International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

ORIGINAL ARTICLE

Effect of Different load conditions using detailed exergy evaluations of multi evaporators and multi expansion valved modified VCRS using HFO & HCFO refrigerants

R. S. Mishra

Department of Mechanical Engineering, Delhi Technological University Delhi, India

Article Information

Received: 19 April 2021
Revised: 11 June 2021
Accepted: 20 June 2021
Available online: 25 April 2021

Keywords:

Energetic and exergetic efficiency evaluation (EEEE);
Percentage exergy destruction computation (PEDC);
HFO&HCFO Refrigerants;
Modified ecofriendly VCRS

Abstract

In this paper comparative thermodynamic analysis (which is based on energy and exergy principles) of modified VCRS using multiple evaporators at the different Temperatures with single compressor using individual expansion valves and back pressure valves nd modified VCRS using multiple evaporators at the different temperatures with single compressor using multiple expansion valves and back pressure valves has been presented. The comparison of both systems-using ecofriendly R1224yd(Z), R1243zf, R1234yf, R1225ye(Z), R1233zd(E), R1234ze(Z), R1234ze(E), R1336mzz(Z) and HFC-134a refrigerants have been done in terms of first law efficiency i.e. COP (energetic efficiency), exergetic efficiency and system exergy destruction ratio (EDR in terms of exergy defect) Numerical models have been developed for modified VCRS using multiple evaporators at the Different Temperatures with single compressor using individual expansion valves and back pressure valves and modified VCRS using multiple evaporators at the different temperatures with single compressor using multiple expansion valves and back pressure valves for finding out irreversibilities (system exergy destruction ratio (EDR in terms of exergy defect) and it was observed that modified VCRS using multiple evaporators at the different temperatures with single compressor using multiple expansion valves and back pressure valves is better system in comparison of modified VCRS using multiple evaporators at the different temperatures with single compressor using individual expansion valves and back pressure valves in all respect for selected HFO &HCFO refrigerants. It was also found that R1234ze(Z), shows better performances than other considered refrigerants for both systems as compared with using HFC-134a

1. Introduction

Refrigeration is a technology which absorbs heat at low temperature and provides temperature lower than the surrounding temperature, by rejecting heat to the surrounding at higher temperature. 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 The working fluid is used in vapour compression refrigeration is refrigerant. To date, the refrigerants used in centrifugal chillers have been replaced several times. Highly toxic and flammable substances were used as refrigerants for chillers manufactured prior to the invention of chlorofluorocarbons (CFCs) since there were no other suitable substances. Following the development of the first non-flammable and low

Corresponding author: R.S. Mishra
Email Address: hod.mechanical.rsm@dtu.ac.in
https://doi.org/10.36037/IJREI.2021.5501

toxic chlorofluorocarbon halomethane CFC-12 in the 1920, we can use a safe and reliable substance as refrigerant. In the 1970s, however, it was posited that CFCs destroy the ozone layer in the stratosphere. As a result, the 1987 Montreal Protocol was enacted as a step toward the abolishment of designated CFCs by 1996 along with a gradual phase-out of substitute hydro-chlorofluorocarbons (HCFCs).

Accordingly, HFCs that do not destroy ozone layer were developed in order to replace HCFCs. In Japan, companies first replaced CFC refrigerants with HCFC refrigerants and then later on with HFC refrigerants in consideration of the environment, ahead of other countries, earlier than the regulation timetable set up in the Montreal Protocol. HFC refrigerants do not destroy the ozone layer, and are non-flammable and low toxic, which make HFC safe and reliable. But GWP of HFC is high. Therefore, a new movement was started for implementing legal regulations on HFCs. In 2006, the EU F-gas Regulation was established first and then the proposal to phase down HFCs under the Montreal Protocol on substances that deplete the ozone layer was issued through the leadership of the U.S. These new endeavors led to the amendment of the "Law Concerning the Recovery and Destruction of Fluorocarbons" to the "Act on Rational Use and Proper Management of Fluorocarbons" (commonly known as "Fluorocarbon Emission Control Law") and came into effect from April 2015, in Japan. As for the global scene, the Parties to the Montreal Protocol reached an agreement at their 28th Meeting of the Parties (MOP28) in October 2016 in Kigali, Rwanda to phase down HFCs (Kigali Amendment [2]. it was decided that the developed countries should gradually reduce their production and consumption of HFCs (on a CO2 equivalent basis) by 10% by 2019, by 40% by 2024, and then by 70% by 2029, and eventually by 85% by 2036. The developing countries, on the other hand, would have to reduce HFCs production and consumption with a time delay of approximately 10 to 13 years. As a whole, all parties are required to reduce HFCs over a period of 30 years. This transition mechanism is similar to that of the past efforts toward reducing HCFCs. In consequence of the Kigali Amendment, the regulations of the Fluorocarbon Emission Control Law in Japan have been gradually strengthened further[3)]. In December 2017, the government announced proposals to add a centrifugal chiller to designated product category, which demands that equipment manufacturers replace existing refrigerants with lower GWP refrigerants, then centrifugal chiller manufacturers must regulate GWP values to 100 or less from 2025 onwards.

The properties of refrigerants change inevitably in order to achieve low-GWP levels. Although substances called natural refrigerants have a very low GWP, they have downsides too. For example, hydrocarbons are highly flammable, whereas ammonia is both highly flammable and toxic. To find a way around these hurdles, hydrofluoroolefins (HFOs) with a carbon–carbon double bond has been developed recently as another candidate for a low-GWP refrigerant. HFOs decompose when exposed to ultraviolet rays and thus has a short atmospheric lifetime and a low GWP. As an inherent trade-off for reducing GWP, however, substances tends to become flammable because the stability of molecules is reduced in order to increase the speed of decomposition. Although different types of low GWP refrigerants have been developed for various refrigeration and air-conditioning equipment, we can summarize that non-flammability is not necessarily-achieved property in the effort to achieve low GWP. 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 systems under vapour compression technology consume enormous amount of electricity, this problem can be solved by improving performance of system.

Thermodynamic performances of systems based on vapour compression refrigeration technology can be improved by following [1]:

- COP means coefficient of performance known as first law efficiency. The performance of refrigerator is defined, 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.
- by adopting multi-stage expansion with flash chamber where the flash vaporish removed after each stage of expansion as a consequence there will be increase in cooling capacity and reduce the size of the evaporator. Because throttling process in VCR is an irreversible expansion process due to internal irreversibility. The expansion process is one of the main factors responsible for exergy loss in cycle thermodynamic performance, since the entering portion of the refrigerant flashing to vapour in evaporator which will not only reduce the cooling capacity but also increase the size of evaporator.
- The 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 sub-cooler after condenser by sub cooling 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 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 greenhouse gases in 1997. The relationship between ozone depletion potential and global warming potential is the major concern in the field of

GRT (green refrigeration technology) 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. 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. By doing detailed exergetic computations the Saravanakumar and Selladurai [3] 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 [4] 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 Reddy et al. [5] 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. Mishra [6] defined the second law effectiveness, , exergetic efficiency and second law efficiency of modified systems because for exergetic analysis when final state of systems kept at dead state, then second law efficiency becomes exergetic efficiency. This paper mainly deals with comparsions of several modified VCRS using HFO and HCFO refrigerants for replacing HFC refrigerants in near future. The effect of different load conditions on the thermodynamic performances also investigated in this paper.

2. Thermodynamic analysis of multi evaporator systems

Energy analysis is concerned with the conservation of energy but it gives no information on how, where, and how much the system performance is degraded or evaluation of actual irreversibility losses occurred in system Therefore exergy analysis which is based on first law and second law of thermodynamic is a powerful tool in the design, optimization, and performance evaluation of energy systems. Exergy analysis (second law analysis) helps in identifying the thermal losses and energy transfer for the processes. As per earlier research, exergetic efficiency, energetic efficiency and irreversibility in each component of VCR system is not same for different refrigerants. In this paper numerical models have been developed for the comparison of performance parameters of systems (Modified VCRS using multiple evaporators at the different temperatures with single compressor using individual expansion valves and back pressure valves and Modified VCRS using multiple evaporators at the Different Temperatures with single compressor using multiple expansion valves and back pressure valves) based on selected refrigerants by using EES software .The performance parameters are evaluated by considering following operating conditions of the systems.

- Adiabatic efficiency of each compressor (η_c):75%.
- Negligible pressure drop in pipelines
- Negligible change in potential and kinetic energy
- Expansion of refrigerant in expansion valves is isenthalpic
- Temperatures of first, second and third evaporators are 263K ,278K and 283K respectively for system-2 and sytem-3 type
- Condenser temperature (T_{cond}): 313K
- Dead state temperature (T_0): 298K
- Dead state enthalpy (ψ_0) and entropy (s_0) of the refrigerants have been calculated corresponding to the dead state temperature (T_0) of 298K.
- Loads on first, second and third evaporator are 105KW, 70KW and 35KW respectively in alternate manners.

2.1 First law and second law analysis

The modified VCRS using multiple evaporators at the Different Temperatures with single compressor using individual expansion valves and back pressure valves consist of compressors ($Comp_1$, $Comp_2$, $Comp_3$), throttle valves (tv_1, tv_2, tv_3), condenser and evaporators(EP_1, EP_2, EP_3) The pressure versus enthalpy chart for the system-1 The main components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor using multiple expansion valves and back pressure valves are compressors ($Comp_{1*}$, $Comp_{2*}$, $Comp_{3*}$) , throttle valves (tv_{1*}, tv_{2*}, tv_{3*}), condenser and evaporators(EP_{1*}, EP_{2*}, EP_{3*}) as shown in Fig. 2(a). The corresponding pressure versus enthalpy chart for this system is shown in Fig. 2(b). According to first law of thermodynamic energetic efficiency /COP is defined as the ratio of net refrigeration effect to the per unit power consumed. First law analysis restricted to calculate only coefficient of performance of the vapour compression systems as given below:

$$\dot{W}_c = \dot{m}_{c1}(\psi_2 - \psi_1) + \dot{m}_{c2}(\psi_4 - \psi_3) + \dot{m}_{c3}(\psi_6 - \psi_5) \quad (1)$$

$$\dot{Q}_e = \dot{m}_{e1}(\psi_1 - \psi_{10}) + \dot{m}_{e2}(\psi_3 - \psi_9) + \dot{m}_{e3}(\psi_5 - \psi_8) \quad (2)$$

$$\mathrm{COP} = \frac{\dot{Q}_e}{\dot{W}_c} \quad (3)$$

$$\dot{W}_{c^*} = \dot{m}_{c1^*}(\psi_b - \psi_a) + \dot{m}_{c2^*}(\psi_d - \psi_c) + \dot{m}_{c3^*}(\psi_f - \psi_e) \quad (4)$$

$$\dot{Q}_{e^*} = \dot{m}_{e1^*}(\psi_a - \psi_l) + \dot{m}_{e2^*}(\psi_c - \psi_j) + \dot{m}_{e3^*}(\psi_e - \psi_h) \quad (5)$$

$$\mathrm{COP}^* = \frac{\dot{Q}_{e^*}}{\dot{W}_{c^*}} \quad (6)$$

The concept of exergy was given by second law of thermodynamics. Exergy is the measure of usefulness, quality or potential of a stream to cause change and an effective measure of the potential of a substance to impact the environment. Irreversibility (exergy destruction) in each component of the system-1 evaluated as per Equations (7) – (14) given below:

