variation in condenser and evaporator temperature during phase changing at constant pressure. These Changes in condenser and evaporator temperature cause for problem in vapour compression refrigeration cycle. Liedenfrostetal

[22] found Freon as refrigerant on the performance of a refrigeration cycle. In the selection of refrigerants, for low GWP and zero ODP consideration, the refrigerants, with better energy characteristics in terms of first and second law thermal performances should be preferred [23,24,25].

Mishra [26] represents that all new alternative gases are better regarding their lower GWP values. Although they have some differences in terms of energy parameters, it can be stated that R-1234ze and R1234yf, R-152a and R245fa refrigerants will be good alternatives to R134a, R404A, R410A and R22, respectively and suggested that above refrigerants can replace R-134a in vapour compression refrigeration cycles

Various hydrofluoroolefins (HFOs) and hydro chloro fluoro olefins (HCFOs) have recently been developed, which show ultra-low GWPs, are non-flammable and are showing potential for use at high, medium, low and ultra-low temperatures (i.e. below -150°C). The thermodynamic properties of these refrigerants allow subcritical VCRS at condensation temperatures in the range of about 40 to 60°C

Mishra [27] computed second law exergetic performances (exergetic efficiency and also rational efficiency) for simple and cascaded systems and found that the exergy destruction in vapour compression system and cascaded vapour compression refrigeration systems using R1234ze(Z), R1224yd(Z), R1234ze(E) & R-1243zf in the high-temperature cycle and HFC-1336mzz(Z) in lower temperature cycle is lower than using R1225ye(Z) in lower temperature cycle up to -90ºC of evaporator temperature. For ultra-low temperature applications, use of R1234ze(Z), R1234ze(E), R1243zf, R1224yd(Z) in high-temperature cycle up to 0ºC and HFO-1336mzz(Z) , R1225ye(Z) and R1234yf in medium temperature cycle up to -50ºC and HFO-1336mzz(Z) or R-1225ye(Z) in low-temperature cycle up to -130ºC to -150ºC have been have been derived for biomedical applications and concluded that for cascaded vapour compression refrigeration systems , the exergy destruction in high temperature cycle is more than 70% lower than the exergy destruction in low temperature cycle and suggested that Three stage cascade vapour compression refrigeration system using R1234ze(Z) in high temperature cycle between temperature range of (55ºC to 0ºC) and R1233zd(E)in medium temperature cycle between temperature range of (0ºC to -70ºC) and R1225ye(Z) in low temperature cycle at evaporator temperature of -140ºC is best. Mishra [28] investigated the environmentally friendly HFOs R1336mzz(Z) and R1234ze(Z) and the HCFOs R1233zd(E) and, R1243zf, R 1225ye(Z) R1234yf, R1234ze(E) in the vapour compression refrigeration systems with a variable-speed reciprocating compressor and compares the coefficient of performance (COP) and the exergetic efficiency with the HFC refrigerants R152a, R-32, R134a and R245fa at different condensation and evaporator temperatures up to -30ºC and. R1224yd(Z) up to -10ºC respectively with internal heat exchanger is used for adequate superheating purpose. [29]. Based on thermal analysis numerical computation was carried out for single stage and multi stages VCRS it is found that , a single-stage VCRS with internal heat exchanger (IHX) using R1234ze(Z) and the HCFOs R1233zd(E) and R1224yd(Z) has been used to compute thermodynamic first and second law performances of various refrigerants for provides 35 kW cooling capacity for temperature of -30ºC in single stages VCRS and for provides 175 kW cooling capacity from -50ºC to -150°C in multi stages cascaded VCRS and found that the R1234ze (Z) and R1233zd(E) gives better thermodynamic performances than using HFC -134a. However, R1224yd (Z)of seven GWP overcome favorable thermodynamic (energy and exergy) performances, above -10ºC of evaporator can suitably replace R134a. Similarly, HFO-1336mzz(Z) also gives better energy exergy performances as compared to HFC-134a. However, R1234yf although gives 4% to 10% lesser thermodynamic (energy and exergy) performances than using high GWP ecofriendly HFC-134a refrigerant. Therefore, these ultra-low GWP ecofriendly HFO refrigerants can serve as new alternative refrigerants for replacing HFC-134a in the vapour compression refrigeration systems for a sustainable environment. Similarly, the system design, theoretical simulations and first experimental test results with a single-stage with internal heat exchanger using R1234ze(E) and R1225ye(Z), R-1336mzz(Z) are suitable for low temperature applications [30].

