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RESEARCH PAPER

Effect of ecofriendly ultralow GWP refrigerants on thermodynamic performances of four modified VCRS using multi valves in different configurations for reducing global warming and ozone depletion

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Abstract

This study evaluates the thermodynamic performance of vapor compression refrigeration (VCR) systems configured with multiple evaporators operating at different temperatures, in combination with multiple compressors and expansion devices. Various configurations were analyzed using energy–energy assessment methods, with a focus on ecofriendly refrigerants including hydrofluoroolefins (HFOs), hydrochlorofluoroolefins (HCFOs), and low-global warming potential (GWP) hydrofluorocarbons (HFCs). Among the refrigerants considered, HFO-1234ze (Z) demonstrated the most favorable thermodynamic behavior. HCFO-1233zd(E) and HCFO-1224yd(Z) followed closely, showing better performance compared to HFO-1336mzz(Z), HFO-1243zf, and HFO-1225ye(Z). HFO-1234yf exhibited the lowest performance among the HFOs evaluated. In contrast, HFC-245fa and HFC-152a performed more efficiently than the traditional CFC-12, which is known for its high GWP and ozone depletion potential. However, HFC-32 and some blended HFO refrigerants displayed relatively lower thermodynamic performance but still serve as viable ecofriendly alternatives to conventional CFCs and HCFCs. The analysis further indicates that system performance improves with increasing load variations, reaching an optimum at configuration condition-5 before declining. These findings support the potential of HFO and HCFO refrigerants as sustainable replacements for environmentally harmful legacy refrigerants.

1. Introduction

Refrigerants play a crucial role in vapor compression-based systems by facilitating heat absorption and transfer between a conditioned space and its surroundings. The basic vapor compression cycle includes four main components: a compressor, condenser, expansion valve, and evaporator. While traditional systems operate with a single evaporator handling the entire cooling load at a uniform temperature, many modern applications—such as those in hotels, food processing plants, and cold storage facilities—require cooling at multiple temperatures. To meet this demand, multi-evaporator vapor compression refrigeration (VCR) systems have been developed. However, most conventional refrigerants are volatile substances that contribute significantly to global warming (high GWP) and ozone layer depletion (ODP). Although refrigerants like R134a and R410a exhibit zero or minimal ODP, they still possess relatively high GWP and long atmospheric lifespans, making them unsuitable for long-term sustainable use. Regulatory efforts such as the 1987 Montreal Protocol, its 2016 Kigali Amendment, and the 2015 Paris Agreement have pushed for the gradual phasing out of high-GWP refrigerants in favor of low-GWP, environmentally safer alternatives. The evolution of refrigerant usage can be categorized into three major phases. Initially, natural refrigerants such as ammonia, carbon dioxide, hydrocarbons, and methyl chloride were used. This

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transitioned to chlorofluorocarbons (CFCs) like Freon in the 1930s, which, while safer in terms of toxicity and flammability, later proved highly damaging to the ozone layer. Following global environmental concerns, CFCs were replaced by hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs), which still pose global warming risks. Recent studies have explored hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) as promising alternatives due to their low GWP and negligible ODP. For example, HFO-1234yf, which is widely used in automotive air conditioning systems, is non-flammable and has a short atmospheric lifetime. HFO-1336mzz (Z) and HFO-1234ze(E) are preferred for chiller systems due to their low toxicity and non-flammable nature. Similarly, HCFO-1233zd (E) and HCFO-1224yd (Z) have emerged as short-lived, low-GWP options suitable for chillers, with minimal ODP impact. Energy analysis methods have been effectively used to evaluate the performance and irreversibilities within various VCR system configurations. Prior research by Mishra and others compared the performance of eight environmentally friendly refrigerants across two modified VCR systems—one featuring a flash intercooler with individual throttle valves, and another incorporating multiple throttle valves. The findings revealed that system-2 outperformed system-1 in terms of coefficient of performance (COP), energy efficiency, and reduced irreversibility (measured via Energy Destruction Ratio, EDR).