2.2 Modified VCRS using multiple evaporators at the different temperatures with single compressor, individual expansion valves and back pressure valves

The exergy destruction in each component can be expressed in the followings

For evaporators

$$\dot{ED}_{e1} = \dot{E}_{x10} + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{E}_{x1} \quad (7)$$
$$= \dot{m}_{e1}(\psi_{10} - T_0 s_{10}) + \dot{Q}_{e1}\left(1 - \frac{T_0}{T_{r1}}\right) - \dot{m}_{e1}(\psi_1 - T_0 s_1)$$

$$\dot{ED}_{e2} = \dot{E}_{x9} + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{E}_{x3} \quad (8)$$
$$= \dot{m}_{e2}(\psi_9 - T_0 s_9) + \dot{Q}_{e2}\left(1 - \frac{T_0}{T_{r2}}\right) - \dot{m}_{e2}(\psi_3 - T_0 s_3)$$

$$\dot{ED}_{e3} = \dot{E}_{x8} + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{E}_{x5} \quad (9)$$
$$= \dot{m}_{e3}(\psi_8 - T_0 s_8) + \dot{Q}_{e3}\left(1 - \frac{T_0}{T_{r3}}\right) - \dot{m}_{e3}(\psi_5 - T_0 s_5)$$

For Compressor

$$\dot{ED}_c = \dot{E}_{x1} + \dot{W}_{c1} - \dot{E}_{x2} = \dot{m}_{c1}(T_0(s_2 - s_1)) \quad (10)$$

Condenser

$$\dot{ED}_{cond} = (\dot{E}_{x66} - \dot{E}_{x7}) \ (13)$$
$$= \dot{m}_c\left((\psi_{66} - T_0 s_{66}) - (\psi_7 - T_0 s_7)\right) \quad (11)$$

Throttle valves

$$\dot{ED}_{t1} = \dot{E}_{x7} - \dot{E}_{x10} = \dot{m}_{c1}(T_0(s_{10} - s_7)) \quad (12)$$

$$\dot{ED}_{t2} = \dot{E}_{x7} - \dot{E}_{x9} = \dot{m}_{c2}(T_0(s_9 - s_7)) \quad (13)$$

$$\dot{ED}_{t3} = \dot{E}_{x7} - \dot{E}_{x8} = \dot{m}_{c3}(T_0(s_8 - s_7)) \quad (14)$$

2.3 Exergy Destruction Ratio (i.e. ratio of system defect to the exergy of input

The total system defect in the modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 100% isentropic efficiency, individual expansion valves and back pressure valves is the sum of irreversibility in each components of the system and is given by

$$\sum \dot{ED}_n = \dot{ED}_e + \dot{ED}_c + \dot{ED}_{cond} + \dot{ED}_t \quad (15)$$

Similarly, exergy destruction in each component of the multiple evaporators and compressors with multiple expansion valves vapour compression refrigeration system is evaluated as per Equations (16) – (26) given below:

2.4 Modified VCRS using multiple evaporators at the Different Temperatures with single compressor multiple expansion valves and back pressure valves

Evaporators

$$\dot{ED}_{e1^*} = \dot{m}_{e1^*}((\psi_l - T_0 s_l) - (\psi_a - T_0 s_a)) + \dot{Q}_{e1^*}\left(1 - \frac{T_0}{T_{r1^*}}\right) \quad (16)$$

$$\dot{ED}_{e2^*} = \dot{m}_{e2^*}((\psi_j - T_0 s_j) - (\psi_c - T_0 s_c)) + \dot{Q}_{e2^*}\left(1 - \frac{T_0}{T_{r2^*}}\right) \quad (17)$$

$$\dot{ED}_{e3^*} = \dot{m}_{e3^*}\left((\psi_h - T_0 s_h) - (\psi_e - T_0 s_e)\right) + \dot{Q}_{e3^*}\left(1 - \frac{T_0}{T_{r3^*}}\right) \quad (18)$$

Compressor

$$\dot{ED}_{c^*} = \dot{E}_{xa} + \dot{W}_{c1^*} - \dot{E}_{xb} = \dot{m}_{c1^*}(T_0(s_b - s_a)) \quad (19)$$

$$\dot{ED}_{c2^*} = \dot{E}_{xc} + \dot{W}_{c2^*} - \dot{E}_{xd} = \dot{m}_{c2^*}(T_0(s_d - s_c)) \quad (20)$$

$$\dot{ED}_{c3^*} = \dot{E}_{xe} + \dot{W}_{c3^*} - \dot{E}_{xf} = \dot{m}_{c3^*}(T_0(s_f - s_e)) \quad (21)$$

Condenser

$$\dot{ED}_{cond^*} = (\dot{E}_{xff} - \dot{E}_{xg}) = \dot{m}_c\left((\psi_{ff} - T_0 s_{ff}) - (\psi_g - T_0 s_g)\right) \quad (22)$$

Throttle valves

$$\dot{ED}_{t1^*} = \dot{E}_{xk} - \dot{E}_{xl} = \dot{m}_{c1^*}(T_0(s_l - s_k)) \quad (23)$$

$$\dot{ED}_{t2^*} = \dot{E}_{xi} - \dot{E}_{xj} = (\dot{m}_{c1^*} + \dot{m}_{c2^*})\left(T_0(s_j - s_i)\right) \quad (24)$$

$$\dot{ED}_{t3^*} = \dot{E}_{xgg} - \dot{E}_{xh} = (\dot{m}_{c1^*} + \dot{m}_{c2^*} + \dot{m}_{c3^*})\left(T_0(s_h - s_{gg})\right) \quad (25)$$

2.5 Exergy Destruction Ratio (i.e. ratio of system defect to the exergy of input

The total system defect in the modified VCRS using multiple evaporators at the different Temperatures with single compressor (of 100% isentropic efficiency), multiple expansion valves and back pressure valves is the sum of irreversibility in each components of the system and is given by

$$\sum \dot{ED}_{n^*} = \dot{ED}_{e^*} + \dot{ED}_{c^*} + \dot{ED}_{cond^*} + \dot{ED}_{t^*} \quad (26)$$

For the multi evaporators vapour compression refrigeration system, product is the exergy of the heat abstracted in to the evaporators from the space to be cooled and exergy of fuel is actual compressor work input. Hence, exergetic efficiency is given by

$$\eta_{ex} = \frac{\text{Exergy in product}}{\text{Exergy of fuel}} = \frac{\dot{EP}}{\dot{EF}} \quad (27)$$

3. Results and Discussion

Table-1(a) shows the validation of thermodynamic energy performances of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency 100 % for a cooling loads on evaporators are in the following manner (Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3}= 263K) and it was observed that developed model of this system is well matching results as shown. To see the performance with respect to R12, the thermodynamic performance using HFC-134a and HFO-1234ze(Z) are also shown in table-1(a) respectively. The thermodynamic energy performance is 3.8298% less than using R134a and electrical energy consumption is 3.944% more as predicted in the thermal model.

Table-1(a): Validation of Developed thermodynamic model for modified VCRS using multiple evaporators and multiple expansion valves of single compressor efficiency=100%, at the cooling load on evaporator loads (Q_{EVA_1}=35 kW at evaporator temperature (T_{Eva1})= 263K, Q_{EVA_2}=70 kW at evaporator temperature (T_{Eva2})= 263K, Q_{EVA_3}=105 kW at evaporator temperature (T_{Eva3})= 263K

Performance Parameters	R12 Model	R12 Ref [7]	% difference	R134a	R-1234 ze(Z)
First Law efficiency (COP)	4.528	4.7	- 3.8298%	4.463	4.68
Total compressor work “kW”	46.38	44.62	3.944%	47.05	44.87

3.1 Thermodynamic performances at compressor efficiency =100%

Table-1(b) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor isentropic efficiency 100 % using different cooling loads (Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW) at same evaporators temperatures (T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3} at 263K and it was found that HFO refrigerants worked well. As compared to R 12, the thermodynamic energy and exergy performance are quite comparable at100% of compressor’s isentropic efficiency. Although CFC-12 is outdated refrigerants did not used now a day and HFC-134a started used which has (1300 to1400) global warming potential but not having chlorine content since 1990s. Now after 2020, HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-1(b) respectively.

It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India as comparing with CFC-12, HFO-refrigerants gives 3.5398% better energy performance with reducing 3.365% electric energy consumption. However as comparing with HFC-134a HFO-refrigerants gives 4.862% better energy performance in terms of COP with reducing 4.4268% electric energy consumption. The lowest performances were observed by using R1234yf with reduction of 3.83 % of COP with 3.996% increment of electrical energy consumption as compared with HFC-134a. It can be seen from table-1(b) that HFO and HCFO and their blends are good replacements of HFC-134a due to similar thermodynamic performances with the variation of 4.5%. Similarly, the exergy destruction in compressor in also 5.3432% more using HFO-1234ze(Z) than HFC-134a, In the throttling valves the total exergy destruction is 24.545% less than using HFC-134a.Similarly exergy destruction from in evaporator using HFO-1234ze(Z) is 5.245% higher than using HFC-134a. Therefore, HFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipment’s in the coming future.