Due to increasing awareness of global warming, the types of refrigerants used in heat pumps are changing globally. Regulations for HFC refrigerants are being introduced due to their high global warming potential (GWP). This can create a shift in demand for different refrigerants since HFCs are still commonly used in many countries. As a result, the refrigerant charge will play a significant role when determining the most feasible refrigerant. Nielsen and S. Thorsén [31] carried out a numerical study of the performance of natural, HFC, and HFO refrigerants for a one-stage cycle and focused on the refrigerant charge influence and found that natural refrigerant ammonia (R717) is the most optimal refrigerant, exhibiting a 51% to 87% smaller charge and 12% to 27% lower cost of heat compared to other refrigerants.

M. Direk, Alper Kelesoglu, A. Akin [32] theoretically investigated, the effects of internal heat exchanger (IHX) effectiveness on the performance parameters of the refrigeration cycle using R1234yf and developed mathematical model based on the energy balance of the cycle. The thermal analysis was performed between -20°C and 0°C evaporation and 40°C and 50°C condensation temperatures based on the effectiveness value of internal heat exchanger The cooling capacity, coefficient of performance (COP), sub cooling, superheat and compressor discharge temperature of the refrigeration cycle was examined. Finally, the performance results of the cycle with R1234yf were compared in the same baseline cycle with that utilized R134a at same 50% effectiveness for comparing results

Through above literature, it was found that energy, exergy analysis of single stage vapour compression refrigeration systems have been done. But no literature contributed for energy and exergy analysis of multi evaporator multi expansion valves and multi compression with different conditions with different load variations in the vapour compression refrigeration systems. Present works analyze the modified vapour compression refrigeration systems in terms of energy and exergy efficiencies and explain the effect of exergy destruction on modified vapour compression refrigeration systems using HFO refrigerants.

1.1 Assumptions used in thermal analysis of modified vapour compression refrigeration systems

Some mathematical calculations are required to analyze the two-stage vapour compression refrigeration system based on energy and exergy method. Two stage vapour compression refrigeration system consist of low and high pressure compressor, condenser, evaporator, expansion valves, water-intercooler and flash chamber. Energy and exergy efficiencies are different for different ecofriendly refrigerants for same system. Following assumptions are taken for thermodynamic analysis of the system:

- Temperature and pressure losses are not considered.
- All components are running under steady state conditions.

- Energy and exergy losses due to potential and kinetic energy are neglected.
- Mechanical efficiencies of low and high pressure compressors are assumed to be 75%.

2. Results and Discussion

Following modified vapour compression refrigeration systems have been used for numerical computations for predicting exergetic performances.

System-1

Modified vapour compression refrigeration system using multiple evaporators, single compressor with single expansion valves (Q_{Eva_1}=35 KW, Q_{Eva_2}=70 KW, Q_{Eva_3}=35 KW, $T\_{EVA\_}$=268K, Eff_{Comp}=0.75, T_Cond=313K, with subcooling of liquid at condenser out let at 303K)

System-2

Modified vapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (Q_{Eva_1}=35 kW, T_{EVA_1}=263K, Q_{Eva_2}=70 kW, T_{EVA_2}=273K, Q_{Eva_3}=35 kW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_Cond=313K, with subcooling of liquid at condenser out let at 303K)

System-3

Modified vapour compression refrigeration system using multiple evaporators, single compressor with multiple expansion valves (Q_{Eva_1}=105 KW, T_{EVA_1}=263K, Q_{Eva_2}=70 kW, T_{EVA_1}=278K, Q_{Eva_3}=35 KW, T_{EVA_1}=283K, Eff_{Comp}=0.75, T_{Cond}=313K, with sub cooling of liquid at condenser out let at 303K)

System-4

Modified vapour compression refrigeration system using multiple evaporators, individual compressors with individual expansion valves (Q_{Eva_1}=35 KW, T_{EVA_1}=263K, Q_{Eva_2}=70 kW, T_{EVA_2}=278K, Q_{Eva_3}=105 KW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_Cond=313K, Subcooling=303K).

System-5

Modified vapour compression refrigeration system using multiple evaporators, individual compressors with multiple expansion valves (Q_{Eva_1}=70 KW, T_{EVA_1}=268K, Q_{Eva_2}=105 KW T_{EVA_2}=273K, Q_{Eva_3}=35 kW, T_{EVA_3}=278K, Eff_{Comp}=0.75, T_{Cond} = 313K, Eff_{Comp}=0.75, with subcooling of liquid at condenser out let at 303K).