Table-1(a): GWP and ODP of eco-friendly HFOs and HCFOs refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves

S.No	Low GWP refrigerants	GWP	ODP
1	HCFO 1233zd(E)	6	0.00034
2	HCFO 1224yd(Z)	1	0.00023
3	HFO 1336mzz(Z)	2	0
4	HFO 1243zf	9	0
5	HFO 1234ze(E)	7	0
6	HFO 1225ye(Z)	14	0
7	HFO 1234yf	4	0

Table-1(b): GWP and ODP of eco-friendly HCFCs and HFCFs refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves

S.No	Low GWP refrigerants	*GWP*	*ODP*
1	HCFC 123	77 / 79	0.06
2	HCFC 124	527 / 609	0.02
3	HFC 134a	1430	0
4	HFC 152a	124	0
5	HFC 32	780	0
6	HFC245fa	977	0

Among the refrigerants assessed, R125 demonstrated the poorest performance, while R600 (a hydrocarbon) and R717 (ammonia) delivered superior thermodynamic results. Although R717 is highly efficient, it is hazardous and suitable only for specialized applications. R600, while flammable, provides 2–3% better performance than R134a and can be used safely under controlled conditions. R134a remains popular due to its widespread availability and reliable performance, while R1234yf offers a GWP as low as four and zero ODP, making it a highly eco-friendly option. The environmental and thermodynamic properties of these refrigerants are comprehensively presented in Tables 1(a) through 1(c).

Table-1(c): GWP and ODP of eco-friendly HFOs blended refrigerants in vapour compression refrigeration systems using multiple evaporators at different temperatures with single/multiple compressors of individual /multiple expansion valves

S.No	Low GWP refrigerants	GWP	ODP
1	R450A	547 to 604	0
2	R513A	631	0
3	R515A	403	0
4	R454b	466	0
5	R454c	146	0

2. Results and Discussions

Four different configurations of modified vapor compression refrigeration (VCR) systems have been selected for a comparative analysis of their thermodynamic performance. The specific layouts and operational distinctions among these systems are detailed in Table 2(a). Corresponding temperature conditions applied across these configurations are presented in Table 2(b).

Table-2(a): Types of vapour compression refrigeration systems

Systems	
System-1	Modified VCR systems using multiple evaporators at different temperatures with compound compression and individual expansion valves
System-2	Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves
System-3	Modified VCR systems using multiple evaporators at different temperatures with compound compression with individual expansion valves with flash chambers
System-4	Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers

Additionally, the input parameters utilized for evaluating system performance are comprehensively outlined in Tables 3 and 4, respectively. These datasets serve as the foundational basis for conducting the energy and exergy analysis across the selected configurations. The ideal thermodynamic performance of four modified vapor compression refrigeration (VCR) systems was evaluated using ultra-low

GWP, ecofriendly refrigerants. The analysis was conducted under the assumption of 100% isentropic efficiency for all three compressors

Table-2(b) Different evaporator loads used in VCRS using ultra-low GWP eco-friendly HFOs and HCFOs refrigerants in VCRS using multiple evaporators at different temperatures with single/multiple compressors of expansion valves.

S. No.	Evaporator load Parameters	"kW"
1	First Evaporator Load ($Q_{\_Eva1}$)	105
2	Second Evaporator Load ($Q_{\_Eva2}$)	70
3	Third Evaporator Load ($Q_{\_Eva3}$)	35

Table-2(c) Different evaporator used in VCRS using ultra-low GWP eco-friendly HFOs and HCFOs refrigerants in VCRS using multiple evaporators at different temperatures

S. No.	Evaporator temperatures	"K"
1	First Evaporator temperature ($T_{\_Eva1}$)	273
2	Second Evaporator temperature ($T_{\_Eva2}$)	278
3	Third Evaporator temperature ($T_{\_Eva3}$)	283

Key performance metrics included first-law efficiency (COP), energy efficiency, and energy destruction across system components, with results presented in Tables 3(a) and 3(d).