Table-1(b): Thermodynamic energy-exergy performances of modified VCRS using multiple evaporators and multiple expansion valves for 100% compressor efficiency using Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3}= 263K, compressor efficiency=100%,

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.528	4.68	4.606	4.647	4.416	4.563	4.443	4.459	4.292	4.463
Exergetic Efficiency	0.507	0.524	0.516	0.5202	0.496	0.5108	0.497	0.4992	0.480	0.4996
Second law Effectiveness	0.603	0.623	0.613	0.6185	0.588	0.6073	0.591	0.5934	0.571	0.5939
Total compressor work“kW”	46.38	44.87	45.6	45.19	47.56	46.02	47.27	47.09	48.93	47.05
Total Condenser Exergy Destruction(%)	24.95	25.63	24.97	24.67	23.67	24.65	23.9	23.95	22.81	24.33
Total Exergy evaporator Destruction(%)	9.568	9.893	9.74	9.84	9.33	9.643	9.38	8.883	9.067	9.401
Total Valve- Exergy Destruction(%)	12.95	10.79	12.28	11.51	15.44	13.17	14.89	15.19	17.56	14.3
Total Exergy compressor Destruction(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total System Exergy Destruction(%)	47.46	46.31	47.0	46.66	48.44	47.46	48.17	48.03	49.44	48.03
Rational Efficiency(%)	52.54	53.69	53.0	53.34	51.56	52.54	51.83	51.97	50.56	51.97

3.2 Thermodynamic performances at compressor efficiency =75%

Table-1(c) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor isentropic efficiency 75% using Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_3}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3}= 263K, Table-1(b) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor isentropic efficiency 100 % using different cooling loads (Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_3}=105 kW)at same evaporators temperatures (T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3} at 263K and it was found that HFO refrigerants worked well. As compared to R 12, the thermodynamic energy and exergy performance are quite comparable at100% of compressor’s isentropic efficiency. Although CFC-12 is outdated refrigerants did not used now a day and HFC-134a started used which has (1300 to1400) global warming potential but not having chlorine content since 1990s. Now after 2020, HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-1(b) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India

As comparing with HFC-134a , HFO-1234ze(Z) refrigerants gives 5.279% better energy (COP) performance However with reducing 3.9845% electric energy consumption by using HFO-1234ze(Z) . The similar performance was observed by using R1234yf . It can be seen from table-1(b) that HFO and HCFO and their blends are good replacements of HFC-134a due to similar thermodynamic performances with the variation range of 4.5% Similarly by using HFO-1234yf the exergy destruction in compressor in also 4.48% less than HFC-134a, In the throttling valves the total exergy destruction is 5.877% less than using HFC-134a.Similarly exergy destruction from in evaporator using HFO-1234ze(Z) is 5.839% lower than using HFC-134a. Similarly, by using HFO-1234ze(Z) the exergy destruction in compressor is same as compared with HFC-134a, In the throttling valves the total exergy destruction is 19.18% less than using HFC-134a. Similarly, exergy destruction from in evaporator using HFO-1234ze(Z) is 11.3378% higher than using HFC-134a. Therefore, HFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipments in the coming future.

3.3 Thermal performances of modified VCRS using multiple evaporators with single compressor and individual expansion valves with back pressure valves

Table-2(a) shows the validation of thermodynamic energy performances of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency 100% for a cooling loads on evaporators (Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= *278*K, T_{Eva3}= 283K) and it was observed that developed model of this system is well matching results are under the range of 10% . To see the performance with respect to R12, the thermodynamic performance using HFC-134a and HFO-1234ze(Z) are also shown in table-2(a) respectively it clearly shows that thermodynamic energy performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency 100% for a cooling loads on evaporators (Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= *278*K, T_{Eva3}= 283K) is higher than HFC-134a and CFC-12 respectively.

Table-1(c): Thermodynamic energy-exergy performances of modified VCRS using multiple evaporators and multiple expansion valves using single compressor isentropic efficiency 75% using Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3}= 263K, compressor efficiency=75%,

Performance Parameters	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First law (Energy)Efficiency(COP)	3.51	3.454	3.485	3.312	3.423	3.332	3.219	3.347	3.334
Compressor work (Exergy of fuel) 'kW'	59.82	60.79	60.25	63.41	61.36	63.02	65.24	62.74	62.79
Exergy Destruction Ratio (EDR)	1.52	1.558	1.538	1.654	1.582	1.639	1.723	1.629	1.63
Exergetic Efficiency	0.3929	0.3867	0.3902	0.3707	0.3831	0.373	0.3603	0.3747	0.3744
Total compressor Exergy Destruction(%)	23.0	23.6	23.38	23.55	23.8	23.34	23.69	22.96	23.62
Total Condenser Exergy Destruction(%)	21.22	20.13	20.60	19.2	19.69	19.59	19.35	18.42	20.29
Total Exergy evaporators Destruction(%)	7.42	7.305	7.38	6.998	7.233	7.036	6.801	7.051	6.662
Total Valves Exergy Destruction(%)	8.09	9.213	8.635	11.58	9.876	11.16	13.17	10.73	11.4
Total Exergy compressor Destruction(%)	59.73	60.25	60.0	61.33	60.6	61.13	62.08	61.08	61.02
Rational Efficiency(%)	40.27	39.75	40.0	38.67	38.4	38.87	37.92	38.92	38.98

Table-2(a): Validation of Developed thermodynamic model for modified VCRS using multiple evaporators with single compressor (isentropic compressor efficiency of 100%) and individual expansion valves with back pressure valves (at different evaporators loads (Q_{EVA_1}=105 kW at T_{Eva1}= 263K,, Q_{EVA_2}=70 kW at T_{Eva2}= 278K, Q_{EVA_3}=35 kW at T_{Eva3}= 283K)

Performance Parameters	R-12 Model	R-12[7]	% difference	R134a	R-1234 ze(Z)
First Law efficiency (COP)	4.171	4.521	-7.742%	4.068	4.366
Total compressor work "kW"	50.35	46.44	8.429%	51.63	48.1

3.4 *Effect of HFO refrigerants on the thermodynamic performances of multiple evaporators and individual expansion valves for 100% compressor efficiency using Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA3}=35 kW, at T_{Eva1}= 263K, T_{Eva1}= 263K, T_{Eva3}= 263K at compressor efficiency =100%*

Table-2(b) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using individual evaporators and multiple expansion valves using single compressor isentropic efficiency 100 % using different cooling loads (Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW) at different evaporators temperatures (T_{Eva1}= 263K, T_{Eva1}= 278K, T_{Eva3} at 283K and it was found that HFO refrigerants worked well. As compared to R 134a since used from 1990s, the thermodynamic energy performance (COP) using HFO-1234ze(Z) is quite comparable at100% of compressor's isentropic efficiency is 7.3255%. with reduced electrical energy consumption around 6.837% with compared with R134a, because HFC-134a has global warming potential(GWP) in the range of (1300 to1400) but not having chlorine content which harmed ozone depletion due to its zero ODP. Now after 2020, other HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-2(b) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India as comparing with HFC-134a, HFO-1224yd(Z) refrigerants gives 5.556% better energy performance with reducing 5.8276% electric energy consumption. However as comparing with HFC-134a Similarly HFO-1336mzz(Z)refrigerant gives 4.7689% better energy performance in terms of COP with reducing 4.552% electric energy consumption However by using R1233zd(E) in this system, the thermodynamic energy efficiency (COP) is 6.834% higher with reducing 6.411% electric energy consumption, Although R1225ye(Z) and R1243zf gives similar thermodynamic performances as compared to HFC-134a. The lowest performances were observed by using R1234yf with reduction of 4.7935 % of COP with 5.0165% increment of electrical energy consumption as compared with HFC-134a. It can be seen from table-2(b) that HFO and HCFO and their blends are good replacements of HFC-134a due to similar thermodynamic performances with the variation of 4.5% Similarly the exergy destruction in compressor in also 5.0295% more using HFO-1234ze(Z) than HFC-134a, In the throttling valves the total exergy destruction is 26.21% less than using HFC-134a.Similarly exergy destruction from in evaporator using HFO-1234ze(Z) is 32.209% higher than using HFC-134a. Therefore, HFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipments in the coming future.

3.5 *Actual thermodynamic performances of multiple evaporators and individual expansion valves for 75% compressor efficiency*

Table-2(c) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and individual expansion valves using single compressor isentropic efficiency

75% using different cooling loads (Q_{EVA_1}=35 kW, at (T_{Eva1}) = 263K, Q_{EVA_2}=70 kW at evaporator temperature (T_{Eva2})= 278K, and Q_{EVA_3}=105 kW at evaporator temperature (T_{Eva3}) = 283K), it was found that HFC refrigerant worked well.

Now after 2020, HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-2(c) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India due to following reasons

Table-2(b): Thermodynamic energy-exergy performances of modified VCRS using multiple evaporators and individual expansion valves for 100% compressor efficiency using Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= 278K, T_{Eva3}= 283K, compressor efficiency=100%,

Performance Parameters	R-12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First law (Energy)Efficiency(COP)	4.171	4.366	4.294	4.346	4.025	4.262	4.054	4.081	3.873	4.068
Compressor work (Exergy of fuel) 'kW'	50.35	48.1	48.9	48.32	52.17	49.28	51.8	51.46	54.22	51.63
Exergy Destruction Ratio (EDR)	2.475	2.628	2.883	2.855	2.869	3.118	2.762	2.878	3.051	2.617
Exergetic Efficiency	0.2968	0.2690	0.2543	0.2528	0.2726	0.2409	0.2796	0.2696	0.2684	0.2901
Total Condenser Exergy Destruction(%)	26.11	26.73	25.74	26.24	24.51	25.3	24.85	24.76	23.63	25.45
Total Exergy evaporators Destruction(%)	11.97	15.17	15.01	15.74	11.66	15.58	11.68	11.9	10.4	11.43
Total Valves Exergy Destruction(%)	35.36	28.8	32.57	30.7	42.05	34.22	40.71	40.94	47.83	39.03
Total Exergy compressor Destructio(%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total system Exergy Destruction(%)	73.44	70.71	73.33	72.18	78.22	75.1	77.24	77.59	81.86	75.92
Rational Efficiency(%)	26.54	29.29	26.67	27.82	21.78	24.9	22.76	22.44	18.14	24.08

As comparing with HFC-134a, HFO-1234ze(Z) refrigerants gives 7.347% better energy (COP) performance However with reducing 6.825% electric energy consumption by using HFO-1234ze(Z). The similar performance (slightly lower) was observed by using R1243zf.

However, R1224yd(Z) reduced 5.2135% electrical energy consumption with increased first law energy performance of 2.558%, R1233zd(E) reduced 6.361% electrical energy consumption with increased first law energy performance of 6.822%, R1336mzz(Z) reduced 4.415% electrical energy consumption with increased first law energy performance of 4.624%, However R1225ye(Z) increased 1.1327% electrical energy consumption with reduced first law energy performance of 1.151%,

The lowest thermodynamic performance was observed by using R1234yf which is 4.887% Lower than using R134a which increased 5.1409% electrical energy consumption in the modified vapour compression refrigeration system.

It can be seen from table-1(b) that HFO and HCFO and their blends are good replacements of HFC-134a due to similar thermodynamic performances Therefore HFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipments in the coming future. Table-2(c) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and individual expansion valves using single compressor isentropic efficiency 75% using different cooling loads (Q_{EVA_1}=105 kW, at (T_{Eva1}) = 263K, Q_{EVA_2}=70 kW at evaporator temperature (T_{Eva2}) = 278K, and Q_{EVA_3}=35 kW at evaporator temperature (T_{Eva3}) = 283K), it was found that HFC refrigerant worked well. Now after 2020, HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-2(d) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India due to following reasons.