System-6

Modified vapour compression refrigeration system using multiple evaporators, compound compression with individual expansion valves with flash intercooler (Q_{Eva_1}=105 KW, T_{EVA_1}=263K, Q_{Eva_2}=70 KW, T_{EVA_2}=278K, Q_{Eva_3}=35 KW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_{Cond}=313K, with sub cooling of liquid at condenser out let at 303K, Efficiency $\_{Comp}$=0.75).

To validate the proposed thermal model of modified vapour compression refrigeration system using multiple evaporators, single compressor with single expansion valves (system-1), using R-12 shown in Table-1 (a), it is found that the developed thermal model predicts first law thermodynamic performances well with zero percent variation while for validating the computed results of total electrical power required to run compressor from predicted thermal model is 3.073% is lower.

Table-1 (a) Modified vapour compression refrigeration system using multiple evaporators, single compressor with single expansion valves (system-1) using R-12 for Q_{Eva_1}=35 KW, T_{EVA}=268K, Q_{Eva_2}=70 KW, Q_{Eva_3}=35 KW, Eff_{Comp}=0.75, T_{Cond}=313K, with sub-cooling of liquid at condenser out let at 303K using isentropic compression.

Performance Parameters	Model	Ref [33]	% Difference
First law efficiency (COP)	5.07	5.07	0.0
Total Compressor Work (Exergy of Fuel) KW”	40.14	41.4	3.073

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, the results are presented in Table 1(b) and Table-1(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a.The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-1) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-1) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-1(b) and also based on total exergy destruction in whole system is shown in Table-1(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the valve by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly, by using R-1234yf, R-1243zf, R1225ye (z0 and R1234ze, the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze(E), R1224yd(Z), R1233zd(E), R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future refrigerants

Table-1 (b) , Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using multiple evaporators at the same temperatures with single isentropic compression , single expansion valve(system-1) using following HFO refrigerants for $Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW,$T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW,$T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K,with subcooling of liquid at condenser out let at 303K, $Eff_{\_Comp}$=0.75%.

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.051	3.885	3.999	4.029	3.846	3.973	3.864	3.75
Total Exergy Destruction(%)	61.8	62.68	62.16	61.99	62.97	62.39	62.83	63.51
Compressor Exergy Destruction(%)	21.13	23.66	23.66	23.47	23.6	23.8	23.42	23.71
Condenser Exergy Destruction(%)	23.5	21.67	22.5	22.95	21.48	22.13	21.83	20.69
Evaporator Exergy Destruction(%)	8.249	7.501	8.144	8.222	7.83	8.088	7.86	7.634
Valve Exergy Destruction(%)	6.923	9.846	7.86	7.347	10.06	6.369	9.722	11.48
System Exergetic Rational efficiency (%)	38.07	37.32	37.84	38.01	37.07	37.61	37.17	36.49

Table-1 (c) , Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using multiple evaporators at the same temperatures with single isentropic compression , single expansion valve(system-1) using following HFO refrigerants for $Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW,$T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW,$T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K,$Eff_{\_Comp}$=0.75%

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.051	3.885	3.999	4.029	3.846	3.973	3.864	3.75
Compressor Exergy Destruction(%)	37.43	37.75	38.06	37.86	37.48	38.15	37.27	37.33
Condenser Exergy Destruction(%)	38.02	34.54	36.19	37.03	34.11	35.47	34.75	32.58
Evaporator Exergy Destruction(%)	13.35	11.97	13.1	13.26	12.43	12.96	12.51	12.02
Valve Exergy Destruction(%)	11.2	15.71	12.65	11.85	15.97	13.41	11.2	18.07
System Exergetic Rational efficiency (%)	38.07	37.32	37.84	38.01	37.07	37.61	37.17	36.49

To validate the proposed thermal model of modified vapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (system-2), using R-12 shown in Table-2 (a), it is found that the developed thermal model predicts first law thermodynamic performances well with 4.977% variation while for validating the computed results of total electrical power required to run compressor from predicted thermal model is 5.4545% is lower.

Table-2 (a) Modified vapour compression refrigeration system with three evaporators at different Temperatures with single isentropic compressor, individual expansion valves (system-2) using R12 ($Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=0.80)

Performance Parameters	Ref [33]	Model	% Difference
First law efficiency (COP)	4.38	4.162	4.977 (lower)
Total Compressor Work (Exergy of Fuel) KW”	31.9	33.64	5.4545 (higher)

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, of system-2, the results are presented in Table 2(b) and Table-2(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-2) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-2) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-2(b) and also based on total exergy destruction in whole system is shown in Table-2(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the valve by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly, by using R-1234yf, R-1243zf, R1225ye(z) and R1234ze(E), the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze€, R1224yd(Z), R1233zd(E), R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future. refrigerants