Based on Table 3(a), the highest thermodynamic efficiency—both first-law and second-law—was achieved using HFO-1234ze (Z), while HFO-1234yf exhibited the lowest performance among all tested refrigerants. The use of HCFO-1233zd (E) and HCFO-1224yd (Z) yielded slightly lower performance than HFO-1234ze (Z), yet still outperformed other alternatives such as HFO-1336mzz (Z), HFO-1243zf, and HFO-1225ye (Z). Among the HCFO group, HCFO-1233zd (E) demonstrated superior efficiency compared to HCFO-1224yd (Z), making it a favorable substitute from a thermodynamic perspective. In terms of electrical power consumption, systems utilizing HFO-1234ze (Z) required the least energy input, while those using CFC-12 exhibited the highest energy demand. According to Table 3(b), the refrigerants HFO-1234ze (E), HFO-1243zf, and HFO-1225ye (Z) showed slightly lower performance than CFC-12 but remain viable alternatives due to their environmental advantages. HFO-1234yf again showed the poorest performance, coupled with the highest energy consumption among the ecofriendly refrigerants evaluated.

Table-3(a): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves using HCFO refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K.

Performance Parameters using *different ecofriendly refrigerants*	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	R12
First law Efficiency (COP_{System})	5.4	5.202	5.258	5.174	5.073
Exergy Destruction Ratio(EDR_{System})	2.116	2.235	2.201	2.252	2.317
Exergetic Efficiency $_{System}$	0.3209	0.3091	0.3124	0.3075	0.3015
Exergy of Fuel $_{System}$ "kW"	38.89	40.37	39.94	40.58	41.40
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48	12.48
Exergy Destruction in condenser(%)	46.76	44.41	45.15	44.0	43.65
Exergy Destruction in evaporator(%)	9.09	9.974	10.1	9.919	9.724
Exergy Destruction in valves(%)	9.382	11.54	10.65	12.12	12.73
Exergy Destruction in sub-cooler(%)	2.633	3.164	2.859	3.213	3.754
Total Exergy Destruction (%)	67.91	69.09	68.76	69.25	69.85
Rational Efficiency (%)	32.09	30.91	31.24	30.75	30.15
First compressor work (kW)	21.27	22.16	21.91	22.31	22.7
Second compressor work (kW)	12.33	12.76	12.63	12.81	13.1
Third compressor work (kW)	5.298	5.447	5.402	5.457	5.602
Mass flow rate in evaporator-1 (kg/sec)	0.6060	0.8054	0.6762	0.7966	0.9289
Mass flow rate in evaporator-2 (kg/sec)	0.3973	0.5238	0.4407	0.5159	0.6078
Mass flow rate in evaporator-3 (kg/sec)	0.1954	0.2557	0.2155	0.2507	0.2965
Mass flow rate in condenser (kg/sec)	1.199	1.585	1.332	1.563	1.835
Exergy Destruction Ratio(EDR_{VCRS})	2.033	2.132	2.109	2.148	2.193
Exergetic Efficiency	0.3297	0.3192	0.3216	0.3177	0.3132
Exergy Destruction Ratio(EDR_{VCRS})	2.116	2.235	2.201	2.252	2.317
Exergetic Efficiency	0.3209	0.3091	0.3124	0.3075	0.3015

The ideal thermodynamic performance of modified vapor compression refrigeration (VCR) systems using low-GWP, ecofriendly refrigerants was assessed based on first-law efficiency (COP), exergy efficiency, and exergy destruction. This evaluation assumed 100% isentropic efficiency for all three compressors across the configurations. The comparative thermal performances of these systems are illustrated in Table 3(b). From the analysis in Table 3(b), HCFC-123 demonstrated the highest performance in terms of both first- and second-law efficiencies across all systems, while HFC-32 yielded the lowest. In System-1, the thermodynamic performance of HFC-152a was slightly inferior to that of HFC-245fa but moderately superior to HFC-134a. A similar evaluation using a different set of low-GWP refrigerants is presented in Table 3(c). The results indicate that R-515a delivered the highest COP and exergy efficiency among the tested options, while R-454c exhibited the lowest performance. Within the same configuration, R-450a showed slightly reduced performance compared to R-513a, yet performed marginally better than R-454b.

