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RESEARCH PAPER

Effect of low and ultra-low GWP refrigerants on thermodynamic performances of modified VCRS using multiple evaporators at different temperatures, with individual expansion valves using a single compressor

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Abstract

The thermodynamic performance of ultra-low global warming potential (GWP), eco-friendly hydrochlorofluoroolefin (HCFO), hydrofluoroolefin (HFO), and their blended refrigerants was evaluated in a vapour compression refrigeration (VCR) system with multiple evaporators operating at different temperatures, a single compressor, and expansion valves. A detailed energy and exergy analysis was conducted to assess thermodynamic behavior and reduce compressor power consumption. The results indicate that HCFO-1224yd(Z) shows slightly lower coefficient of performance (COP) and exergetic efficiency compared to HCFO-1233zd(E). However, several HFO and HFO-blended refrigerants demonstrate strong potential as alternatives to high-GWP refrigerants. Numerical simulations were performed to determine the minimum electrical energy consumption under six evaporator loading conditions in the multi-evaporator VCR system, identifying an optimal performance at loading condition V when using HFO-1234ze(E) and HFO-1234yf. Furthermore, the effect of varying evaporator temperatures at optimal loading was analyzed in terms of exergetic efficiency, second-law efficiency, and relative COP. The findings highlight the suitability of HFOs, HCFOs, low-GWP HFCs, HCFCs, and HFO/HFC blends as next-generation sustainable refrigerants for replacing high-GWP refrigerants.

1. Introduction

Refrigeration is a technology that absorbs heat at a low temperature and provides a temperature below the surroundings by rejecting heat to the surroundings at a higher temperature. A simple vapour compression system, which consists of four major components: compressor, expansion valve, condenser, and evaporator, in which the total cooling load is carried at one temperature by a single evaporator, but in many applications, like large hotels, food storage, and food processing plants, food items are stored in different compartments and at different temperatures. Therefore, there is a need for a multi-evaporator VCRS. VCRS consume a significant amount of electrical energy, and their efficiency can be enhanced by improving overall system performance. The performance of a VCRS is evaluated in terms of the coefficient of performance (COP), defined as the ratio of refrigeration effect to the net work input. The COP can be improved either by increasing the refrigeration effect or by reducing the work input. The throttling process in such systems is an irreversible expansion that leads to exergy losses due to partial flashing of the refrigerant into vapour in the evaporator, decreasing cooling capacity and increasing evaporator size. This limitation can be addressed by adopting multistage expansion with a flash chamber, where flash vapour is removed after each stage, thereby enhancing

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cooling capacity and reducing evaporator size. Additionally, work input can be minimized by replacing multistage or compound compression with single-stage compression. The refrigeration effect can also be increased by subcooling the refrigerant after condensation before it enters the evaporator.

2. VCRS using multiple evaporators and compressors with individual expansion valves

Refrigeration plays a vital role in modern life and is widely used in both domestic and industrial applications. Most refrigeration systems operate on the work-based cycle of a vapour compression refrigeration system (VCRS). A comparative thermodynamic study of VCRS configurations with multiple evaporators and compressors, employing either individual or multiple expansion valves, has been carried out using eco-friendly refrigerants, with energy and exergy analyses. The evaluation was conducted in terms of coefficient of performance (COP), exergetic efficiency, and system defects, and a numerical model was developed to assess system irreversibility. The results indicated that VCRS with multiple evaporators and compressors using multiple expansion valves performs more efficiently than systems with individual expansion valves for the selected eco-friendly refrigerants, with R152a exhibiting superior performance among the considered refrigerants [2].

It has also been reported that the work input required to operate VCRS can be reduced through compound compression and further minimized by incorporating flash intercooling between compressors. The COP of the system can be enhanced by compressing the refrigerant closer to the saturation line, which can be achieved through multistage compression with intermediate intercoolers. The refrigeration effect can be improved by maintaining the refrigerant in a highly liquid state at the evaporator inlet, which can be achieved by expanding it near the liquid line. This can be achieved through refrigerant subcooling and the removal of flashed vapours using a flash chamber within the cycle. As a result, the evaporator size can be reduced because unwanted vapours are separated before the liquid refrigerant enters the evaporator. Various multistage vapour compression systems have been investigated, including systems with flash intercoolers and individual throttle valves (system-1), and systems with multiple evaporators operating at different temperatures, compound compression, flash intercooling, and multiple throttle valves (system-3).

Additionally, VCRS configurations with multiple evaporators at different temperatures, using either individual compressors with multiple expansion valves (system-4) or individual expansion valves (system-5), have been studied [3]. Changes in evaporator and condenser temperatures in a two-stage vapour compression refrigeration system using R22 significantly influence plant irreversibility, highlighting the need to optimize condenser and evaporator operating conditions [4]. Experimental studies on domestic refrigerators using hydrocarbons such as isobutene and butane, based on energy and exergy analyses, revealed that their energy efficiency ratios are comparable to R134a, while their exergy efficiency and sustainability index are considerably higher at the examined evaporator temperatures. The compressor was found to exhibit the highest system defect, approximately 70%, among all system components [5]. Comparative experimental investigations of R32, R152a, and R134a refrigerants showed that R32 performs worst, while R134a and R152a show nearly identical results, with R152a providing the best overall performance [6]. Exergy-based investigations of vapour compression refrigeration cycles have also examined the effects of condensing and evaporating temperatures on pressure losses, COP, second-law efficiency, and exergy losses. Variations in condenser temperature had a minimal impact on compressor and expansion valve exergy losses. In contrast, increases in evaporator and condenser temperatures led to improved energetic and exergetic efficiencies and reduced total system exergy losses [7]. Similarly, exergy analysis of domestic VCRS using R12 and R413A showed that R413A performs better in terms of power consumption, irreversibility, and exergy efficiency, suggesting that R12 can be replaced by R413A in domestic applications [8]. The literature indicates that most studies have focused on first-law analysis in terms of COP and on second-law analysis in terms of exergetic efficiency for simple vapour-compression refrigeration systems with a single evaporator. However, irreversibility analysis of advanced configurations, including systems with liquid–vapour heat exchangers, flash intercoolers, flash chambers, water intercoolers, liquid subcoolers, and multistage compression (double and triple stage), has received limited attention. Furthermore, comprehensive studies of multiple evaporator systems with multistage expansion and compound compression, as well as detailed thermodynamic analyses of 13 eco-friendly refrigerants, remain insufficient. Therefore, to improve the thermal performance of vapour compression refrigeration systems, the integration of multiple evaporator configurations with liquid–vapour heat exchangers can enhance both first-law efficiency (COP) and second-law efficiency (exergetic efficiency), while reducing system defects by minimizing exergy destruction in system components and consequently lowering the required work input.