Table-2 (b) Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with single compressor, individual expansion valves (system-2) for $Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 kW, $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, T_Cond=313K

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf	R-134a	R1233 zd(E)
First law efficiency (COP)	3.266	3.037	3.199	2.997	3.162	3.024	2.876	3.014	3.239
Total Exergy Destruction(%)	75.45	82.43	77.85	83.1	79.06	82.19	86.65	81.1	76.17
Compressor Exergy Destruction(%)	22.4	23.07	22.99	23.04	23.42	22.85	23.23	22.49	22.57
Condenser Exergy Destruction(%)	22.28	20.2	21.02	20.04	20.33	20.48	19.2	21.26	21.86
Evaporator Exergy Destruction(%)	6.97	5.399	6.911	5.382	6.972	5.372	4.818	5.256	6.9
Valve Exergy Destruction(%)	23.79	33.76	26.93	34.64	28.34	33.49	39.39	32.09	24.84
System Exergetic Rational efficiency (%)	28.3	17.57	22.15	16.90	20.94	17.81	13.35	18.9	20.52

Table 2 (c) Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using three evaporators at the Different Temperatures with single compressor, individual expansion valves(system-2) for $Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf	R-134a	R1233 zd(E)
First law efficiency (COP)	3.266	3.037	3.199	2.997	3.162	3.024	2.876	3.014	3.239
Compressor Exergy Destruction(%)	29.7	27.99	29.53	27.73	29.62	27.8	26.81	27.73	
Condenser Exergy Destruction(%)	29.53	24.5	27.0	24.11	25.72	24.91	22.16	26.21	
Evaporator Exergy Destruction(%)	9.329	6.549	8.877	6.477	8.816	6.536	5.561	6.481	
Valve Exergy Destruction(%)	31.53	40.96	34.6	41.68	35.35	40.75	45.46	39.57	

To validate the proposed thermal model of modified vapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (system-2), using R-12 shown in Table-3 (a), it is found that the developed thermal model predicts first law thermodynamic performances well with 9% variation while for validating the computed results of total electrical power required to run compressor from predicted thermal model is 8.20% is lower.

Table-3 (a) modifiedvapour compression refrigeration system using three evaporators at the different temperatures with single isentropic compression, individual expansion valves (system-3) using R12 ($Q_{\_Eva\_1}$=70 KW, $T_{\_EVA\_1}$=268K, $Q_{\_Eva\_2}$=35 KW $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=280K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=100%)

Performance Parameters	Ref [33]	Model	% Difference
First law Efficiency (COP)	4.80	5.232	9% higher
Total Compressor Work (Exergy of Fuel) KW”	43.73	40.14	8.2095 Lower
Mass flow rate in first Evaporator (kg/min)	28.13	28.11	0.0777
Mass flow rate in second Evaporator (kg/min)	44.82	44.694	0.2811
Mass flow rate in third Evaporator (kg/min)	29.55	29.394	0.52799
Exergetic efficiency	---	0.40	
Second law efficiency	----	0.52	

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, of system-3, the results are presented in Table 3(b) and Table-3(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-3) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-1) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-3(b) and also based on total exergy destruction in whole system is shown in Table-3(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the valve by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly by using R-1234yf, R-1243zf, R1225ye(z0 and R1234ze(E) , the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze€, R1224yd(Z), R1233zd(E), R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future.

Table-3 (b) Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using multiple evaporators at the different temperatures with single compressor, multiple expansion valves (system-3) using following HFO refrigerants ($Q_{\_Eva\_1}$=105 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_1}$=280K, $Eff_{\_Comp}$=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.054	3.904	4.015	4.042	3.864	3.994	3.876	3.775
Total Exergy Destruction(%)	61.84	61.83	62.58	62.58	61.96	63.32	61.62	62.14
Compressor Exergy Destruction(%)	22.80	23.35	23.33	23.08	23.31	23.67	23.13	23.46
Condenser Exergy Destruction(%)	24.04	22.13	22.94	23.48	21.93	22.4	22.31	21.12
Evaporator Exergy Destruction(%)	11.84	11.69	12.77	12.72	11.88	13.55	11.44	11.97
Valve Exergy Destruction(%)	3.157	4.658	3.546	3.298	4.836	3.693	4.733	5.593