Table-3(b): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves using HFC refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K.

Performance Parameters *different ecofriendly refrigerants*	HFC-152a	HFC-245fa	HFC-32	HFC-134a	R123	R124
First law Efficiency (COP $_{VCRS}$)	5.148	5.214	4.738	4.992	5.296	5.079
Exergy Destruction Ratio(EDR_{VCRS})	2.269	2.226	2.552	2.371	2.177	2.313
Exergetic Efficiency	0.3059	0.310	0.2815	0.2966	0.3147	0.3018
Exergy of Fuel “kW”	40.79	40.26	44.33	42.07	39.65	41.35
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency(%)	31.63	31.0	28.25	29.66	31.47	30.18
Total Exergy Destruction (%)	69.41	69.0	71.85	70.34	68.53	69.82
Exergy Destruction in condenser(%)	45.1	44.38	46.03	42.48	45.63	43.1
Exergy Destruction in evaporator(%)	9.859	9.992	9.081	9.534	9.967	9.49
Exergy Destruction in valves(%)	11.18	11.49	12.62	14.15	10.16	13.4
Exergy Destruction in sub-cooler(%)	3.271	3.143	4.12	4.178	2.771	3.826
System total Exergy Destruction (%)	69.41	69.0	71.85	70.34	68.53	69.82
Rational Exergetic efficiency (%)	30.59	31.0	28.25	29.66	31.47	30.18
Second law efficiency(COP/COP_$_{Carnot}$)	0.4714	0.4777	0.4339	0.4571	0.485	0.465
First compressor work (kW)	22.35	22.10	24.3	23.11	21.72	22.72
Second compressor work (kW)	12.91	12.73	14.03	13.29	12.55	13.06
Third compressor work (kW)	5.53	5.437	6.002	5.668	5.377	5.566
Total system (3 compressors) work (kW)	40.79	40.26	44.33	42.07	39.65	41.35
Mass flow rate in evaporator-1 (kg/sec)	0.4468	0.6908	0.4376	0.7378	0.7458	0.9129
Mass flow rate in evaporator-2 (kg/sec)	0.2936	0.4497	0.2907	0.4821	0.4867	0.5936
Mass flow rate in evaporator-3 (kg/sec)	0.1448	0.2197	0.1450	0.2364	0.2383	0.2897
Mass flow rate in condenser (kg/sec)	0.8852	1.36	0.8739	1.456	1.471	1.796
Exergy Destruction Ratio(EDR_{VCRS})	2.169	2.226	2.552	2.371	2.177	2.313
Exergetic Efficiency	0.3059	0.310	0.2815	0.2966	0.3147	0.3018
Exergy Destruction Ratio(EDR_{VCRS})	2.162	2.125	2.406	2.23	2.089	2.186
Exergetic Efficiency	0.3153	0.320	0.2936	0.3026	0.3237	0.3138

Table-3(c): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves using HFO blended refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K

Performance Parameters using *different ecofriendly refrigerants*	R-450a	R-513a	R-515a	R454b	R454c
First law Efficiency (COP $_{VCRS}$)	3.854	3.881	3.973	3.633	3.251
Exergy Destruction Ratio(EDR_{VCRS})	3.366	3.336	3.236	3.632	4.177
Exergetic Efficiency	0.2290	0.2307	0.2361	0.2159	0.1932
Exergy of Fuel “kW”	54.49	54.10	52.86	57.81	64.60
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48
Rational Efficiency(%)	28.63	28.63	29.51	26.99	24.15
Total Exergy Destruction (%)	71.37	71.17	70.49	73.01	75.85
Exergy Destruction in condenser(%)	41.24	40.76	43.08	45.74	41.76
Exergy Destruction in evaporator(%)	10.91	9.224	8.995	8.445	12.91
Exergy Destruction in valves(%)	15.04	16.35	14.23	14.13	16.59
Exergy Destruction in sub-cooler(%)	4.189	4.84	4.187	4.697	4.527
System total Exergy Destruction (%)	71.37	71.17	70.49	73.01	75.85
Rational Exergetic efficiency (%)	28.63	28.83	29.51	26.99	24.15