As comparing with HFC-134a, HFO-1234ze(Z) refrigerants gives 7.309% better energy (COP) performance However with reducing 6.827% electric energy consumption by using HFO-1234ze(Z). The similar performance means slightly lower (.0.3196% higher electrical energy consumption along with 0.3278% lower first law energy efficiency (COP)) by using R1243zf

However R1224yd(Z) reduced 5.2876% electrical energy consumption with increased first law energy performance of 5.572.%, R1233zd(E) reduced 6.421% electrical energy consumption with increased first law energy performance of 6.850.%, R1336mzz(Z) reduced 4.415% electrical energy consumption with increased first law energy performance of 4.7525.%, However R1225ye(Z) increased 1.1327% electrical energy consumption with reduced first law energy performance of 1.048.%,The similar thermodynamic performance was observed by using R1234yf which is 4.7853% Lower than using R134a which increased 5.026% electrical energy consumption in the modified vapour compression refrigeration system. It can be seen from table-2(d) that HFO and HCFO and their blends are good replacements of HFC-134a due to similar thermodynamic performances Similarly the percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75% ,isentropic efficiency using individual expansion valves and back pressure valves ($Q_{\_Eva\_1}$=35 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70"kW, $T_{\_EVA\_1}$=278K,$Q_{\_Eva\_3}$=105"kW,$T_{\_EVA\_1}$=283K,). and the percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using individual expansion valves and back pressure 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,) are also be shown in Table-2(e) and table-2(f) respectively. .

Therefore HFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipment in the coming future.

Table-2(c)Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor, individual expansion valves and back pressure valves ($Q_{\_Eva\_1}$=35 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70"kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW,$T_{\_EVA\_1}$=283K)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.127	3.273	3.127	3.257	3.015	3.191	3.038	3.057	2.90	3.049
Compressor work(Exergy of fuel) "kW"	67.16	64.16	65.27	64.48	69.64	65.82	69.13	68.7	72.4	68.87
Exergy Destruction Ratio (EDR)	3.378	3.552	3.853	3.819	3.828	4.114	3.699	3.839	4.041	3.549
Exergetic Efficiency	0.2291	0.2102	0.1993	0.1986	0.211	0.1895	0.2163	0.2093	0.2073	0.2238
Exergy of product"kW"	15.38	13.49	13.01	12.8	14.7	12.47	14.95	14.38	15.01	15.41
Total Exergy compressor Destruction	22.13	22.16	22.72	22.41	22.84	23.12	22.65	22.84	23.03	22.30
Total Condenser Exergy Destruction(%)	22.39	22.82	21.53	22.21	20.49	20.81	20.99	20.67	19.64	21.73
Total Exergy evaporator Destruction(%)	6.267	8.028	8.061	8.507	5.865	8.282	5.813	6.019	5.136	6.038
Total Valves Exergy Destruction(%)	26.59	21.66	24.5	22.71	31.63	25.74	30.62	30.8	35.98	29.35
Total system Exergy Destruction(%)	77.38	74.68	76.8	75.84	80.82	77.95	80.01	80.33	83.7	79.42
Rational efficiency(%)	22.62	25.32	23.19	24.16	19.16	22.05	19.99	19.67	16.21	20.58

Table-2(d) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor, individual expansion valves and back pressure 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,).

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.128	3.274	3.221	3.26	3.019	3.196	3.041	3.06	2.905	3.051
Compressor work(Exergy of fuel) "kW"	67.14	64.14	65.2	64.42	69.56	65.7	69.06	68.62	72.3	68.84
Exergy Destruction Ratio (EDR)	3.598	3.867	4.194	4.173	4.091	4.502	3.955	4.114	4.293	3.766
Exergetic Efficiency	0.2226	0.2018	0.1908	0.1896	0.2022	0.1806	0.2097	0.2022	0.2013	0.2176
Exergy of product "kW"	14.94	14.94	12.94	12.44	13.88	11.87	14.44	13.88	14.55	14.98
Total Exergy compressor Destruction(%)	22.09	22.12	22.67	22.35	22.80	23.06	22.61	22.8	22.99	22.27
Total Condenser Exergy Destruction(%)	22.49	22.93	21.63	22.33	20.58	20.91	21.03	20.77	19.73	21.82
Total Exergy evaporator Destruction(%)	8.975	11.38	11.26	11.8	8.744	11.69	8.759	8.922	7.803	21.82
Total Valves Exergy Destruction(%)	26.52	21.6	24.43	22.65	31.54	25.67	30.53	30.7	35.87	29.28
Total system Exergy Destruction(%)	80.08	78.03	80.0	79.13	83.66	81.33	82.93	83.2	86.4	81.94
Rational Efficiency(%)	19.92	21.97	20.0	20.87	16.34	18.67	17.07	0.1680	13.6	18.06

Table-2(e) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using individual expansion valves and back pressure valves ($Q_{\_Eva\_1}$=35 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70"kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW, $T_{\_EVA\_1}$=283K,).

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.127	3.273	3.221	3.26	3.257	3.196	3.041	3.06	2.905	3.051
Effectiveness_Second	0.4626	0.4521	0.4364	0.4383	0.4335	0.4239	0.4426	0.4363	0.4235	0.4516
Second Law efficiency	0.2906	0.2736	0.2613	0.2612	0.2701	0.2507	0.2758	0.2689	0.2642	0.2838
Rational efficiency	0.2262	0.2532	0.2319	0.2416	0.1918	0.2205	0.1999	0.1967	0.1621	0.2058
Total Exergy compressor Destruction	28.6	29.68	29.58	29.55	28.25	29.66	28.31	28.44	27.49	27.36

Total Condenser Exergy Destruction(%)	28.94	30.56	28.03	29.29	25.35	26.69	26.16	25.73	23.44	7.602
Total Exergy evaporator Destruction(%)	8.099	10.75	10.49	11.22	7.257	10.62	7.265	7.493	6.13	11.22
Total Valves Exergy Destruction(%)	34.36	29.01	31.9	29.25	39.14	33.02	38.26	38.34	42.94	36.96
Rational efficiency(%)	22.62	25.32	23.19	24.16	19.16	22.05	19.99	19.67	16.21	20.58

Table-2(f) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using individual expansion valves and back pressure 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)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.128	3.274	3.221	3.26	3.019	3.196	3.041	3.06	2.905	3.051
Total Exergy compressor Destruction(%)	27.59	28.34	38.34	28.25	27.25	28.36	27.26	27.41	26.61	27.18
Total Condenser Exergy Destruction(%)	28.09	29.39	27.04	28.22	24.60	25.71	25.36	24.96	22.84	26.63
Total Exergy evaporator Destruction(%)	11.21	14.58	14.08	14.92	10.45	14.37	10.56	10.2	9.032	10.46
Rational Efficiency(%)	19.92	21.97	20.0	20.87	16.34	18.67	17.07	0.1680	13.6	18.06
Second law efficiency	0.4556	0.4430	0.4273	0.4287	0.4285	0.4146	0.4357	0.4289	0.4172	0.4449
Effectiveness second	0.2839	0.2628	0.2525	0.2520	0.2633	0.2416	0.2690	0.2616	0.2580	0.2774

3.6 Performances of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency

Table-3(a) shows the validation of thermodynamic energy performances of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency 100% for a cooling loads on evaporators (Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= *278*K, T_{Eva3}= 283K) and it was observed that developed model of this system is well matching results are under the range of 10%. To see the performance with respect to R12, the thermodynamic performance using HFC-134a and HFO-1234ze(Z) are also shown in table-2(a) respectively it clearly shows that thermodynamic energy performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor of isentropic efficiency 100% for a cooling loads on evaporators (Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA_1}=105 kW, at T_{Eva1}= 263K, T_{Eva1}= *278*K, T_{Eva3}= 283K) is higher than HFC-134a and CFC-12 respectively.

Table-3(a): Validation of Developed thermodynamic model for modified VCRS using multiple evaporators using single compressor efficiency=100%, and also using multiple expansion valves with back pressure valves at cooling loads of evaporators (Q_{EVA_1}=105 kW at evaporator temperature T_{Eva1}= 263K, , Q_{EVA_2}=70 kW at evaporator temperature T_{Eva2}= 278K,, Q_{EVA_3}=35 Kw at evaporator temperature T_{Eva3}= 283K,),

Performance Parameters	R-12 Model	R12 Ref [7]	% difference	R134a	R-1234 ze(Z)
First Law efficiency (COP)	4.530	4.50	%	4.473	4.689
Total compressor work "kW"	46.36	46.7	%	46.95	44.79

Table-3(b) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and multiple expansion valves using single compressor isentropic efficiency 100 % using different cooling loads (Q_{EVA_1}=105 kW, Q_{EVA_2}=70 kW, Q_{EVA_3}=35 kW) at different evaporators temperatures (T_{Eva1}= 263K, T_{Eva1}= 278K, T_{Eva3} at 283K and it was found that HFO refrigerants worked well. As compared to R 134a since used from 1990s, the thermodynamic energy performance (COP) using HFO-1234ze(Z) is quite comparable at100% of compressor's isentropic efficiency is higher with reduced electrical energy consumption with compared with R134a, because HFC-134a has global warming potential(GWP) in the range of (1300 to1400) but not having chlorine content which harmed ozone depletion due to its zero ODP. Now after 2020, other HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy –exergy analysis of modified vapour compression refrigeration is shown in Table-3(b) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India as comparing with HFC-134a, HFO-1224yd(Z) refrigerants gives slightly lower energy performance in terms of COP with reduced electric energy consumption as compared with R1234ze(Z) but higher. Thermodynamic energy-exergy performances as compared with HFC-134a Similarly HFO-1336mzz(Z)refrigerant and HCFO-1233zd(E) gives better energy performance in terms of COP with reduced electric energy consumption as compared with HFC-134a.Although R1225ye(Z) and R1243zf gives similar thermodynamic performances as compared to HFC-134a. The lowest performances were observed by using R1234yf with reduction of of COP with increment of electrical energy consumption as compared with HFC-134a. It can be seen from table-3(b) that HFO and HCFO are good replacements of HFC-134a due to similar thermodynamic performances as shown in Table-3(c) to Table 3(f) respectively at different evaporator loads at different evaporator temperatures respectively. Similarly table-4(a) to table-4(e) show the percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of ideal compressor working conditions (i.e. at 100% of isentropic compressor efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures and it was found that maximum exergy destruction occurred in the condenser and lowest total exergy destruction was found in all throttle valves. similarly, total exergy destruction in all evaporators around 50% less than condenser more than double than the all expansion valves Therefore HFO and HCFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipment in the coming future