Table-3 (c) Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using multiple evaporators at the Different Temperatures with single compressor, multiple expansion valves (system-3) using following HFO refrigerants ($Q_{\_Eva\_1}$=105 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_1}$=283K, $Eff_{\_Comp}$=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.054	3.904	4.015	4.042	3.864	3.994	3.876	3.775
Compressor Exergy Destruction(%)	36.86	37.77	37.28	36.88	37.62	37.38	37.54	37.75
Condenser Exergy Destruction(%)	38.88	35.79	36.65	37.52	35.4	35.38	36.21	33.99
Evaporator Exergy Destruction(%)	19.15	18.91	20.40	20.33	19.18	21.4	18.56	19.26
Valve Exergy Destruction(%)	5.106	7.533	5.666	5.27	7.805	5.832	7.682	9.0
System Exergetic Rational efficiency (%)	38.16	38.17	37.42	37.42	24.04	36.68	38.38	37.86

Table-4 (a) modified vapour compression refrigeration system using multiple evaporators at the Different Temperatures with individual compressors, individual expansion valves using R12 ($Q_{\_Eva\_1}$=35 kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 kW, $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 kW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=0.80)

Performance Parameters	Model
First law efficiency (COP)	7.157
Total Compressor Work KW"	29.34
Exergy Destruction Ratio (EDR)	1.53
Exergetic efficiency	0.3842
% Rational Efficiency	41.21
% Exergy Destruction	58.79
Exergy of Fuel KW"	29.34

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, of system-4, the results are presented in Table 4(b) and Table-4(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-4) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-1) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-4(b) and also based on total exergy destruction in whole system is shown in Table-1(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the valve by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly, by using R-1234yf, R-1243zf, R1225ye (z0 and R1234ze(E), the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze€, R1224yd(Z), R1233zd(E), R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future. To validate the proposed thermal model of modified vapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (system-2), using R-12 shown in Table-5 (a), it is found that the developed thermal model predicts first law thermodynamic performances well with 10.26% variation while for validating the computed results of total electrical power required to run compressor from predicted thermal model is 8.533% is lower.

Table-4 (b) Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using multiple evaporators at the Different Temperatures with individual compressors, individual expansion valves(system-4)using following HFO refrigerants ($Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW,$T_{\_EVA\_2}$=278K, $Q_{\_Eva\_3}$=105 KW,$T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, T_Cond=313K, Subcooling=303K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	5.531	5.363	5.484	5.515	5.302	5.468	5.315	5.193
Total Exergy Destruction(%)	68.36	68.97	68.95	68.93	69.14	69.04	69.11	69.30
Compressor Exergy Destruction(%)	23.3	23.7	23.71	23.56	23.66	23.8	23.51	23.74
Condenser Exergy Destruction(%)	29.97	28.08	29.07	29.51	27.78	28.78	28.09	26.90
Evaporator Exergy Destruction(%)	10.5	9.748	10.41	10.49	10.06	10.37	10.08	9.855
Valve Exergy Destruction(%)	5.099	7.435	5.771	5.372	7.647	6.087	7.428	8.813
System Exergetic Rational efficiency (%)	31.04	31.03	31.05	31.07	30.85	30.96	30.89	30.70

Table-4 (c) Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with individual compressors, individual expansion valves(system-4)using following HFO refrigerants($Q_{\_Eva\_1}$=35 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW,$T_{\_EVA\_2}$=278K, $Q_{\_Eva\_3}$=105 KW,$T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, T_Cond=313K, Subcooling=303K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	5.531	5.363	5.484	5.515	5.302	5.468	5.315	5.193
Compressor Exergy Destruction(%)	33.83	34.37	34.38	34.18	34.21	34.48	34.02	34.25
Condenser Exergy Destruction(%)	43.42	40.71	42.16	42.81	40.18	41.68	40.65	38.81
Evaporator Exergy Destruction(%)	15.24	14.13	15.09	15.22	14.55	15.02	14.58	14.22
Valve Exergy Destruction(%)	7.404	10.78	8.37	7.793	11.06	8.817	10.75	12.72
System Exergetic Rational efficiency (%)	31.04	31.03	31.05	31.07	30.85	30.96	30.89	30.70

Table-5 (a) Multiple evaporators at the Different Temperatures with single isentropic compression, individual expansion valves using R12 ($Q_{\_Eva\_1}$=70 KW, $T_{\_EVA\_1}$=268K, $Q_{\_Eva\_2}$=105 KW $T_{\_EVA\_2}$=273K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=278K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=100%)

Performance Parameters	Ref [33]	Model	% Difference
First law Efficiency (COP)	5.56	6.128	10.216
Total Compressor Work (Exergy of Fuel) KW"	48.4	44.27	8.533

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, of system-5, the results are presented in Table 5(b) and Table-5(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-4) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-5) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-5(b) and also based on total exergy destruction in whole system is shown in Table-5(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the valve by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly, by using R-1234yf, R-1243zf, R1225ye (z0 and R1234ze(E), the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze€, R1224yd(Z), R1233zd(E), R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore, it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future.