3. Ecofriendly low GWP refrigerants

The working fluid used in refrigeration systems is called a refrigerant, which absorbs and transfers heat between a conditioned space and the surrounding environment, primarily in vapour-compression systems. Most conventional refrigerants are volatile substances that raise environmental concerns due to their heat-trapping ability, global warming potential (GWP), and, in some cases, ozone-depleting potential (ODP) [5]. Commonly used refrigerants such as R134a and R410 have negligible or zero ODP but still exhibit high GWPs, with atmospheric lifetimes that may extend up to 100 years. Consequently, these refrigerants are expected to be phased out gradually over the coming decade. The selection of refrigerants in the HVAC industry has evolved through three major stages. The early phase, beginning with the development of vapour compression cooling systems and continuing until the late 1920s, relied mainly on natural refrigerants such as ammonia, carbon dioxide, hydrocarbons, sulphur dioxide, chloroethene, air, ether, and methyl chloride. The introduction of Freon in 1930 led to its widespread adoption; however, environmental concerns associated with chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), particularly their high GWP and ODP, prompted restrictions on their use. International environmental agreements have further accelerated the transition toward environmentally sustainable refrigerants by promoting significant reductions in high-GWP substances [1]. Hydrofluoroolefins (HFOs) have emerged as promising alternatives to conventional refrigerants due to their lower GWPs and shorter atmospheric lifetimes than hydrofluorocarbons (HFCs). Although some HFOs exhibit toxicity or flammability, HFO-1234yf has low flammability and unstable combustion characteristics, making it suitable for automotive air-conditioning systems and a potential replacement for R134a [2].

Similarly, HFO-1234ze(E) and HFO-1336mzz(Z) are non-flammable, low-toxicity refrigerants that are considered appropriate for chiller applications. Hydrochlorofluoroolefins (HCFOs), a newer class of refrigerants containing fluorine and chlorine, offer relatively low GWP and negligible ODP, along with short atmospheric lifetimes. For instance, HCFO-1233zd(E) exhibits an ODP of less than 0.0004, while HCFO-1224yz(Z) is currently under investigation. Ongoing research also focuses on blending HFOs with refrigerants such as R32, R134a, and R227ea to replace high-GWP HFCs. In this context, the present study evaluates the thermodynamic performance of vapour-compression refrigeration systems using low-GWP refrigerants. Similarly, the results obtained from the developed computer code were also validated under different loading and temperature conditions, as shown in Table 1(b). It was found that the computed values from the developed model match the reference values very well, with an accuracy of 10% or less, as shown in Table 1(a).

4. Results and Discussion

The computer code was developed for a given evaporator's load conditions and evaporator temperature conditions using EES for modified VCRS with multiple evaporators at different temperatures, with individual expansion valves and a single compressor using R-12. The results were compared in Table 1(a). The computed values from the developed model closely match the reference values, with an accuracy of 10% or less, as shown in Table 1.

Table 1(a) Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^{o}C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -5^{o}C (268K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0^{o}C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = -7^{o}C (280K), isentropic compressors efficiency =100%

Refrigerant (R-12)	Ref [5]	Model	% Difference
COP $_{VCRS}$	4.80	5.23	9% increase
Compressor work (kW)	43.73	40.14	-8.21% decrease

Table 1(b) Effect of ecofriendly refrigerants system performances of modified VCRS-2 for (T_Cond =40^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^{o}C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10^{o}C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0^{o}C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10^{o}C (283K), isentropic compressors efficiency =100%

CFC Refrigerant (R-12)	Ref [5]	Model	% Difference
COP $_{VCRS}$)	4.38	4..166	4.886
Total compressor work in kW	31.9	33.61	-5.36

4.1 Effect of low GWP ecofriendly HFCs &HCFCs refrigerants on Thermodynamic performances of modified VCRS

Thermodynamic performances of modified VCRS modified VCRS using multiple evaporators at different temperatures, with individual expansion valves using single compressor have been computed using low GWP ecofriendly refrigerants and also was compared with HFC -134a and it was found that best performances were obtained by using HCFC-123. Although HFC-152a and HFC-245fa have higher thermodynamic performances than HFC-134a and lower than HCFC-124 and HCFC-123. The lowest thermodynamic performances were found by using HFC-32. Although HFC-32 has lowest thermodynamic performances as shown in table-2(a) respectively. It was concluded the lower GWP ecofriendly refrigerants can easily replace high GWP ecofriendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a and HFC-407c before 2027. Similarly for another system-2, same trends were observed as shown in table-2(b) respectively.

Table 2(a): Effect of ecofriendly HFCs &HCFCs refrigerants on maximum system performances (ideal performances) of modified VCRS-2 for (T_Cond =40^{o}C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^{o}C, Q_ $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5^{o}C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0^{o}C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7^{o}C (280K),, isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	R152a	R245fa	R32	R124	R123	R134a
First law Efficiency (COP $_{VCRS}$)	5.277	5.371	4.939	5.263	5.422	5.176
Exergy Destruction Ratio (EDR_{VCRS})	1.147	1.27	1.028	1.28	1.289	1.224
Exergetic Efficiency	0.4118	0.3899	0.4342	0.3863	0.3873	0.3950
Exergy of Fuel “kW”	39.8	39.10	42.52	39.9	38.73	40.57
Exergy of product “kW”	16.39	16.55	18.49	15.41	15.0	16.03
Second law Efficiency	0.5166	0.4955	0.5348	0.4899	0.4937	0.4975
Relative_COP	0.8082	0.7908	0.8104	07795	0.7915	0.7830

Table 2(b): Effect of ecofriendly HFCs &HCFCs refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	R152a	R245fa	R32	R124	R123	R134a
First law Efficiency (COP $_{VCRS}$)	4.229	4.291	3.931	4.154	4.389	4.061
Exergy Destruction Ratio(EDR$_{VCRS}$)	1.815	2.215	1.454	2.324	2.225	2.184
Exergetic Efficiency	0.3403	0.2993	0.4061	0.30	0.2912	0.3174
Exergy of Fuel "kW"	33.11	32.62	35.61	33.71	31.9	34.48
Exergy of product"kW"	11.26	9.763	14.46	10.11	9.29	10.94
Second law Efficiency	0.6589	0.6185	0.7103	0.6099	0.6164	0.6224

4.2 Effect of ecofriendly HFOs &HCFOs refrigerants on (maximum) thermodynamic performances of modified VCRS modified VCRS using multiple evaporators at different temperatures,

Effect of ecofriendly HFOs &HCFOs refrigerants on (maximum) thermodynamic performances of modified VCRS modified VCRS using multiple evaporators at different temperatures, with individual expansion valves using single compressor have been computed using low GWP ecofriendly refrigerants and it was found that best performances was obtained by using HCFO-1233zd(E). Although HCFO-1224yd(Z). and HFO-1336mzz(Z) have higher thermodynamic performances than HFC-134a and lower than HCFO-1233zd(E). The lowest thermodynamic performances were found by using HFO- R1234yf as shown in table-2(c) respectively. It was concluded the lower GWP ecofriendly HFOs and HCFO refrigerants can easily replace high GWP ecofriendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a and HFC-407c before 2027. Similarly for another system-2, same trends were observed as shown in table-2(d) respectively.