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Table-3 (b) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor (100% isentropic efficiency), multiple expansion valves and back pressure 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,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.53	4.689	4.646	4.675	4.457	4.619	4.471	4.504	4.348	4.473
Compressor work(Exergy of fuel) "kW"	46.36	44.79	45.2	44.92	47.11	45.46	46.97	46.63	48.29	46.95
System Exergy Destruction Ratio (EDR)	1.054	1.157	1.229	1.232	1.149	1.304	1.117	1.152	1.167	1.076
Exergetic Efficiency	0.3820	0.3672	0.3530	0.3540	0.3606	0.3406	0.3669	0.3603	0.3539	0.3752
$Exergy_{\_Fuel}$ "kW"	46.36	44.79	45.2	44.92	47.11	45.46	46.97	46.63	48.29	46.95
$Exergy_{\_Product}$ "kW"	17.71	16.45	15.96	15.91	16.99	15.58	17.23	16.8	17.09	17.61
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	25.64	26.24	25.34	25.77	24.14	25.01	24.46	24.38	23.29	25.02
% Total Exergy evaporator Destruction	10.08	12.9	14.27	14.31	12.13	15.48	11.48	12.17	12.06	10.52
% Total Valves Exergy Destruction	4.548	3.364	3.772	3.521	5.15	3.932	5.055	4.96	5.957	4.851
% Total system Exergy Destruction	40.27	42.50	43.39.	43.60	41.41	44.42	40.99	41.52	41.3	40.39
% Rational Efficiency	59.73	57.5	56.61	56.4	58.59	55.58	59.01	54.48	58.7	59.61

Table-3 (c) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor (of 100% isentropic efficiency), multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=105 "kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 "kW, $T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Compressor work(Exergy of fuel) "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
System Exergy Destruction Ratio (EDR)	1.052	1.254	1.343	1.367	1.157	1.447	1.12	1.181	1.153	1.064
Exergetic Efficiency	0.3394	0.3122	0.2998	0.2962	0.3177	0.2840	0.3243	0.3146	0.3148	0.3344
$Exergy_{\_Fuel}$ "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
$Exergy_{\_Product}$ "kW"	15.73	13.97	13.41	13.27	14.92	12.84	15.2	14.62	15.13	15.68
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	25.97	26.57	25.62	26.09	24.40	25.2	24.74	24.65	23.54	25.33
% Total Exergy evaporator Destruction	5.604	9.523	10.95	11.22	7.679	12.35	6.998	7.998	7.327	5.8477
% Total Valves Exergy Destruction	4.122	3.052	3.425	3.189	4.688	3.564	4.599	4.515	5.427	4.411
% Total system Exergy Destruction	35.7	39.15	39.99	40.50	36.77	41.11	36.34	37.16	36.3	35.59
% Rational Efficiency	64.33	60.85	60.01	59.5	63.23	58.89	63.66	62.84	63.7	64.41

Table-3(d) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor (of 100% isentropic efficiency), multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=35 "kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW, $T_{\_EVA\_1}$=283K)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Compressor work(Exergy of fuel) "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
System Exergy Destruction Ratio (EDR)	1.052	1.254	1.343	1.367	1.157	1.447	1.12	1.181	1.153	1.064
Exergetic Efficiency	0.3394	0.3122	0.2998	0.2962	0.3177	0.2840	0.3243	0.3146	0.3148	0.3344
$Exergy_{\_Fuel}$ "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
$Exergy_{\_Product}$ "kW"	15.73	13.97	13.41	13.27	14.92	12.84	15.2	14.62	15.13	15.68
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	25.97	26.57	25.62	26.09	24.40	25.2	24.74	24.65	23.54	25.33
% Total Exergy evaporator Destruction	5.604	9.523	10.95	11.22	7.679	12.35	6.998	7.998	7.327	5.8477
% Total Valves Exergy Destruction	4.122	3.052	3.425	3.189	4.688	3.564	4.599	4.515	5.427	4.411
% Total system Exergy Destruction	35.7	39.15	39.99	40.50	36.77	41.11	36.34	37.16	36.3	35.59
% Rational Efficiency	64.33	60.85	60.01	59.5	63.23	58.89	63.66	62.84	63.7	64.41

Table-3 (e) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor (of 100% isentropic efficiency), multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=105 "kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 "kW, $T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Compressor work(Exergy of fuel) "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
System Exergy Destruction Ratio (EDR)	1.052	1.254	1.343	1.367	1.157	1.447	1.12	1.181	1.153	1.064
Exergetic Efficiency	0.3394	0.3122	0.2998	0.2962	0.3177	0.2840	0.3243	0.3146	0.3148	0.3344
$Exergy_{\_Fuel}$ "kW"	46.34	44.75	45.05	44.82	46.96	45.19	46.86	46.46	48.08	46.9
$Exergy_{\_Product}$ "kW"	15.73	13.97	13.41	13.27	14.92	12.84	15.2	14.62	15.13	15.68
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	25.97	26.57	25.62	26.09	24.40	25.2	24.74	24.65	23.54	25.33
% Total Exergy evaporator Destruction	5.604	9.523	10.95	11.22	7.679	12.35	6.998	7.998	7.327	5.8477
% Total Valves Exergy Destruction	4.122	3.052	3.425	3.189	4.688	3.564	4.599	4.515	5.427	4.411
% Total system Exergy Destruction	35.7	39.15	39.99	40.50	36.77	41.11	36.34	37.16	36.3	35.59
% Rational Efficiency	64.33	60.85	60.01	59.5	63.23	58.89	63.66	62.84	63.7	64.41

Table-3 (f) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor (of 100% isentropic efficiency) , multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=35 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=70 "kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.533	4.696	4.672	4.692	4.482	4.664	4.489	4.53	4.38	4.48
Compressor work(Exergy of fuel) "kW"	46.33	44.72	44.95	44.75	46.86	45.03	46.79	46.36	47.94	46.87
System Exergy Destruction Ratio (EDR)	1.067	1.347	1.456	1.499	1.186	1.592	1.143	1.227	1.168	1.075
Exergetic Efficiency	0.3132	0.2787	0.2639	0.2607	0.2911	0.249	0.298	0.2862	0.2902	0.3091
$Exergy_{\_Fuel}$ "kW"	46.33	44.72	44.95	44.75	46.86	45.03	46.79	46.36	47.94	46.87
$Exergy_{\_Product}$ "kW"	14.51	12.46	11.86	11.67	13.64	11.21	13.94	13.27	13.92	14.49
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	26.19	26.81	25.82	26.93	24.6	25.37	24.94	24.85	23.73	25.55
% Total Exergy evaporator Destruction	3.42	7.926	9.44	9.833	5.605	11.0	4.877	6.10	5.152	3.613
% Total Valves Exergy Destruction	3.807	2.806	3.149	2.924	4.339	3.267	4.258	4.175	5.031	4.082
% Total system Exergy Destruction	33.42	37.54	38.41	39.08	34.54	39.64	34.08	35.12	33.91	33.24
% Rational Efficiency	66.58	62.46	61.59	60.92	65.46	60.36	65.92	64.88	66.09	66.76

Table-4(a) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=105 "kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.53	4.689	4.646	4.675	4.457	4.619	4.471	4.504	4.348	4.473
Second law effectiveness	0.473	0.4604	0.4449	0.4464	0.4496	0.4316	0.4563	0.4501	0.4408	0.4650
Second law efficiency	0.7248	0.7196	0.7012	0.7042	0.6966	0.6859	0.7044	0.6994	0.6819	0.7136
Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	63.69	61.73	58.41	59.1	58.28	56.29	59.66	58.73	56.38	61.95
% Total Exergy evaporator Destruction	25.02	30.35	32.89	32.82	29.29	34.35	28.0	29.32	29.20	26.04
% Total Valves Exergy Destruction	11.29	7.917	8.693	8.076	12.44	8.851	12.33	11.95	14.42	12.01
% Rational Efficiency	59.73	57.5	56.61	56.4	58.59	55.58	59.01	58.45	58.7	59.61

Table-4(b) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=105 "kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Second law effectiveness	0.4289	0.4034	0.3879	0.3866	0.4054	0.3734	0.4124	0.4030	0.4005	0.4227
Second law efficiency	0.6786	0.6599	0.6421	0.6420	0.6509	0.6261	0.6587	0.6508	0.6406	0.6694
%Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	72.75	67.88	64.06	64.43	66.37	61.3	68.08	66.33	64.86	71.18
% Total Exergy evaporator Destruction	15.7	24.33	27.38	27.70	20.88	30.03	19.26	21.52	20.19	16.43
% Total Valves Exergy Destruction	11.55	7.795	8.565	7.874	12.75	8.670	12.66	12.15	14.95	12.40

Table-4(c) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=35 "kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Second law effectiveness	0.4289	0.4034	0.3879	0.3866	0.4054	0.3734	0.4124	0.4030	0.4005	0.4227
Second law efficiency	0.6786	0.6599	0.6421	0.6420	0.6509	0.6261	0.6587	0.6508	0.6406	0.6694
%Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	72.75	67.88	64.06	64.43	66.37	61.3	68.08	66.33	64.86	71.18
% Total Exergy evaporator Destruction	15.7	24.33	27.38	27.70	20.88	30.03	19.26	21.52	20.19	16.43
% Total Valves Exergy Destruction	11.55	7.795	8.565	7.874	12.75	8.670	12.66	12.15	14.95	12.40

Table-4(d) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=105 "kW,$T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=35 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.532	4.693	4.661	4.686	4.472	4.647	4.482	4.52	4.368	4.478
Second law effectiveness	0.4289	0.4034	0.3879	0.3866	0.4054	0.3734	0.4124	0.4030	0.4005	0.4227
Second law efficiency	0.6786	0.6599	0.6421	0.6420	0.6509	0.6261	0.6587	0.6508	0.6406	0.6694
% Total Condenser Exergy Destruction	75.75	67.88	64.06	64.43	66.37	61.3	68.08	66.33	64.86	71.18
% Total Exergy evaporator Destruction	15.7	24.33	27.38	27.70	20.88	30.03	19.26	21.52	20.19	16.43
% Total Valves Exergy Destruction	11.55	7.795	8.565	7.874	12.75	8.670	12.66	12.15	14.95	12.40

Table-4(e) Percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of75%, isentropic efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	4.533	4.696	4.672	4.692	4.482	4.664	4.489	4.53	4.38	4.48
Second law effectiveness	0.4017	0.3687	0.3530	0.350	0.3780	0.3374	0.3852	0.3736	0.3753	0.3966
Second law efficiency	0.6501	0.6236	0.6059	0.6038	0.6226	0.5892	0.6306	0.6205	0.6147	0.6420
%Total Exergy compressor Destruction	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Total Condenser Exergy Destruction	78.37	71.42	67.23	67.36	71.21	64.01	73.19	70.75	69.97	76.85
% Total Exergy evaporator Destruction	10.23	21.11	24.58	25.16	16.23	27.75	14.31	17.37	15.19	10.87
% Total Valves Exergy Destruction	11.39	7.473	8.199	7.481	12.56	8.242	12.49	11.89	14.84	12.28
Second Law Effectiveness	0.6501	0.6246	0.6059	0.6038	0.6226	0.5892	0.6306	0.6205	0.6147	0.642
Effectiveness Second	0.4017	0.3687	0.353	0.350	0.378	0.3374	0.3852	0.3736	0.3753	0.3966

3.7 Actual Thermodynamic energy-exergy performances of modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using different evaporators cooling load at different evaporator temperatures

Table-5(a) shows the effect of ultra-low GWP ecofriendly HFO&HCFO refrigerants on thermodynamic performance of modified VCRS using multiple evaporators and individual expansion valves using single compressor isentropic efficiency 75% using different cooling loads at evaporator temperatures (it was found that HFC refrigerant worked well.