Table-5 (b) Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with individual compressors, multiple expansion valves (system-5) using following HFO refrigerants for (Q_{Eva_1}=70 KW, T_{EVA_1}=268K, ,Q_{Eva_2}=105 KW T_{EVA_2}=273K, Q_{Eva_3}=35 KW,T_{EVA_3}=278K, Eff_{Comp}=0.75, T_{Cond}=313K,,Eff_{Comp}=0.75,, Subcooling=303K)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.724	4.601	4.693	4.715	4.556	4.685	4.563	4.475
Total Exergy Destruction(%)	67.73	69.2	68.37	68.08	69.48	68.79	69.22	70.23
Compressor Exergy Destruction(%)	23.23	23.69	23.69	23.53	23.64	23.8	23.48	23.73
Condenser Exergy Destruction(%)	26.41	24.79	25.56	25.96	24.54	25.29	24.83	23.8
Evaporator Exergy Destruction(%)	13.91	14.54	14.41	14.21	14.89	14.74	14.67	15.26
Valve Exergy Destruction(%)	4.176	6.187	4.718	4.38	6.407	4.95	6.245	7.431
System Exergetic Rational efficiency (%)	32.27	30.8	31.63	31.92	30.52	31.21	30.78	29.77

Table-5 (c) Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with individual compressors, multiple expansion valves (system-5) using following HFO refrigerants (Q_{Eva_1}=70 KW, T_{EVA_1}=268K, ,Q_{Eva_2}=105 KW T_{EVA_2}=273K, Q_{Eva_3}=35 KW,T_{EVA_3}=278K, Eff_{Comp}=0.75, T_{Cond}=313K,,Eff_{Comp}=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.724	4.601	4.693	4.715	4.556	4.685	4.563	4.475
Compressor Exergy Destruction(%)	34.31	34.23	34.65	34.56	34.03	34.60	33.92	33.79
Condenser Exergy Destruction(%)	38.99	35.82	37.38	38.13	35.32	36.77	35.87	33.89
Evaporator Exergy Destruction(%)	20.53	21.01	21.07	20.88	21.43	21.43	21.19	21.73
Valve Exergy Destruction(%)	6.167	8.94	6.90	6.433	9.222	7.197	9.021	10.58
System Exergetic Rational efficiency (%)	32.27	30.8	31.63	31.92	30.52	31.21	30.78	29.77

To validate the proposed thermal model of modified vapour compression refrigeration system using multiple evaporators, single compressor with individual expansion valves (system-6), using R-12 shown in Table-6 (a), it is found that the developed thermal model predicts first law thermodynamic performances well with 6.64% variation while for validating the computed results of total electrical power required to run compressor from predicted thermal model is 5.977% is lower.

Table-6(a): Multiple evaporators at the Different Temperatures with compound isentropic compression, individual expansion valves and flash intercooler using R12 (Q_{Eva_1}=105 KW, T_{EVA_1}=263K, Q_{Eva_2}=70 KW, T_{EVA_2}=278K, Q_{Eva_3}=35 kW, T_{EVA_3}=283K, Eff_{Comp}=0.75, T_{Cond}=313K, Eff_{Comp}=100%)

Performance Parameters	Model	Ref [33]	% Difference
First law Efficiency (COP)	5.076	4.76	6.64
Total Compressor Work (Exergy of Fuel) KW"	41.37	44.0	5.977

For actual conditions with compressor efficiency is 75%, using HFO refrigerants, of system-6, the results are presented in Table 6(b) and Table-6(c) respectively. respectively. It was found that HFO refrigerants has good promising feature for replacing R134a. The first law performance in terms of COP using HFO-1234ze(Z) is highest while using R-1234yf is lowest. With comparing with R-134a, the COP of modified system (system-4) using R1234ze(Z) is 4.434% higher, while by using HFO-1234yf, the first law efficiency is 3.356% lower than using HFC-134a. Similarly, first law performance (COP) is slightly higher by using R1224yd(Z) and R-1233zd(E) and R-1336mzz(Z) as compared to R134a. similarly the thermodynamic performance (COP) by using R1225ye(Z) and R1243zf is nearly similar than using R-134a. The percentage exergy destruction in components of modified VCRs (system-6) based on exergy of fuel in terms of electrical energy consumption (i.e. compressor work in kW) is shown in Fig-6(b) and also based on total exergy destruction in whole system is shown in Table-6(c) respectively. It is found that condenser has maximum exergy destruction while minimum occurred in the in the flash chambers by using R-1234ze(Z), R1224yd(Z), R1233zd(E) and R-1336mzz(Z). Similarly by using R-1234yf, R-1243zf, R1225ye (z0 and R1234ze(E) , the minimum exergy destruction was found in the evaporator, while in expansion valve is slightly higher. The exergy destruction in compressor using R-1234ze€, R1224yd(Z), R1233zd(E) ,R1225ye(Z), R1336mzz(Z), R1243zf and R1234yf is higher than condenser, while by using R1234ze(z) is lower. Therefore it is concluded that above ultra-low GWP refrigerants are very suitable for replacing High GWP refrigerants such as R-134a in near future.