Second law efficiency(COP/COP_Carnot)	0.4412	0.4443	0.4548	0.4159	0.3721
First compressor work (kW)	23.96	23.83	23.25	25.33	28.21
Second compressor work (kW)	13.77	13.65	13.35	14.64	16.39
Third compressor work (kW)	5.867	5.801	5.684	6.27	7.083
Total compressor work (kW)	43.59	43.28	42.29	46.24	51.68
Mass flow rate in evaporator-1 (kg/sec)	0.8023	0.8726	0.8349	0.5431	0.7932
Mass flow rate in evaporator-2 (kg/sec)	0.5223	0.5675	0.5421	0.3593	0.5180
Mass flow rate in evaporator-3 (kg/sec)	0.2549	0.2770	0.2643	0.1783	0.2540
Mass flow rate in condenser (kg/sec)	1.581	1.717	1.641	1.081	1.566
Exergy Destruction Ratio(EDR_{VCRS}) (by second Method)	2.493	2.468	2.388	2.706	3.141
Exergetic Efficiency(by second Method)	0.2863	0.2863	0.2951	0.2699	0.2415
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	2.347	2.301	2.247	2.532	2.954
Exergetic Efficiency(by third Method)	0.2988	0.3030	0.3080	0.2832	0.2529

This study investigates the impact of various ecofriendly, ultra-low GWP refrigerants on the ideal thermodynamic performance of modified vapor compression refrigeration (VCR) system with multiple evaporators, individual compressors, and multiple expansion valves—designated as System-2. The analysis was conducted assuming 80% isentropic efficiency for all three compressors. Key performance indicators such as first-law efficiency (COP), exergy efficiency, and component-wise exergy destruction are compared across different refrigerants, as presented in Tables 4(a) and 4(b). Among the evaluated refrigerants, HFO-1234ze (Z) demonstrated the highest thermodynamic efficiency under both energy and exergy criteria, while HFO-1234yf showed the lowest performance. The actual thermodynamic performance of System-2 using HCFO-1233zd (E) was found to be slightly below that of HFO-1234ze (Z), yet superior to that of HCFO-1224yd (Z). In turn, HCFO-1224yd (Z) outperformed HFO-1336mzz (Z), although the latter exhibited better efficiency than several other tested ultra-low GWP refrigerants within the HFO category. In terms of electrical power consumption, which correlates with the exergy input or fuel usage, the highest demand was recorded when using HFO-1234yf, indicating its relatively lower thermodynamic effectiveness in this system configuration.

Table-4(a): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of vapour compression refrigeration system (system-2) using multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K.

Performance Parameters using *different ecofriendly refrigerants*	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	R12
First law Efficiency (COP_{System})	7.366	7.204	7.228	7.203	7.045
Exergy Destruction Ratio(EDR_{System})	1.285	1.336	1.328	1.336	1.388
Exergetic Efficiency $_{System}$	0.4377	0.4281	0.4295	0.4281	0.4187
Exergy of Fuel $_{System}$ "kW"	28.51	29.15	29.15	29.15	29.81
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3954	0.3764	0.3806	0.3728	0.3688
Total Exergy Destruction (%)	60.46	62.36	61.94	62.72	63.12
Exergy Destruction in condenser(%)	38.11	36.54	36.87	36.38	36.02
Exergy Destruction in evaporator(%)	16.63	18.98	18.78	15.33	18.49
Exergy Destruction in valves(%)	3.872	4.718	4.364	4.884	5.852
Exergy Destruction in sub-cooler(%)	1.84	2.119	1.923	2.123	2.753
Rational Efficiency(%)	39.54	37.64	38.06	37.28	36.88
First compressor work (kW)	14.05	14.05	14.11	13.91	14.38
Second compressor work (kW)	8.497	8.566	8.583	8.526	8.765
Third compressor work (kW)	5.958	6.541	6.359	6.718	6.663
Mass flow rate in evaporator-1 (kg/sec)	0.4887	0.6175	0.5282	0.5990	0.7147
Mass flow rate in evaporator-2 (kg/sec)	0.3435	0.4375	0.3733	0.4258	0.5080
Mass flow rate in evaporator-3 (kg/sec)	0.2853	0.3959	0.3279	0.3959	0.4597
Mass flow rate in condenser (kg/sec)	1.118	1.451	1.229	1.422	1.682
Exergy Destruction Ratio(EDR_{VCRS}) (by second Method)	1.381	1.457	1.442	1.465	1.507
Exergetic Efficiency(by second Method)	0.4199	0.4071	0.4095	0.4057	0.3988
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	1.529	1.657	1.627	1.682	1.711
Exergetic Efficiency(by third Method)	0.3954	0.3764	0.3806	0.3728	0.3688
Second law efficiency(COP/COP_Carnot)	0.6745	0.6597	0.6619	0.6596	0.6452