Now after 2020, HFO refrigerants are started using by several companies in the USA and Europe, which has around zero ozone depletion potential and ultra-low global warming potential. The thermodynamic performances using energy – exergy analysis of modified vapour compression refrigeration is shown in Table-5(c) respectively. It was found that HFO refrigerants are the excellent replacement for HFC refrigerants in the coming future after 2025 in India due to following reasons. As comparing with HFC-134a, HFO- refrigerants gives better (R1234ze(Z) refrigerants (around 4.8%), R1224yd(Z) (around 3.845%), R1233zd(E) (around 4.5%) and R1336mzz(Z) (around 3.28%) first law performance. However, R1243zf give similar (nearly same) first law performance (COP) as compared with HFC-134a. Similarly, R1234ze(E) and R1225ye(Z) also gives similar performance with minor variations (i.e. R-1234ze(E) is 0.6855% higher and R-1225ye(Z) is 0.358% lower thermodynamic performances. However lowest performance was observed by using R1234yf (around 2.8% to 4.5%) as compared to HFC-134a. The percentage exergy destruction in components based on total compressor work (i.e. exergy of fuel) of modified VCRS using multiple evaporators at the different temperatures with single compressor of ideal compressor working conditions (i.e. at 75% of isentropic compressor efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures using ultra-low GWP ecofriendly HFO&HCFO refrigerants as compared with HFC-134a refrigerant and it was found that maximum exergy destruction occurred in the compressors and slightly lower in the condenser of the system. The lowest percentage of exergy destruction in components based on total exergy of the system is found in the throttle valves. However exergy destruction in the evaporators is significantly higher than the exergy destruction in the throttle valves The lowest total exergy destruction was found in all throttle valves Similarly table-5(f) to table-(j) show the percentage exergy destruction in components based on total exergy destruction of modified VCRS using multiple evaporators at the different temperatures with single compressor of ideal compressor working conditions (i.e. at 75% of isentropic compressor efficiency using multiple expansion valves and back pressure valves using different evaporator loads at different evaporators temperatures using ultra-low GWP ecofriendly HFO&HCFO refrigerants as compared with HFC-134a refrigerant and it was found that maximum exergy destruction occurred in the compressors and slightly lower in the condenser of the system. The lowest percentage of exergy destruction in components based on total exergy of the system is found in the throttle valves. However, exergy destruction in the evaporators is significantly higher than the exergy destruction in the throttle valves The lowest total exergy destruction was found in all throttle valves. Therefore, HFO and HCFO refrigerants are promising future for replacing CFC&HFC refrigerants in the refrigeration and air conditioning equipments in the coming future

Table-5(a) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure 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,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.398	3.516	3.484	3.506	3.343	3.465	3.353	3.378	3.261	3.355
Compressor work(Exergy of fuel) "kW"	61.81	59.72	60.27	59.89	62.82	60.61	62.62	62.17	64.39	62.6
Exergy Destruction Ratio (EDR)	1.927	2.065	2.173	2.173	2.073	2.283	2.026	2.078	2.109	1.965
Exergetic Efficiency	0.2865	0.2754	0.2648	0.2655	0.2704	0.2555	0.2752	0.2702	0.2655	0.2814
$Exergy_{\_Fuel}$ "kW"	61.81	59.72	60.27	59.89	62.82	60.61	62.62	62.17	64.39	62.6
$Exergy_{\_Product}$ "kW"	17.71	16.45	15.96	15.91	16.99	15.58	17.23	16.8	17.09	17.61
% Total Exergy compressor Destruction	22.32	22.41	22.99	22.69	23.03	23.4	22.83	23.05	23.2	22.48
% Total Condenser Exergy Destruction	21.91	22.26	21.02	21.64	20.08	20.35	20.51	20.23	19.26	21.28
% Total Exergy evaporator Destruction	7.557	9.673	10.7	10.73	9.097	11.61	8.609	9.131	9.044	7.887
% Total Valves Exergy Destruction	3.411	2.523	2.829	2.641	3.863	2.949	3.791	3.72	4.467	3.638
% Total Exergy Destruction	55.2	56.87	57.54	57.70	56.06	58.30	55.74	56.14	55.98	55.29
% Rational Efficiency	44.8	43.13	42.46	42.30	43.94	41.69	44.26	43.86	45.2	44.7

Table-5(b) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=105 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=35 "kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=70 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.398	3.516	3.484	3.506	3.343	3.465	3.353	3.378	3.261	3.355
Compressor work(Exergy of fuel) "kW"	61.81	59.72	60.27	59.89	62.82	60.61	62.62	62.17	64.39	62.6
Exergy Destruction Ratio (EDR)	1.927	2.065	2.173	2.173	2.073	2.283	2.026	2.078	2.109	1.965
Exergetic Efficiency	0.2865	0.2754	0.2648	0.2655	0.2704	0.2555	0.2752	0.2702	0.2655	0.2814
$Exergy_{\_Fuel}$ "kW"	61.81	59.72	60.27	59.89	62.82	60.61	62.62	62.17	64.39	62.6
$Exergy_{\_Product}$ "kW"	17.71	16.45	15.96	15.91	16.99	15.58	17.23	16.8	17.09	17.61
% Total Exergy compressor Destruction	22.32	22.41	22.99	22.69	23.03	23.4	22.83	23.05	23.2	22.48
% Total Condenser Exergy Destruction	21.91	22.26	21.02	21.64	20.08	20.35	20.51	20.23	19.26	21.28
% Total Exergy evaporator Destruction	7.557	9.673	10.7	10.73	9.097	11.61	8.609	9.131	9.044	7.887
% Total Valves Exergy Destruction	3.411	2.523	2.829	2.641	3.863	2.949	3.791	3.72	4.467	3.638
% Total Exergy Destruction	55.2	56.87	57.54	57.70	56.06	58.30	55.74	56.14	55.98	55.29
% Rational Efficiency	44.8	43.13	42.46	42.30	43.94	41.69	44.26	43.86	45.2	44.7

Table-5(c) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves ($Q_{\_Eva\_1}$=70 "kW, $T_{\_EVA\_1}$=263K, $Q_{\_Eva\_2}$=35 "kW, $T_{\_EVA\_1}$=278K, $Q_{\_Eva\_3}$=105 "kW,$T_{\_EVA\_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.399	3.52	3.514	3.496	3.354	3.485	3.361	3.390	3.276	3.358
Compressor work(Exergy of fuel) "kW"	61.79	59.67	59.76	60.07	62.61	60.26	62.48	61.95	64.11	62.53
Exergy Destruction Ratio (EDR)	2.034	2.322	2.493	2.462	2.206	2.621	2.148	2.241	2.212	2.061
Exergetic Efficiency	0.2546	0.2342	0.2221	0.2233	0.2383	0.2130	0.2432	0.2360	0.2361	0.2508
$Exergy_{\_Fuel}$ "kW"	61.79	59.67	59.76	60.07	62.61	60.26	62.48	61.95	64.11	62.53
$Exergy_{\_Product}$ "kW"	15.73	13.97	13.27	13.41	14.92	12.84	15.2	14.62	15.13	15.68
% Total Exergy compressor Destruction	22.16	22.2	22.45	22.76	22.85	23.16	22.67	22.86	23.04	22.33
% Total Condenser Exergy Destruction	22.32	22.73	22.12	21.45	20.45	20.75	20.89	20.82	19.62	21.67
% Total Exergy evaporator Destruction	4.203	7.142	8.413	8.21	5.759	9.259	5.248	5.998	5.495	4.385
% Total Valves Exergy Destruction	3.091	2.289	2.392	2.569	3.516	2.673	3.449	3.386	4.07	3.309
% Total Exergy Destruction	51.77	54.36	55.37	54.99	52.58	55.83	52.25	52.87	52.22	51.69
% Rational Efficiency	48.23	45.64	44.63	45.01	47.42	44.17	47.75	47.13	47.78	48.31

Table-5(d) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves (Q_{Eva_1}=70 "kW, T_{EVA_1}=263K, Q_{Eva_2}=105 "kW,T_{EVA_1}=278K, Q_{Eva_3}=35 "kW,T_{EVA_1}=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.399	3.52	3.514	3.496	3.354	3.485	3.361	3.390	3.276	3.358
Compressor work(Exergy of fuel) "kW"	61.79	59.67	59.76	60.07	62.61	60.26	62.48	61.95	64.11	62.53
Exergy Destruction Ratio (EDR)	2.034	2.322	2.493	2.462	2.206	2.621	2.148	2.241	2.212	2.061
Exergetic Efficiency	0.2546	0.2342	0.2221	0.2233	0.2383	0.2130	0.2432	0.2360	0.2361	0.2508
$Exergy_{Fuel}$ "kW"	61.79	59.67	59.76	60.07	62.61	60.26	62.48	61.95	64.11	62.53
$Exergy_{Product}$ "kW"	15.73	13.97	13.27	13.41	14.92	12.84	15.2	14.62	15.13	15.68
% Total Exergy compressor Destruction	22.16	22.2	22.45	22.76	22.85	23.16	22.67	22.86	23.04	22.33
% Total Condenser Exergy Destruction	22.32	22.73	22.12	21.45	20.45	20.75	20.89	20.82	19.62	21.67
% Total Exergy evaporator Destruction	4.203	7.142	8.413	8.21	5.759	9.259	5.248	5.998	5.495	4.385
% Total Valves Exergy Destruction	3.091	2.289	2.392	2.569	3.516	2.673	3.449	3.386	4.07	3.309
% Total Exergy Destruction	51.77	54.36	55.37	54.99	52.58	55.83	52.25	52.87	52.22	51.69
% Rational Efficiency	48.23	45.64	44.63	45.01	47.42	44.17	47.75	47.13	47.78	48.31