Table 2(c): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =100%

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf	R134a
First law Efficiency (COP $_{VCRS}$)	5.323	5.354	5.389	5.071	5.152	5.205	5.033	5.176
EDR$_{VCRS}$	1.366	1.306	1.30	1.29	1.284	1.271	1.315	1.224
Exergetic Efficiency	0.3740	0.3830	0.3854	0.3832	0.3839	0.3865	0.3766	0.3950
Exergy of Fuel (kW)	39.43	39.44	38.97	41.41	40.76	40.35	41.73	40.57
Exergy of product"kW"	14.75	15.05	15.02	15.87	15.65	15.59	15.71	16.03
Second law Efficiency	0.4782	0.4888	0.4911	0.4834	0.4856	0.4891	0.475	0.4975
Compressor Work (W_{Comp}) "kW"	39.43	39.44	38.97	41.41	40.76	40.35	41.73	40.57

Table 2(d): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf	R134a
First law Efficiency (COP $_{VCRS}$)	4.237	4.279	4.335	3.969	4.01	4.064	3.853	R134a
EDR$_{VCRS}$	2.492	2.309	2.253	2.3424	2.417	2.417	2.630	4.061
Exergetic Efficiency	0.2789	0.2910	0.2911	0.3047	0.3015	0.3005	0.2951	2.184
Exergy of Fuel "kW"	33.04	32.72	32.29	35.28	34.92	34.45	36.34	0.3174
Exergy of product"kW"	9.215	9.521	9.40	10.75	10.53	10.35	10.72	34.48
Second law Efficiency	0.5926	0.6086	0.6125	0.6024	0.6017	0.6044	0.5840	0.6224

4.3 Effect of HFO blended low GWP refrigerants on thermodynamic performances of modified VCRS modified VCRS using multiple evaporators at different temperatures

Effect of ecofriendly HFO blended low GWP refrigerants on (maximum) thermodynamic performances of modified VCRS modified VCRS using multiple evaporators at different temperatures, with individual expansion valves using single compressor have been computed using low GWP ecofriendly refrigerants and it was found that best performances was obtained by using R515a Although R515a have similar thermodynamic performances than HFC-134a and lower than HCFO-1233zd(E). The lowest thermodynamic performances were found by using R 454c as shown in table-2(e) respectively. It was concluded the lower GWP ecofriendly HFOs blended refrigerants (R450a, R515a, R513a, R454b &R454c) can easily replace high GWP ecofriendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a and HFC-407c before 2027. Similarly for another system-2, same trends were observed as shown in table-2(f) respectively.

Table 2(e): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K),, isentropic compressors efficiency =100%

Ecofriendly Refrigerants	R515A	R513A	R450A	R454B	R454C	R452A	R449A	R448A
First law Efficiency (COP_{VCRS})	5.17	5.075	5.003	4.741	4.219	4.384	4.443	4.494
Exergy Destruction Ratio (EDR_{VCRS})	1.297	1.259	1.355	1.119	1.688	1.567	1.507	1.485
Exergetic Efficiency	0.382	0.387	0.374	0.414	0.3325	0.3413	0.3538	0.3571
Exergy of Fuel (kW)	40.62	41.38	41.98	44.29	49.77	47.90	47.26	46.73
Exergy of product"kW"	15.51	16.0	15.7	18.34	16.55	16.35	16.72	16.68
Second law Efficiency	0.4838	0.487	0.473	0.510	0.4164	0.4283	0.4423	0.4465
Compressor Work (W_{Comp}) "kW"	40.62	41.38	41.98	44.29	49.77	47.90	47.26	46.73

Table 2(f): Effect of ecofriendly refrigerants system performances of modified VCRS-2 for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	R515A	R513A	R454B	R454C	R452A	R450A	R449A	R448A
First law Efficiency (COP_{VCRS})	4.053	3.923	3.732	3.308	3.329	3.916	3.470	3.538
EDR_{VCRS}	2.416	2.427	1.853	3.0485	3.133	2.510	2.671	2.559
Exergetic Efficiency	0.2965	0.3062	0.3584	0.2526	0.2685	0.2919	0.2815	0.2834
Exergy of Fuel "kW"	34.54	35.69	37.51	42.32	42.06	35.75	40.35	39.57
Exergy of product"kW"	10.24	10.93	13.44	10.69	11.29	10.44	11.36	11.22
Second law Efficiency	0.5992	0.6009	0.6447	0.5006	0.5193	0.5849	0.5431	0.5498

4.4 Actual Thermodynamic Performances

4.4.1 Effect of low GWP HFCs &HCFCs refrigerants on actual thermodynamic performances using 75% of compressor of modified VCRS modified VCRS

Thermodynamic performances of modified VCRS with multiple evaporators at different temperatures, each with an individual expansion valve, using a single compressor, have been computed with low-GWP eco-friendly refrigerants and compared with HFC-134a and HCFC-123; the best performance was obtained with HCFC-123. However, HFC-152a and HFC-245fa have higher thermodynamic performance than HFC-134a, but lower than HCFC-124 and HCFC-123. The lowest thermodynamic performance was obtained with HFC-32. Although HFC-32 has the lowest thermodynamic performance, as shown in Table 3 (a). It was concluded that lower-GWP eco-friendly refrigerants can easily replace high-GWP eco-friendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a, and HFC-407c before 2027. Similarly, for another system-2, the same trends were observed, as shown in Table 3(b).

Table 3(a): Effect of ecofriendly refrigerants actual system performances of modified VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R152a	R245fa	R32	R124	R123	R134a
First law Efficiency (COP_{VCRS})	3.958	4.029	3.705	3.948	4.067	3.882
EDR_{VCRS}	1.956	2.125	1.705	2.143	2.15	2.067
Exergetic Efficiency	0.3088	0.2925	0.3262	0.2897	0.2905	0.2963
Exergy of Fuel ("kW")	53.06	52.13	56.69	53.2	51.64	54.1
Exergy of product"kW"	16.39	16.55	18.49	15.41	15.0	16.03
Second law Efficiency	0.3874	0.3716	0.4011	0.3674	0.3703	0.3771
Effectiveness Second	0.6062	0.5931	0.6078	0.5846	0.5936	0.5873
Work required to run Compressor (W_{Comp}) "kW"	53.06	52.13	56.69	53.2	51.64	54.1

Table 3(b): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R152a	R245fa	R32	R134a	R124	R123
First law Efficiency (COP_{VCRS})	3.172	3.219	2.948	3.045	3.115	3.292
EDR_{VCRS}	2.795	3.329	2.275	3.234	3.435	3.369
Exergetic Efficiency	0.2552	0.2245	0.3046	0.38	0.225	0.2184
Exergy of Fuel ("kW")	44.14	43.5	47.48	45.97	44.94	42.53
Exergy of product"kW"	11.26	9.763	14.46	10.94	10.11	9.29
Second law Efficiency	0.4942	0.4639	0.5328	0.4668	0.4574	0.4623
Work required to run Compressor (W_{Comp}) "kW"	44.14	43.5	47.48	45.97	44.94	42.53