Table-6 (b) Variation of rational exergetic efficiency and first law efficiency (COP) and percentage exergy destruction in components based on exergy of fuel of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with compound compression, individual expansion valves and flash inter cooler(system-6) using following HFO refrigerants for $Q_{\_Eva\_1}$=105 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_2}$=278K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.616	4.529	4.598	4.613	4.485	4.597	4.486	4.421
Total Exergy Destruction(%)	67.09	70.91	67.7	67.38	69.26	68.02	69.05	70.23
Compressor Exergy Destruction(%)	24.23	24.51	24.5	24.41	24.47	24.57	24.36	24.52
Condenser Exergy Destruction(%)	25.58	24.6	25.05	25.33	24.12	24.91	24.29	23.52
Evaporator Exergy Destruction(%)	12.55	12.93	12.96	12.8	13.28	13.21	13.10	13.56
Valve Exergy Destruction(%)	3.367	5.047	3.766	3.509	5.266	3.916	5.176	6.14
Sub cooler Exergy Destruction(%)	1.258	2.009	1.398	1.271	2.093	1.395	2.065	2.48
Flash chambers Exergy Destruction(%)	0.1062	0.01537	0.0388	0.06072	0.0355	0.0092	0.05612	0.0138
System Exergetic Rational efficiency (%)	32.91	29.09	32.30	32.62	30.74	31.98	30.95	29.77
First Compressor Exergy Destruction(%)	4.703	4.683	4.737	4.73	4.669	4.77	4.655	4.647
Second Compressor Exergy Destruction(%)	2.578	2.556	2.58	2.582	2.553	2.585	2.551	2.538
Third Compressor Exergy Destruction(%)	16.95	17.27	17.19	17.10	17.24	17.22	17.16	17.33
First Evaporator Exergy Destruction(%)	4.879	4.511	4.862	4.884	4.739	4.857	4.737	4.671
Second Evaporator Exergy Destruction(%)	3.725	3.776	3.823	3.806	3.835	3.909	3.789	3.882
Third Evaporator Exergy Destruction(%)	3.951	4.638	4.260	4.109	4.703	4.446	4.571	5.006
First Valve Exergy Destruction(%)	0.2957	0.4154	0.3296	0.3176	0.4362	0.3589	0.4290	0.4988
Second Valve Exergy Destruction(%)	0.5112	0.7543	0.5650	0.5358	0.7954	0.5929	0.790	0.9237
Third Valve Exergy Destruction(%)	2.56	3.878	2.871	2.656	4.035	2.964	3.957	4.718

Table-6 (c) Variation of Rational exergetic efficiency, first law efficiency (COP) and percentage exergy destruction in components based on total exergy destruction of modified vapour compression refrigeration system using Multiple evaporators at the Different Temperatures with compound compression, individual expansion valves and flash inter cooler(system-6) using following HFO refrigerants ($Q_{\_Eva\_1}$=105 KW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 KW, $T_{\_EVA\_2}$=278K, $Q_{\_Eva\_3}$=35 KW, $T_{\_EVA\_3}$=283K, $Eff_{\_Comp}$=0.75, $T_{\_Cond}$=313K, $Eff_{\_Comp}$=0.75)