Table-5(e) Exergy Destruction in components of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves (Q_{Eva_1}=35 "kW, T_{EVA_1}=263K, Q_{Eva_2}=70 "kW,T_{EVA_1}=278K, Q_{Eva_3}=105 "kW,T_{EVA_1}=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.40	3.522	3.504	3.512	3.361	3.498	3.3366	3.398	3.285	3.360
Compressor work(Exergy of fuel) "kW"	61.77	59.69	59.94	59.67	62.48	60.03	62.38	61.81	63.92	62.49
Exergy Destruction Ratio (EDR)	2.132	2.543	2.719	2.778	2.331	2.930	2.262	2.392	2.317	2.154
Exergetic Efficiency	0.2349	0.2090	0.1979	0.1955	0.2184	0.1868	0.2235	0.2146	0.2177	0.2318
$Exergy_{Fuel}$ "kW"	61.77	59.69	59.94	59.67	62.48	60.03	62.38	61.81	63.92	62.49
$Exergy_{Product}$ "kW"	14.51	12.46	11.86	11.67	13.64	11.21	13.94	13.27	13.92	14.49
% Total Exergy compressor Destruction	22.05	22.08	22.62	22.3	22.75	23.0	22.57	22.75	22.94	22.23
% Total Condenser Exergy Destruction	22.59	23.03	21.75	22.4	20.7	21.03	21.14	20.89	19.86	21.93
% Total Exergy evaporator Destruction	2.565	5.945	7.08	7.374	4.204	8.248	3.658	4.575	3.864	2.71
% Total Valves Exergy Destruction	2.856	2.104	2.362	2.193	3.254	2.45	3.193	3.131	3.773	3.061
% Total Exergy Destruction	50.06	53.16	53.81	54.31	50.91	54.73	50.56	51.34	50.43	49.93.07
% Rational Efficiency	49.94	46.84	46.19	45.69	49.09	45.27	49.44	48.66	49.57	50.07

Table-5(f) Percentage exergy destruction in components with respect of total exergy destruction of *modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure 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,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.398	3.516	3.484	3.506	3.343	3.465	3.353	3.378	3.261	3.355
% Effectiveness _second	35.48	34.53	0.3337	0.3348	0.3372	0.3237	0.3423	0.3375	0.3306	0.3487
Second law efficiency	0.5436	0.5397	0.5259	0.5282	0.5224	0.5144	0.5283	0.5246	0.5114	0.5352
% Total Exergy compressor Destruction	40.44	39.41	39.95	39.32	41.07	40.13	40.96	41.07	41.45	40.67
% Total Condenser Exergy Destruction	39.69	39.15	36.54	37.5	35.81	34.9	36.79	36.04	34.41	38.49
% Total Exergy evaporator Destruction	13.69	17.01	18.60	18.60	16.23	19.91	15.5	16.27	16.16	14.26
% Total Valves Exergy Destruction	6.179	4.437	4.916	4.577	6.89	5.056	6.802	6.621	7.981	6.581
% Rational Efficiency	44.8	43.13	42.46	42.3	43.94	41.69	44.26	43.86	45.02	44.7

Table-5(g) Percentage exergy destruction in components with respect of total exergy destruction of *modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves(Q_$_{Eva_1}$=105 "kW, T_$_{EVA_1}$=263K, Q_$_{Eva_2}$=35 "kW,T_$_{EVA_1}$=278K, Q_$_{Eva_3}$=70 "kW,T_$_{EVA_1}$=283K,)*

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.398	3.516	3.484	3.506	3.343	3.465	3.353	3.378	3.261	3.355
Effectiveness _second	0.3548	0.3453	0.3337	0.3348	0.3372	0.3237	0.3423	0.3375	0.3306	0.3487
Second law efficiency	0.5436	0.5397	0.5259	0.5282	0.5224	0.5144	0.5283	0.5246	0.5114	0.5352
% Total Exergy compressor Destruction	40.44	39.41	39.95	39.32	41.07	40.13	40.96	41.07	41.45	40.67
% Total Condenser Exergy Destruction	39.69	39.15	36.54	37.50	35.81	34.9	36.79	36.04	34.41	38.49
% Total Exergy evaporator Destruction	13.69	17.01	18.60	18.60	16.23	19.91	15.50	16.27	16.16	14.26
% Total Valves Exergy Destruction	6.179	4.437	4.946	4.577	6.89	5.056	6.802	6.626	7.981	6.581
% Rational Efficiency	44.8	43.13	42.46	42.30	43.94	41.69	44.26	43.86	45.02	44.7

Table-5(h) Percentage exergy destruction in components with respect of total exergy destruction of modified *VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves(Q_$_{Eva_1}$=70 "kW, T_$_{EVA_1}$=263K, Q_$_{Eva_2}$=35 "kW,T_$_{EVA_1}$=278K, Q_$_{Eva_3}$=105 "kW,T_$_{EVA_1}$=283K,)*

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.399	3.52	3.514	3.496	3.354	3.485	3.361	3.390	3.276	3.358
% Rational Efficiency	48.23	45.64	44.63	45.01	47.42	44.17	47.75	47.13	47.78	48.31
% Total Exergy compressor Destruction	42.8	40.85	40.54	41.39	43.47	41.41	43.38	43.24	44.12	43.19
% Total Condenser Exergy Destruction	43.11	41.8	39.95	39.01	38.89	37.16	39.97	39.0	37.56	41.43
% Total Exergy evaporator Destruction	8.118	13.14	15.19	14.93	10.95	16.58	10.04	11.35	10.52	8.483
% Total Valves Exergy Destruction	5.971	4.21	4.319	4.671	6.687	4.788	6.601	6.405	7.792	6.401

Table-5(i) Percentage exergy destruction in components with respect of total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves(Q_$_{Eva_1}$=35 "kW, T_$_{EVA_1}$=263K, Q_$_{Eva_2}$=70 "kW,T_$_{EVA_1}$=278K, Q_$_{Eva_3}$=105 "kW,T_$_{EVA_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.40	3.522	3.504	3.512	3.361	3.498	3.3366	3.398	3.285	3.360
Rational Efficiency	49.94	46.84	46.19	45.69	49.09	45.27	49.44	48.66	49.57	50.07
Second law efficiency	0.3013	0.2765	0.4619	0.4569	0.4909	0.4527	0.4944	0.4866	0.4957	0.5007
% Total Exergy compressor Destruction	44.05	41.53	42.044	41.06	44.69	42.03	44.63	44.3	45.48	44.52
% Total Condenser Exergy Destruction	45.12	43.33	40.41	41.32	40.66	38.42	41.81	40.69	39.37	43.93
% Total Exergy evaporator Destruction	5.124	11.18	13.16	13.58	8.258	15.07	17.235	8.911	7.661	5.427
% Total Valves Exergy Destruction	5.704	3.958	4.39	4.037	6.392	4.477	6.316	6.098	7.481	6.131
Rational Efficiency	49.94	46.84	46.19	45.69	49.09	45.27	49.44	48.66	49.57	50.07
% Effectiveness _second	48.76	46.77	45.44	45.28	46.69	44.19	47.29	4653	46.10	48.15

Table-5(j) Percentage exergy destruction in components with respect of total exergy destruction of modified VCRS using multiple evaporators at the Different Temperatures with single compressor of 0.75% efficiency using multiple expansion valves and back pressure valves(Q_$_{Eva_1}$=35 "kW, T_$_{EVA_1}$=263K, Q_$_{Eva_2}$=70 "kW,T_$_{EVA_1}$=278K, Q_$_{Eva_3}$=105 "kW,T_$_{EVA_1}$=283K,)

Performance Parameters	R12	R-1234 ze(Z)	R-1224 yd(Z)	R-1233 zd(E)	R-1225 ye(Z)	HFO-1336 mzz(Z)	R1243 zf	R1234 ze(E)	R1234 yf	R-134a
First Law efficiency (COP)	3.40	3.522	3.504	3.512	3.361	3.498	3.3366	3.398	3.285	3.360
Rational Efficiency	49.94	46.84	46.19	45.69	49.09	45.27	49.44	48.66	49.57	50.07
% Effectiveness _second	48.76	46.77	45.44	45.28	46.69	44.19	47.29	4653	46.10	48.15
Second law efficiency	0.3013	0.2765	0.4619	0.4569	0.4909	0.4527	0.4944	0.4866	0.4957	0.5007
% Total Exergy compressor Destruction	42.8	40.85	40.54	41.39	43.47	41.41	43.38	43.24	44.12	43.19
% Total Condenser Exergy Destruction	43.11	41.8	39.95	39.01	38.89	37.16	39.97	39.0	37.56	41.43
% Total Exergy evaporator Destruction	8.118	13.14	15.19	14.93	10.95	16.58	10.04	11.35	10.52	8.483
% Total Valves Exergy Destruction	5.971	4.21	4.319	4.671	6.687	4.788	6.601	6.405	7.792	6.401

3.8 Effect of Different Load conditions in Modified VCRS

System- 1

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=105 kW, Q_{EVA_2}=35 kW, Q_{EVA_3}=70 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%.

System-2

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=105 kW, Q_{EVA_2}=105kW, Q_{EVA_3}=70 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%,

System-3

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=70 kW, Q_{EVA_2}=105 kW, Q_{EVA_3}=35 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%.

System-4

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=70 kW, Q_{EVA_2}=35kW, Q_{EVA_3}=105 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%,

System-5

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=35 kW, Q_{EVA_2}=70 kW, Q_{EVA_3}=105 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%.