4.4.2 Effect of ecofriendly HFOs &HCFOs refrigerants on (maximum) thermodynamic performances of modified VCRS modified VCRS using multiple evaporators

The effect of eco-friendly HFOs &HCFOs refrigerants on actual thermodynamic performances for 75% of compressor efficiency of modified VCRS using multiple evaporators at different temperatures, with individual expansion valves using a single compressor, has been computed using low GWP eco-friendly refrigerants, and it was found that the best performance was obtained by using HCFO-1233zd(E). However, HCFO-1224yd(Z). and HFO-1336mzz(Z) have higher thermodynamic performances than HFC-134a and lower than HCFO-1233zd(E). The lowest thermodynamic performance was observed with HFO-1234yf, as shown in Table 3(c). It was concluded that lower-GWP eco-friendly HFOs and HCFO refrigerants can easily replace high-GWP eco-friendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a, and HFC-407c before 2027. Similarly, for another system-2, the same trends were observed, as shown in Table 3(d).

Table 3(c): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =75%.

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP_{VCRS})	3.994	4.015	4.042	3.804	3.864	3.902	3.775
EDR_{VCRS}	2.257	2.174	2.165	2.160	2.152	2.133	2.20
Exergetic Efficiency	0.2804	0.2878	0.2891	0.2874	0.2879	0.2899	0.2825
Exergy of Fuel “kW”	52.58	52.30	51.96	55.21	54.35	53.80	55.63
Exergy of product“kW”	14.75	15.05	15.02	15.87	15.65	15.59	15.71
Second law Efficiency	0.3587	0.3666	0.3683	0.3626	0.3642	0.3668	0.3570

Table-3(d) Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP_{VCRS})	3.176	3.209	3.251	2.977	3.007	3.048	2.889
EDR_{VCRS}	3.687	3.455	3.398	3.436	3.523	3.51	3.760
Exergetic Efficiency	0.2092	0.2183	0.2183	0.2285	0.2261	0.2254	0.2213
Exergy of Fuel (kW)	44.15	43.62	43.06	47.03	46.55	45.93	48.45
Exergy of product “kW”	9.215	9.521	9.40	10.75	10.53	10.35	10.72
Second law Efficiency	0.4445	0.4565	0.4594	0.4518	0.4513	0.4533	0.4380
Work required to run Compressor (W_{Comp})	44.15	43.62	43.06	47.03	46.55	45.93	48.45

4.4.3 Effect of ecofriendly HFO blended low GWP refrigerants on actual thermodynamic performances at 75% of compressor efficiency of modified VCRS modified VCRS using multiple evaporators

Effect of eco-friendly HFO-blended low-GWPP refrigerants on actual thermodynamic performance for 75% compressor efficiency, with S using multiple evaporators at different temperatures, with individual and expansion valves using a single, hasted, and using low found that the best performance was achieved with R515a. However, R515a has similar actual thermodynamic performances to HFC-134a and lower than HCFO-1233zd(E). The lowest thermodynamic performance was found using R 454c, as shown in Table 3 (e). It was concluded that the lower-GWP eco-friendly HFO-blended refrigerants (R450a, R515a, R513a, R454b & R454c) can easily replace high-GWP eco-friendly refrigerants such as HFC-134a, HFC-404a, HFC-507a, HFC-227ea, HFC-125, HFC-410a, and HFC-407c before 2027. For another system-2, the same trends were observed, as shown in Table 3 f

Table-3(e) Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =75%.

Ecofriendly Refrigerants	R515A	R513A	R450A	R454B	R454C	R452A	R449A	R448A
First law Efficiency (COP_{VCRS})	3.878	3.807	3.752	3.556	3.164	3.288	3.333	3.371
Exergy Destruction Ratio (EDR_{VCRS})	2.17	2.121	2.247	1.924	2.690	2.553	2.449	2.418
Exergetic Efficiency	0.2865	0.290	0.2805	0.3105	0.2494	0.2559	0.2654	0.2678
Exergy of Fuel “kW”	54.16	55.17	55.97	59.06	66.36	66.87	63.02	62.3
Exergy of product“kW”	15.51	16.0	15.7	18.34	16.55	16.35	16.72	16.68
Second law Efficiency	0.3629	0.3653	0.3546	0.3824	0.3123	0.3212	0.3318	0.3349

Table 3(f): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40ºC, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30ºC, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10ºC (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0ºC (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10ºC (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R515A	R513A	R454B	R454C	R452A	R450A	R449A	R448A
First law Efficiency (COP_{VCRS})	3.04	2.942	2.799	2.481	2.497	2.937	2.603	2.653
% Total Exergy Destruction in VCRS	78.73	80.74	74.21	83.46	88.07	79.95	81.38	79.39
% Exergy Destruction in compressors.	22.87	22.82	20.98	21.72	22.26	22.60	21.63	21.40
% Exergy Destruction in condenser.	21.10	20.26	26.47	24.59	20.81	20.66	24.18	25.37
% Exergy Destruction in Evaporators.	2.48	1.172	4.636	0.9522	0.9923	2.911	0.0	0.0
% Exergy Destruction in throttle valves.	32.35	36.48	31.40	36.20	44.01	33.11	35.65	33.06
% Rational Efficiency	21.27	19.26	25.79	16.54	11.93	20.05	18.62	20.61

4.4.4 Effect of ecofriendly HFCs and HCFCs low GWP refrigerants on actual exergy destruction in each component and rational exergy efficiency (detailed thermodynamic performances) of modified VCRS modified VCRS

Table 4(a) presents the performance analysis of different eco-friendly refrigerants in a modified VCRS operating at a condenser temperature of 40°C, sub-cooled condenser liquid temperature of 30°C, and three evaporators with cooling capacities of 70 kW at −5°C (268 K), 105 kW at 0°C (273 K), and 35 kW at 7°C (280 K), assuming 100% isentropic compressor efficiency. The first law performance shows that the highest COP is obtained with R123 (5.422), followed by R245fa (5.371), R152a (5.277), R124 (5.263), R134a (5.176), and the lowest with R32 (4.939).
The total exergy destruction in the system varies from 44.69% to 49.94%, where the minimum value is observed for R32 (44.69%), indicating better thermodynamic performance, while the maximum is recorded for R123 (49.94%). Since the compressor efficiency is assumed to be 100%, the exergy destruction in compressors is 0% for all refrigerants. In the condenser, the highest exergy destruction occurs with R32 (31.66%), while the lowest is with R134a (27.75%). In evaporators, R245fa (16.55%) and R123 (16.49%) show higher exergy losses, whereas R32 exhibits the lowest value of 7.19%. For the throttle valves, R134a shows the highest exergy destruction (6.055%), while R123 has the lowest value (4.309%). The rational efficiency varies significantly, with the highest value for R32 (55.31%) and the lowest for R152a (16.39%), indicating better overall exergy performance for R32 among the considered refrigerants.