Performance Parameters	R-1234 ze(Z)	R1234 ze(E)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 yf
First law efficiency (COP)	4.616	4.529	4.598	4.613	4.485	4.597	4.486	4.421
Compressor Exergy Destruction(%)	36.11	35.57	36.19	36.23	35.33	36.13	35.28	34.91
Condenser Exergy Destruction(%)	38.12	35.41	37.0	37.59	34.83	36.63	35.18	33.49
Evaporator Exergy Destruction(%)	18.71	18.76	19.12	19.0	19.17	19.42	18.97	19.3
Valve Exergy Destruction(%)	5.019	7.326	5.562	5.208	7.604	5.757	7.495	8.742
Sub cooler Exergy Destruction(%)	1.875	2.917	2.065	1.886	3.022	2.052	2.991	3.531
Flash chambers Exergy Destruction(%)	0.1583	0.0223	0.0572	0.09013	0.0513	0.01348	0.08127	0.01964
System Exergetic Rational efficiency (%)	32.91	29.09	32.30	32.62	30.74	31.98	30.95	29.77
First Compressor Exergy Destruction(%)	7.01	4.683	6.997	7.02	6.742	7.012	6.742	6.617
Second Compressor Exergy Destruction(%)	3.842	2.556	3.812	3.832	3.686	3.80	3.695	3.614
Third Compressor Exergy Destruction(%)	25.26	17.26	25.39	25.38	25.31	25.31	24.85	24.68
First Evaporator Exergy Destruction(%)	7.272	6.548	0.7182	7.245	7.141	7.141	6.859	6.65
Second Evaporator Exergy Destruction(%)	5.553	5.481	5.642	5.649	5.746	5.746	5.487	5.528
Third Evaporator Exergy Destruction(%)	5.889	6.731	6.292	6.099	6.537	6.537	6.619	7.126
First Valve Exergy Destruction(%)	0.4408	0.603	0.4868	0.4714	0.6298	0.5276	0.6213	0.7102
Second Valve Exergy Destruction(%)	0.762	1.095	0.8346	0.7952	1.148	0.8717	1.144	1.315
Third Valve Exergy Destruction(%)	3.816	5.628	4.241	3.942	5.826	4.358	5.730	6.717
Flash chambers Exergy Destruction(%)	0.1385	0.0236	0.0512	0.0794	0.0448	0.01263	0.07096	0.0175
Flash chambers Exergy Destruction(%)	0.0198	0.0013	0.0605	0.01075	0.0064	0.00085	0.01032	0.00218
Compressor Exergy Destruction(%)	24.23	24.51	24.5	24.41	24.47	24.57	24.36	24.52
Condenser Exergy Destruction(%)	25.58	24.6	25.05	25.33	24.12	24.91	24.29	23.52
Evaporator Exergy Destruction(%)	12.55	12.93	12.96	12.8	13.28	13.21	13.10	13.56
Valve Exergy Destruction(%)	3.367	5.047	3.766	3.509	5.266	3.916	5.176	6.14
Sub cooler Exergy Destruction(%)	1.258	2.009	1.398	1.271	2.093	1.395	2.065	2.48
Flash chambers Exergy Destruction(%)	0.1062	0.0153	0.0388	0.06072	0.0355	0.0092	0.05612	0.0138
System Exergetic Rational Efficiency (%)	32.91	29.09	32.30	32.62	30.74	31.98	30.95	29.77

3. Conclusions

Following conclusions were drawn from present investigation.

- R-1234ze(Z), R-1234ze(E), R1224yd(Z), R1233zd(E) R1336mzz(Z), R1225ye(Z) R1243zf and R-1234yf, refrigerants will be good alternatives to replace R134a up to -10ºC sin the single stage VCRS.
- R-1234ze(Z), R-1234ze(E), R1233zd(E) R1336mzz(Z), R1225ye(Z) R1243zf and R-1234yf refrigerants will be good alternatives to replace R134a up to -30ºC sin the single stage VCRS
- R-1234yf, R1233zd(E), R-1336mzz(Z) and, R1225ye(Z) refrigerants will be good alternatives to replace R134a up to -50ºC in the double stages stage cascaded VCRS
- R1233zd(E), R-1336mzz(Z) and, R1225ye(Z) refrigerants will be good alternatives to replace R134a up to --75ºC in the double stages stage cascaded VCRS
- R-1336mzz(Z) and, R1225ye(Z) refrigerants will be good alternatives to replace R134a up to -100ºC in the double stages stage cascaded VCRS
- For very low temperature applications, R-1336mzz(Z) and, R1225ye(Z) refrigerants will be good alternatives to replace R404a up to -135ºC in the three stages stage cascaded VCRS
- For ultra-low temperature applications, R-1336mzz(Z) and, R1225ye(Z) refrigerants will be good alternatives to replace hydrocarbons up to -155ºC in the three stages stage cascaded VCRS
- Exergy destruction based on exergy of fuel or exergy of output, it was found the total exergy destruction in whole system is more for HFO-1234yf and lower by using HFO-1234ze(Z)
- HFO-1234ze(Z) can replace the conventional HFC-134a after having slight modification in the design as the performance parameters are 4% to 5% more than using R134a.

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