System-6

Modified VCRS using multiple evaporators and multiple expansion valves for 75% compressor efficiency using Q_{EVA_1}=35 kW, Q_{EVA_2}=105kW, Q_{EVA_3}=70 kW, at T_{Eva1}= 263K, T_{Eva2}= 278K, T_{Eva3}= 283K, compressor efficiency=100%,

3.9 Effect of First Law Efficiency (COP)

Table-6(a) shows the exergetic efficiency using single compressor with using multiple expansion valves with back pressure ratio while table 6(b) shows the exergetic efficiency using single compressor with using individual expansion valves with back pressure ratio and it was observed that system- having multiple expansion valves using evaporators loads (Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’) gives better exergetic efficiency with minimum exergy destruction and it was also observed that system-5 (Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’) gives better exergetic efficiency using multiple expansion valves. While system-2 (Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’) of modified vapour compression refrigeration system using R-1233zd(E) in single compressor and individual expansion valves gives better exergetic efficiency Similarly by comparing all six systems using single compressor the modified vapour compression refrigeration system using multiple expansion valve of load Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’ gives best exergetic efficiency. Table-7(a) shows the second law effectiveness using single compressor with using multiple expansion valves with back pressure ratio while table 7(b) shows the second law effectiveness using single compressor with using individual expansion valves with back pressure ratio and it was observed that system having multiple expansion valves gives better second law effectiveness with minimum exergy destruction. While system-5 of modified vapour compression refrigeration system using R-1234ze(Z) in single compressor and individual expansion valves gives better second law effectiveness Similarly by comparing all six systems using single compressor the modified vapour compression refrigeration system using multiple expansion valve of load Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’ gives best second law effectiveness. Table-8(a) shows the rational efficiency using single compressor with using multiple expansion valves with back pressure ratio while table 8(b) shows the rational efficiency using single compressor with using individual expansion valves with back pressure ratio and it was observed that system- having multiple expansion valves gives better rational efficiency with minimum exergy destruction and it was also observed that system-5 gives better rational efficiency using multiple expansion valves. While system-6 of modified vapour compression refrigeration system using R-1233zd(E) in single compressor and individual expansion valves gives better rational efficiency Similarly by comparing all six systems using single compressor the modified vapour compression refrigeration system using multiple expansion valve of load Q_{eva1}=35‘kW’, Q_{eva2}=105‘kW’ and Q_{eva1}=70‘kW’ gives best rational efficiency. Table-9(a) shows the second law efficiency using single compressor with using multiple expansion valves with back pressure ratio while table 9(b) shows the second law efficiency using single compressor with using individual expansion valves with back pressure ratio and it was observed that system- having multiple expansion valves gives better second law efficiency with minimum exergy destruction and it was observed that system-2 gives better rational efficiency using multiple expansion valves. While system-5 of modified vapour compression refrigeration system using single compressor and individual expansion valves gives better second law efficiency Similarly by comparing all six systems using single compressor the modified vapour compression refrigeration system using multiple expansion valve of load Q_{eva1}=105‘kW’, Q_{eva2}=70‘kW’ and Q_{eva1}=35‘kW’ gives best exergetic efficiency

Table-6(a): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.3674	0.3752	0.3501	0.3344	0.3091	0.3170
R-1234ze(Z)	0.3565	0.3672	0.3337	0.3122	0.2787	0.2894
R1234ze(E)	0.3516	0.3603	0.3323	0.3146	0.2862	0.2951
R-1224yd(Z)	0.3423	0.3530	0.3194	0.2978	0.2639	0.2748
R-1233zd(E)	0.3428	0.3540	0.3187	0.2962	0.2607	0.2720
R-1225ye(Z)	0.3523	0.3606	0.3344	0.3177	0.2911	0.2996
HFO-1336mzz(Z)	0.3297	0.3406	0.3062	0.2840	0.2490	0.2603
R1243zf	0.3587	0.3669	0.3409	0.3243	0.2980	0.3064
R1234yf	0.3465	0.3539	0.330	0.31484	0.2902	0.2980

Table-6(b): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.3182	0.2901	0.2984	0.3541	0.3622	0.3346
R-1234ze(Z)	0.3058	0.2690	0.2803	0.3536	0.3648	0.3282
R1234ze(E)	0.3015	0.2696	0.2790	0.3419	0.3509	0.3199
R-1224yd(Z)	0.2919	0.2543	0.2658	0.3402	0.3514	0.3145
R-1233zd(E)	0.2920	0.2528	0.2647	0.3426	0.3543	0.3156
R-1225ye(Z)	0.3024	0.2726	0.2815	0.3401	0.3486	0.3197
HFO-1336mzz(Z)	0.2799	0.2409	0.2526	0.3207	0.3411	0.3030
R1243zf	0.3089	0.2796	0.2884	0.3463	0.3549	0.3262
R1234yf	0.2960	.2684	0.2764	0.3306	0.3382	0.3117

Table-7(a): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.4569	0.455	0.4390	0.4227	0.3966	0.4047
R-1234ze(Z)	0.4493	0.4604	0.4257	0.4034	0.3687	0.3798
R1234ze(E)	0.4410	0.4501	0.4212	0.4030	0.3736	0.3820
R-1224yd(Z)	0.4338	0.4449	0.4102	0.3879	0.3530	0.3642
R-1233zd(E)	0.4338	0.4464	0.410	0.3866	0.350	0.3617
R-1225ye(Z)	0.4411	0.4496	0.4226	0.4054	0.3780	0.3867
HFO-1336mzz(Z)	0.4203	0.4316	0.3962	0.3734	0.3374	0.3490
R1243zf	0.4479	0.4563	0.4295	0.4124	0.3852	0.3939
R1234yf	0.4331	0.4408	0.4162	0.4005	0.3753	0.3833

Table-7(b): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.3989	0.3698	0.3784	0.4360	0.4444	0.4158
R-1234ze(Z)	0.3901	0.3531	0.3647	0.4405	0.4521	0.4143
R1234ze(E)	0.3817	0.3489	0.3585	0.4232	0.4325	0.4006
R-1224yd(Z)	0.3753	0.3366	0.3484	0.4251	0.4366	0.3986
R-1233zd(E)	0.3764	0.3360	0.3483	0.4286	0.4407	0.4007
R-1225ye(Z)	0.3816	0.3510	0.3601	0.4204	0.4292	0.3994
HFO-1336mzz(Z)	0.3622	0.3221	0.3342	0.3006	0.4249	0.3859
R1243zf	0.3889	0.3588	0.3678	0.4275	0.4363	0.4067
R1234yf	0.3723	0.3440	0.3523	0.4078	0.4156	0.3884

Table-8(a): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.6083	0.5961	0.6201	0.6441	0.6627	0.6557
R-1234ze(Z)	0.5837	0.5750	0.5914	0.6034	0.6246	0.6161
R1234ze(E)	0.5962	0.5848	0.6058	0.6284	0.6488	0.6306
R-1224yd(Z)	0.5751	0.5661	0.5823	0.6001	0.6159	0.6071
R-1233zd(E)	0.5723	0.5640	0.5786	0.5950	0.6092	0.6011
R-1225ye(Z)	0.5978	0.5859	0.6086	0.6323	0.6465	0.6428
HFO-1336mzz(Z)	0.5648	0.5558	0.5712	0.5889	0.6036	0.5949
R1243zf	0.6019	0.5901	0.6131	0.6366	0.6592	0.6475
R1234yf	0.5999	0.5870	0.6113	0.6370	0.6609	0.6481

Table-8(b): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.2318	0.2408	0.2743	0.2339	0.2412	0.2710
R-1234ze(Z)	0.310	0.2929	0.3377	0.3254	0.3411	0.3767
R1234ze(E)	0.2279	0.2241	0.2623	0.2307	0.2375	0.2698
R-1224yd(Z)	0.2879	0.2667	0.3092	0.3058	0.3269	0.3570
R-1233zd(E)	0.3017	0.2782	0.3222	0.3230	0.3398	0.3768
R-1225ye(Z)	0.2190	0.2178	0.2557	0.2221	0.2297	0.2606
HFO-1336mzz(Z)	0.2794	0.2490	0.2940	0.4133	0.3156	0.3520
R1243zf	0.2253	0.2276	0.2665	0.2282	0.2359	0.2666
R1234yf	0.1782	0.1814	0.2162	0.1779	0.1826	0.2122

Table-9(a): Thermodynamic second law performance (exergetic efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.7051	0.7136	0.6864	0.6694	0.6420	0.6506
R-1234ze(Z)	0.7079	0.7196	0.6832	0.6599	0.6236	0.6352
R1234ze(E)	0.6901	0.6994	0.6696	0.6508	0.6205	0.630
R-1224yd(Z)	0.6896	0.7012	0.6652	0.6421	0.6059	0.6175
R-1233zd(E)	0.6921	0.7042	0.6662	0.6420	0.6038	0.6160
R-1225ye(Z)	0.6878	0.6966	0.6687	0.6509	0.6226	0.6316
HFO-1336mzz(Z)	0.6743	0.6859	0.6495	0.6261	0.5892	0.6010
R1243zf	0.6956	0.7044	0.6765	0.6587	0.6306	0.6395
R1234yf	0.6740	0.6819	0.6566	0.6406	0.6147	0.6228

Table-9(b): Thermodynamic second law performance (rational efficiency) of modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions)

Performance Parameters	System-1	System-2	System-3	System4	System5	System6
R-134a	0.6233	0.5932	0.6021	0.6619	0.6706	0.6409
R-1234ze(Z)	0.6303	0.5906	0.6028	0.6818	0.6939	0.6544
R1234ze(E)	0.6054	0.5718	0.5817	0.6479	0.6574	0.6248
R-1224yd(Z)	0.6096	0.5698	0.5819	0.6609	0.6728	0.6335
R-1233zd(E)	0.6135	0.5716	0.5844	0.6676	0.6802	0.6388
R-1225ye(Z)	0.6026	0.5713	0.5606	0.6424	0.6513	0.6209
HFO-1336mzz(Z)	0.5937	0.5528	0.5652	0.6458	0.6577	0.6178
R1243zf	0.6119	0.5809	0.5902	0.6517	0.6607	0.6303
R1234yf	0.5849	0.5563	0.5647	0.6209	0.6288	0.6012

4. Conclusions and recommendations

Following conclusions were drawn from this paper

(i) The developed thermal models predict the well thermodynamic (energy) performance in terms of coefficient of performance (COP) of modified VCRS using multiple evaporators at same and at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants.

(ii) Thermodynamic first law performance (energetic efficiency i.e. COP) of modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions) is better than Thermodynamic first law performance (energetic efficiency i.e. COP) of modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions).

(iii) HFO-1234ze(Z) gives best thermodynamic (energy-exergy) performances in modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves or individual using ecofriendly HFO refrigerants with different load conditions).

(iv) Maximum percentage exergy destruction was observed in condenser and lowest in evaporators at ideal conditions (i.e. at 100% isentropic efficiency of compressor compressors) in all modified systems.

(v) The percentage total exergy destruction in all throttle valves in the modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves using ecofriendly HFO refrigerants with different load conditions is lower than the total exergy destruction in all throttle valves in the modified VCRS using multiple evaporators at different temperatures with single compressor with individual expansion valves or using ecofriendly HFO refrigerants with different load conditions

(vi) The percentage of total exergy destruction in all throttle valves is lower than the total exergy destruction in all evaporators in the modified VCRS using multiple evaporators at different temperatures with single compressor with multiple expansion valves using ecofriendly HFO refrigerants with different load conditions

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Cite this article as: R.S. Mishra, effect of Different load conditions using detailed exergy evaluations of multi evaporators and multi expansion valved modified VCRS using HFO & HCFO refrigerants, International journal of research in engineering and innovation (IJREI), vol 5, issue 5 (2021), 211-231. *https://doi.org/10.36037/IJREI.2021.5501*