Table 4(a): Effect of ecofriendly refrigerants system performances of ideal exergy destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40ºC, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30ºC, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5ºC (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0ºC (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7ºC (280K), isentropic compressors efficiency =100%

Ecofriendly Refrigerants	R152a	R245fa	R32	R124	R123	R134a
First law Efficiency (COP_{VCRS})	5.277	5.371	4.939	5.263	5.422	5.176
% Total Exergy Destruction in VCRS	47.22	49.54	44.69	49.44	49.94	48.33
% Exergy Destruction in compressors.	0.0	0.0	0.0	0.0	0.0	0.0
% Exergy Destruction in condenser.	29.49	28.28	31.66	27.82	29.14	27.75
% Exergy Destruction in Evaporators.	12.9	16.55	7.19	16.01	16.49	14.52
% Exergy Destruction in throttle valves.	4.831	4.708	5.849	5.615	4.309	6.055
% Rational Efficiency	16.39	50.16	55.31	50.56	50.06	51.67

4.4.5 Effect of ecofriendly HFOs and HCFOs ultra-low GWP refrigerants on actual exergy destruction in each component and rational exergy efficiency (detailed thermodynamic performances) of modified VCRS modified VCRS using multiple evaporators

Table 4(b) presents the thermodynamic performance of several eco-friendly HFO refrigerants in a modified VCRSoperating under the conditions of condenser temperature 40°C, sub-cooled liquid temperature 30°C, and three evaporators providing cooling capacities of 70 kW at −5°C (268 K), 105 kW at 0°C (273 K), and 35 kW at 7°C (280 K). The system analysis considers ideal compressor operation with 100% isentropic efficiency, therefore the exergy destruction in the compressor is zero for all refrigerants.
The first-law performance of the system, represented by the Coefficient of Performance (COP), ranges from 5.033 to 5.389. Among the studied refrigerants, R1233zd(E) provides the highest COP of 5.389, indicating better refrigeration performance, followed by R1224yd(Z) (5.354) and HFO-1336mzz(Z) (5.323). Lower COP values are observed for R1234ze(E) (5.205), R1225ye(Z) (5.152), R1243zf (5.071), and the lowest COP for R1234yf (5.033). These values indicate that most of the considered HFO refrigerants offer comparable refrigeration performance.
The total exergy destruction in the system varies between 49.10% and 51.10%. The highest exergy destruction is observed with HFO-1336mzz(Z) (51.10%), while the lowest total exergy destruction occurs with R1234ze(E) (49.10%), suggesting relatively better thermodynamic efficiency. Other refrigerants show close values such as R1224yd(Z) (50.11%), R1233zd(E) (50.10%), R1243zf (49.44%), R1225ye(Z) (49.28%), and R1234yf (49.52%).
Component-wise analysis shows that the condenser accounts for a significant portion of exergy destruction, with values

ranging from 26.11% to 28.74%. The highest condenser exergy loss occurs with R1233zd(E) (28.74%), while the lowest is recorded for R1234yf (26.11%). In the evaporators, the exergy destruction varies from 15.59% to 18.07%, where HFO-1336mzz(Z) exhibits the highest loss (18.07%) and R1234ze(E) shows the lowest value (15.59%). The throttle valves also contribute noticeable irreversibility, with values ranging from 4.397% to 7.457%. The lowest throttling loss occurs with R1233zd(E) (4.397%), whereas R1234yf shows the highest loss (7.457%).

The rational efficiency of the system varies between 48.90% and 50.90%, where the maximum value is obtained for R1234ze(E) (50.90%), followed by R1225ye(Z) (50.72%) and R1243zf (50.56%). These results indicate that several low-GWP HFO refrigerants provide comparable performance and can be considered promising alternatives for environmentally sustainable refrigeration systems.

Table-4(b) Effect of ecofriendly refrigerants system performances of ideal exergy destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =100%

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP $_{VCRS}$)	5.323	5.354	5.389	5.071	5.152	5.205	5.033
% Total Exergy Destruction in VCRS	51.10	50.11	50.1	49.44	49.28	49.1	49.52
% Exergy Destruction in compressors.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Exergy Destruction in condenser.	28.10	28.36	28.74	26.81	26.99	27.30	26.11
% Exergy Destruction in Evaporators.	18.07	17.02	16.97	16.26	15.84	15.59	15.96
% Exergy Destruction in throttle valves.	4.924	4.728	4.397	6.377	6.447	6.21	7.457
% Rational Efficiency	48.90	49.89	49.9	50.56	50.72	50.9	50.48

Table 4(d): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP $_{VCRS}$)	4.237	4.279	4.335	3.969	4.01	4.064	3.853
% Total Exergy Destruction in VCRS	69.5	67.2	65.57	71.37	72.88	72.16	77.60
% Exergy Destruction in compressors.	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Exergy Destruction in condenser.	25.12	25.51	25.98	24.27	24.28	24.53	23.41
% Exergy Destruction in Evaporators.	6.913	6.078	6.561	3.135	2.802	3.0	2.134
% Exergy Destruction in throttle valves.	37.47	35.61	33.03	43.97	45.79	44.63	52.06
% Rational Efficiency	30.5	32.8	34.43	28.63	27.12	27.84	22.40

Table 4(d) presents the performance analysis of a simple VCRSusing different eco-friendly HFO refrigerants under the operating conditions of condenser temperature 40°C, sub-cooled liquid temperature 30°C, and three evaporators operating at −10°C (263 K) with 35 kW, 0°C (273 K) with 70 kW, and 10°C (283 K) with 35 kW, assuming 100% isentropic compressor efficiency. Since the compressor is considered ideal, the exergy destruction in the compressor is zero for all refrigerants. The first-law performance of the system, represented by the Coefficient of Performance (COP), varies between 3.853 and 4.335. The highest COP is obtained with R1233zd(E) (4.335), followed by R1224yd(Z) (4.279) and HFO-1336mzz(Z) (4.237). Lower COP values are observed for R1234ze(E) (4.064) and R1225ye(Z) (4.01), while R1243zf (3.969) and R1234yf (3.853) show comparatively lower refrigeration performance.

The total exergy destruction in the system ranges from 65.57% to 77.60%. The minimum total exergy destruction is observed for R1233zd(E) (65.57%), indicating relatively better thermodynamic performance. In contrast, the maximum exergy destruction occurs with R1234yf (77.60%), followed by R1225ye(Z) (72.88%) and R1234ze(E) (72.16%).

Component-wise analysis shows that the condenser contributes moderate exergy losses, ranging from 23.41% to 25.98%. The highest condenser exergy destruction occurs with R1233zd(E) (25.98%), while the lowest value is recorded for R1234yf (23.41%). In the evaporators, the exergy destruction is relatively smaller, varying from 2.134% to 6.913%, where HFO-1336mzz(Z) exhibits the highest evaporator loss (6.913%), while R1234yf shows the lowest value (2.134%).

A significant portion of the irreversibility in the system occurs in the throttle valves, with values ranging from 33.03% to 52.06%. The lowest throttling loss is observed with R1233zd(E) (33.03%), whereas R1234yf exhibits the highest value (52.06%), indicating greater energy degradation during expansion.

The rational efficiency of the system varies from 22.40% to 34.43%, with the highest value obtained for R1233zd(E) (34.43%), followed by R1224yd(Z) (32.8%) and HFO-1336mzz(Z) (30.5%). Overall, the results indicate that R1233zd(E) provides better thermodynamic performance among the considered refrigerants, while R1234yf shows comparatively higher irreversibility in the system.

Table 4(e): Effect of ecofriendly refrigerants system performances of ideal exergy destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =100%

Ecofriendly Refrigerants	R515A	R513A	R450A	R454B	R454C	R452A	R449A	R448A
First law Efficiency (COP_{VCRS})	5.17	5.075	5.003	4.741	4.219	4.384	4.443	4.494
% Total Exergy Destruction in VCRS	49.55	48.69	50.7	46.33	56.12	53.80	53.72	53.01
% Exergy Destruction in compressors.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Exergy Destruction in condenser.	28.13	26.74	26.84	32.36	30.54	26.15	29.93	31.28
% Exergy Destruction in Evaporators.	15.44	14.92	17.25	7.538	17.72	18.21	15.82	14.76
% Exergy Destruction in throttle valves.	5.971	7.021	6.613	6.436	7.85	9.436	7.573	6.968
% Rational Efficiency	50.45	51.31	49.3	53.67	43.88	46.2	46.68	46.99

Table-4(f) Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =100%.

Ecofriendly Refrigerants	R515A	R513A	R454B	R454C	R452A	R450A	R449A	R448A
First law Efficiency (COP_{VCRS})	4.053	3.923	3.732	3.308	3.329	3.916	3.470	3.538
% Total Exergy Destruction in VCRS	71.64	74.32	65.61	77.95	84.10	73.26	75.15	72.52
% Exergy Destruction in compressors.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Exergy Destruction in condenser.	25.29	24.11	29.92	28.41	24.10	24.35	27.75	29.02
% Exergy Destruction in Evaporators.	3.224	1.562	0.0	1.27	1.323	3.0	0.0	0.0
% Exergy Destruction in throttle valves.	43.14	48.65	41.86	48.27	58.68	44.63	47.54	44.08
% Rational Efficiency	28.36	25.68	34.39	22.05	15.90	26.74	24.85	27.48

Table 4(e) presents the performance analysis of a modified VCRS using different eco-friendly refrigerant blends under operating conditions of condenser temperature 40°C, sub-cooled liquid temperature 30°C, and three evaporators operating at −5°C (70 kW), 0°C (105 kW), and 7°C (35 kW) with 100% isentropic compressor efficiency. The Coefficient of Performance (COP) ranges from 4.219 to 5.17, where the highest COP is observed for R515A (5.17) followed by R513A (5.075) and R450A (5.003), while R454C shows the lowest COP of 4.219. The total exergy destruction in the system varies from 46.33% to 56.12%, with the minimum value for R454B (46.33%) indicating better thermodynamic performance, whereas the maximum value occurs for R454C (56.12%). Since the compressor is assumed ideal, the exergy destruction in compressors is zero for all refrigerants. In the condenser, exergy destruction ranges from 26.15% (R452A) to 32.36% (R454B). In the evaporators, the losses vary between 7.538% for R454B and 18.21% for R452A. The throttle valves contribute noticeable irreversibility, with values ranging from 5.971% (R515A) to 9.436% (R452A). The rational efficiency lies between 43.88% and 53.67%, where R454B exhibits the highest value (53.67%), followed by R513A (51.31%), indicating improved exergy performance. Table 4(f) shows the performance of a simple VCRS configuration with evaporator temperatures of −10°C, 0°C, and 10°C and cooling capacities of 35 kW, 70 kW, and 35 kW, respectively. The COP values range from 3.308 to 4.053, with R515A showing the highest COP (4.053) and R454C the lowest (3.308). The total exergy destruction increases significantly, ranging from 65.61% to 84.10%, where R454B shows the lowest destruction (65.61%) and R452A the highest (84.10%). Condenser exergy losses vary between 24.10% and 29.92%, while evaporator losses remain relatively small (0–3.224%). The throttle valve accounts for the largest exergy destruction, ranging from 41.86% to 58.68%, highlighting the major irreversibility during expansion. The rational efficiency ranges from 15.90% to 34.39%, where R454B achieves the highest efficiency (34.39%), demonstrating comparatively better thermodynamic performance among the studied refrigerants in the simple VCRS system.

Table-5(a) Effect of ecofriendly refrigerants system performances of actual exery destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R152a	R245fa	R32	R124	R123	R134a
First law Efficiency (COP_{VCRS})	3.958	4.029	3.705	3.948	4.067	3.882
% Total Exergy Destruction in VCRS	60.42	62.15	58.52	62.08	62.46	61.25
% Exergy Destruction in compressors.	22.17	23.27	20.9	23.27	22.84	22.81
% Exergy Destruction in condenser.	24.95	22.94	27.84	22.59	24.01	23.01
% Exergy Destruction in Evaporators.	9.674	12.41	5.392	12.01	12.37	10.89
% Exergy Destruction in throttle valves.	3.623	3.531	4.386	4.211	3.232	4.541
% Rational Efficiency	39.58	37.85	41.48	37.92	37.54	38.75

Table 5(a) presents the performance of a modified VCRS using different eco-friendly refrigerants when the compressor operates at 75% isentropic efficiency. The operating conditions include a condenser temperature of 40°C, sub-cooled liquid temperature of 30°C, and three evaporators operating at −5°C (70 kW), 0°C (105 kW), and 7°C (35 kW).

The Coefficient of Performance (COP) ranges from 3.705 to 4.067. The highest COP is observed for R123 (4.067) followed by R245fa (4.029) and R152a (3.958), whereas R32 shows the lowest COP of 3.705. The total exergy destruction varies between 58.52% and 62.46%, where R32 shows the lowest value (58.52%) indicating relatively better thermodynamic performance, while R123 exhibits the highest exergy destruction (62.46%). A major portion of irreversibility occurs in the compressor, ranging from 20.9% (R32) to 23.27% (R245fa and R124) due to the reduced compressor efficiency. In the condenser, exergy destruction ranges from 22.59% (R124) to 27.84% (R32). The evaporator losses vary from 5.392% (R32) to 12.41% (R245fa), while the throttle valve contributes relatively smaller losses, ranging from 3.232% (R123) to 4.541% (R134a). The rational efficiency lies between 37.54% and 41.48%, where R32 shows the highest value (41.48%), indicating improved exergy utilization compared to other refrigerants.

Table-5(b) Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10°C (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10°C (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R152a	R245fa	R32	R134a	R124	R123
First law Efficiency (COP $_{VCRS}$)	3.172	3.219	2.948	3.045	3.115	3.292
% Total Exergy Destruction in VCRS	71.33	74.72	69.29	76.98	77.3	73.59
% Exergy Destruction in compressors.	21.63	22.78	20.45	22.39	22.83	22.27
% Exergy Destruction in condenser.	23.63	21.32	26.66	21.52	20.95	22.6
% Exergy Destruction in Evaporators.	5.997	4.009	6.114	1.23	2.943	5.113
% Exergy Destruction in throttle valves.	25.42	26.61	28.3	31.84	30.57	23.61
% Rational Efficiency	28.67	25.72	69.29	76.98	77.3	73.59

Table 5(a) presents the performance of a modified VCRS using different eco-friendly refrigerants when the compressor operates at 75% isentropic efficiency. The operating conditions include a condenser temperature of 40°C, sub-cooled liquid temperature of 30°C, and three evaporators operating at −5°C (70 kW), 0°C (105 kW), and 7°C (35 kW). The Coefficient of Performance (COP) ranges from 3.705 to 4.067. The highest COP is observed for R123 (4.067) followed by R245fa (4.029) and R152a (3.958), whereas R32 shows the lowest COP of 3.705. The total exergy destruction varies between 58.52% and 62.46%, where R32 shows the lowest value (58.52%) indicating relatively better thermodynamic performance, while R123 exhibits the highest exergy destruction (62.46%). A major portion of irreversibility occurs in the compressor, ranging from 20.9% (R32) to 23.27% (R245fa and R124) due to the reduced compressor efficiency. In the condenser, exergy destruction ranges from 22.59% (R124) to 27.84% (R32). The evaporator losses vary from 5.392% (R32) to 12.41% (R245fa), while the throttle valve contributes relatively smaller losses, ranging from 3.232% (R123) to 4.541% (R134a). The rational efficiency lies between 37.54% and 41.48%, where R32 shows the highest value (41.48%), indicating improved exergy utilization compared to other refrigerants.

Table 5(b) illustrates the performance of a simple VCRS configuration under similar condenser conditions but with evaporator temperatures of −10°C, 0°C, and 10°C and cooling loads of 35 kW, 70 kW, and 35 kW, respectively. The COP varies from 2.948 to 3.292, where R123 shows the highest COP (3.292) while R32 shows the lowest (2.948). The total exergy destruction ranges from 69.29% to 77.30%, with R32 showing the minimum value (69.29%) and R124 exhibiting the maximum (77.30%). Compressor exergy losses remain significant, ranging from 20.45% to 22.83%. The condenser losses vary from 20.95% to 26.66%, while evaporator losses remain relatively small (1.23%–6.114%). A large portion of irreversibility occurs in the throttle valve, where exergy destruction ranges from 23.61% (R123) to 31.84% (R134a). These results show that the simple VCRS experiences higher exergy destruction and lower efficiency compared with the modified system, indicating the thermodynamic advantage of the modified multi-evaporator configuration. Tables 5(c) and 5(d) present the performance evaluation of different eco-friendly HFO refrigerants in a VCRS operating at a condenser temperature of 40°C and sub-cooled condenser liquid temperature of 30°C, with compressor isentropic efficiency of 75%. The tables compare system performance in terms of COP, total exergy destruction, component-wise exergy destruction, and rational efficiency under two different cooling load conditions.

Table 5(c): Effect of ecofriendly refrigerants system performances of actual exergy destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40°C, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30°C, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5°C (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0°C (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7°C (280K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP $_{VCRS}$)	3.994	4.015	4.042	3.804	3.864	3.902	3.775
% Total Exergy Destruction in VCRS	63.32	62.58	62.57	62.08	61.96	61.83	62.14
% Exergy Destruction in compressors.	23.67	23.33	23.08	23.03	23.31	23.35	23.46
% Exergy Destruction in condenser.	22.40	22.94	23.48	22.08	21.93	22.13	21.12
% Exergy Destruction in Evaporators.	13.55	12.17	12.72	12.19	11.88	11.69	11.97
% Exergy Destruction in throttle valves.	3.693	3.546	3.298	4.782	4.836	4.658	5.593
% Rational Efficiency	36.68	37.42	37.43	37.92	38.4	38.17	37.86

Table 5(d): Effect of ecofriendly refrigerants system performances of simple VCRS for (T_Cond =40^oC, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^oC, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10^oC (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0^oC (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10^oC (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	HFO-1336 mzz(Z)	R1224 yd(Z)	R1233 zd(E)	R1243 zf	R1225 ye(Z)	R1234 ze(E)	R1234 yf
First law Efficiency (COP_{VCRS})	3.176	3.209	3.251	2.977	3.007	3.048	2.889
% Total Exergy Destruction in VCRS	77.12	75.40	74.18	78.53	79.66	79.12	83.20
% Exergy Destruction in compressors.	23.25	22.84	22.52	22.62	22.93	22.94	23.12
% Exergy Destruction in condenser.	20.59	21.30	21.96	20.58	20.29	20.45	19.44
% Exergy Destruction in Evaporators.	5.185	4.591	4.921	2.352	2.101	2.25	1.601
% Exergy Destruction in throttle valves.	28.10	26.71	24.77	32.97	34.34	33.47	39.04
% Rational Efficiency	22.88	24.60	25.82	21.47	20.34	20.88	16.80

In Table 5(c), higher cooling loads are considered (QEvap1 = 70 kW, QEvap2 = 105 kW, QEvap3 = 35 kW). The results indicate that R1233zd(E) shows the highest COP (4.042) among the considered refrigerants, indicating better energy efficiency. The lowest total exergy destruction (61.83%) occurs for R1234ze(E), suggesting improved thermodynamic performance. Compressor and condenser components contribute significantly to exergy losses, accounting for about 23% and 21–23%, respectively. Evaporator exergy destruction ranges from 11.69% to 13.55%, while throttle valve losses remain comparatively small (about 3–5%). The highest rational efficiency (38.4%) is observed for R1225ye(Z), indicating better utilization of available energy.

In contrast, Table 5(d) represents lower cooling load conditions. Under these conditions, the COP values decrease, with R1233zd(E) still providing the highest COP (3.251). Total exergy destruction increases significantly, reaching up to 83.20% for R1234yf, indicating reduced system efficiency. A major portion of irreversibility occurs in throttle valves (24–39%), which becomes the dominant source of exergy destruction in this operating condition. Rational efficiency also decreases to 16.8–25.82%, reflecting lower thermodynamic performance at reduced cooling loads.

Table 5(e): Effect of ecofriendly refrigerants system performances of actual exergy destruction in components and total exergy destruction in system along with rational thermal efficiency VCRS for (T_Cond =40^oC, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^oC, $Q_{\_Evap1}$ =70 kW, $T_{\_Evap1}$ = -5^oC (268K), $Q_{\_Evap2}$ =105 kW, $T_{\_Evap2}$ = 0^oC (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ =7^oC (280K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R515A	R513A	R450A	R454B	R454C	R452A	R449A	R448A
First law Efficiency (COP_{VCRS})	3.878	3.807	3.752	3.556	3.164	3.288	3.333	3.371
% Total Exergy Destruction in VCRS	62.16	61.51	63.02	59.75	67.09	65.35	64.99	64.76
% Exergy Destruction in compressors.	23.3	23.19	23.03	21.41	22.17	22.60	22.05	21.88
% Exergy Destruction in condenser.	22.80	21.87	22.10	27.86	25.74	22.01	25.39	26.58
% Exergy Destruction in Evaporators.	11.58	11.19	12.93	5.653	13.29	13.66	11.86	11.07
% Exergy Destruction in throttle valves.	4.478	5.266	4.96	4.827	5.887	7.077	5.68	5.226
% Rational Efficiency	37.84	38.49	36.98	40.25	32.91	34.65	35.01	35.24

Table 5(f): Effect of ecofriendly refrigerants system performances of modified VCRS for (T_Cond =40^oC, $T_{\_sub\_cooled\ condenser\ liquid}$ = 30^oC, $Q_{\_Evap1}$ =35 kW, $T_{\_Evap1}$ = -10^oC (263K), $Q_{\_Evap2}$ =70 kW, $T_{\_Evap2}$ = 0^oC (273K), $Q_{\_Evap3}$ =35 kW, $T_{\_Evap3}$ = 10^oC (283K), isentropic compressors efficiency =75%

Ecofriendly Refrigerants	R515A	R513A	R454B	R454C	R452A	R450A	R449A	R448A
First law Efficiency (COP_{VCRS})	3.04	2.942	2.799	2.481	2.497	2.937	2.603	2.653
% Total Exergy Destruction in VCRS	78.73	80.74	74.21	83.46	88.07	79.95	81.38	79.39
% Exergy Destruction in compressors.	22.87	22.82	20.98	21.72	22.26	22.60	21.63	21.40
% Exergy Destruction in condenser.	21.10	20.26	26.47	24.59	20.81	20.66	24.18	25.37
% Exergy Destruction in Evaporators.	2.48	1.172	4.636	0.9522	0.9923	2.911	0.0	0.0
% Exergy Destruction in throttle valves.	32.35	36.48	31.40	36.20	44.01	33.11	35.65	33.06
% Rational Efficiency	21.27	19.26	25.79	16.54	11.93	20.05	18.62	20.61

Tables 5(e) and 5(f) present the thermodynamic performance evaluation of different eco-friendly refrigerant blends used in a VCRS. The analysis considers operating conditions of condenser temperature (Tcond = 40°C), sub-cooled condenser liquid temperature of 30°C, and compressor isentropic efficiency of 75%. The system performance is evaluated in terms of Coefficient of Performance (COP), total exergy destruction, component-wise exergy destruction (compressor, condenser, evaporator, and throttle valve), and rational efficiency. In Table 5(e), the system operates under higher cooling load conditions with QEvap1 = 70 kW, QEvap2 = 105 kW, and QEvap3 = 35 kW. The results show noticeable variations in system performance for the selected refrigerants. Among the refrigerants analyzed, R515A exhibits a relatively high COP of 3.878, indicating efficient energy performance. However, R513A demonstrates the lowest total exergy destruction (61.51%), which implies better thermodynamic utilization of available energy. In contrast, R454C shows the highest total exergy destruction (67.09%), indicating larger system irreversibility. The compressor contributes significantly to exergy losses for all refrigerants, with destruction values ranging between 21.41% and 23.30%. The lowest compressor exergy destruction occurs for R454B (21.41%), suggesting relatively better compression efficiency. The condenser also shows notable exergy losses, ranging from 21.87% to 27.86%, with R454B experiencing the highest losses in this component. Exergy destruction in the evaporators varies widely, from 5.653% for R454B to 13.66% for R452A, indicating differences in heat transfer effectiveness and thermodynamic matching between the refrigerant and evaporator temperature levels. The throttle valve contributes comparatively smaller exergy losses, ranging from 4.478% to 7.077%. The lowest throttling losses are observed for R515A, while R452A shows the highest losses in this component. Regarding overall system effectiveness, R454B provides the highest rational efficiency (40.25%), indicating superior thermodynamic performance in terms of useful energy utilization, whereas R454C shows the lowest rational efficiency (32.91%). In Table 5(f), the analysis is carried out for a modified VCRS configuration with lower cooling loads (QEvap1 = 35 kW, QEvap2 = 70 kW, QEvap3 = 35 kW). Under these operating conditions, the COP values decrease significantly compared with Table 5(e), indicating reduced energy performance at lower loads. The highest COP in this case is observed for R515A (3.04), while R454C shows the lowest COP (2.481). Total exergy destruction increases considerably under these conditions, ranging from 74.21% to 88.07%. The lowest total exergy destruction occurs for R454B (74.21%), while R452A exhibits the highest destruction (88.07%), indicating poorer thermodynamic efficiency. The compressor exergy destruction remains relatively consistent across refrigerants, varying between 20.98% and 22.87%. A key observation in this configuration is the significant increase in throttling losses, which range from 31.40% to 44.01%, making the throttle valve the dominant source of irreversibility in the system. Conversely, evaporator exergy destruction becomes very small, reaching nearly zero for R449A and R448A, indicating improved heat transfer matching under these conditions.

5. Conclusions

In this paper, first- and second-law analyses of VCRS using multiple evaporators at different temperatures and a single compressor with individual expansion valves, with low-GWP, eco-friendly refrigerants, have been presented. The conclusions of the present analysis are summarized below:

- The First law efficiency (COP) and second law efficiency of VCRS using multiple evaporators at different temperatures and a single compressor and individual expansion valves are higher when using HCFO-1233zd(E) refrigerants than eco-friendly HCFO-1224yd(Z) and HFO-1336mzz(Z) refrigerants.
- The First law efficiency (COP) and Second law efficiency of VCRS using multiple evaporators at different temperatures and a single compressor and individual expansion valves are higher when using R515a refrigerant than eco-friendly low GWP R513a and R450a. The lowest energy-exergy performance was observed using R454c.
- COP and exergetic efficiency of HFC-152a VCRS using multiple evaporators at different temperatures and a single compressor and individual expansion valves is slightly lower than HFC-245fa but higher than HFC-32 for domestic applications
- The component from the viewpoint of highest irreversibility (exergy destruction in the compressor) is the compressor, and the condenser is slightly lower in some refrigerants, and the lowest exergy destruction was found in the throttle valve due to internal irreversibility
- The increase in dead state temperature has a positive effect on exergetic efficiency and EDR, i.e., EDR decreases, and exergetic efficiency increases with an increase in dead state temperature. Both HCFO-1224yd(Z) and HCFO-1233zd(E) exhibit identical trends in exergetic efficiency. The exergetic efficiency of R-152a is slightly lower than that of R-245fa over the range of dead-state temperatures considered.

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