Table-4(b): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using *different ecofriendly refrigerants*	HFO-1234 Ze(E)	HFO-1225 ye(Z)	HFO-1243zf	HFO-1234yf	R12
First law Efficiency (COP $_{System}$)	7.081	7.014	6.899	6.928	7.045
Exergy Destruction Ratio(EDR_{System})	1.376	1.399	1.439	1.4360	1.388
Exergetic Efficiency $_{System}$	0.4208	0.4168	0.410	0.4105	0.4187
Exergy of Fuel $_{System}$ "kW"	29.65	29.94	30.44	30.40	29.81
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3613	0.3569	0.3527	0.3449	0.3688
Total Exergy Destruction (%)	63.87	64.31	64.73	65.51	63.12
Exergy Destruction in condenser(%)	35.46	35.01	34.51	34.11	36.02
Exergy Destruction in evaporator(%)	18.96	19.44	20.54	19.81	18.49
Exergy Destruction in valves(%)	6.409	6.694	6.658	7.489	5.852
Exergy Destruction in sub-cooler(%)	3.039	3.162	3.022	3.75	2.753
Rational Efficiency(%)	36.13	35.69	35.27	34.49	36.88
First compressor work (kW)	13.90	14.02	14.42	13.96	14.38
Second compressor work (kW)	8.579	7.269	8.839	8.679	8.765
Third compressor work (kW)	7.179	6.541	7.185	7.765	6.663
Mass flow rate in evaporator-1 (kg/sec)	0.5915	0.6945	0.5425	0.6693	0.7147
Mass flow rate in evaporator-2 (kg/sec)	0.4249	0.4988	0.3883	0.4848	0.5080
Mass flow rate in evaporator-3 (kg/sec)	0.4223	0.4986	0.3762	0.5156	0.4597
Mass flow rate in condenser (kg/sec)	1.439	1.692	1.307	1.670	1.682
Exergy Destruction Ratio(EDR_{VCRS}) (by second Method)	1.517	1.543	1.579	1.596	1.507
Exergetic Efficiency(by second Method)	0.3972	0.3933	0.3877	0.3852	0.3988
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	1.768	1.802	1.836	1.90	1.711
Exergetic Efficiency(by third Method)	0.3613	0.3569	0.3527	0.3449	0.3688
Second law efficiency(COP/COP_$_{Carnot}$)	0.6485	0.6423	0.6317	0.6326	0.6452

The ideal thermodynamic performance of the modified vapor compression refrigeration system with multiple evaporators, individual compressors, and multiple expansion valves (System-2) was evaluated using ultra-low GWP ecofriendly refrigerants, assuming 100% isentropic efficiency for all three compressors. The comparison included first-law efficiency (COP), exergy efficiency, and exergy destruction across system components, with results presented in Table 4(c). According to the analysis, the highest performance in terms of both energy and exergy efficiency was achieved using HFC-245fa, while HFC-32 exhibited the lowest thermodynamic effectiveness among the tested refrigerants. The performance of System-2 using HFC-152a was slightly below that of HFC-245fa but exceeded that of HFC-134a. Additionally, the use of HCFC-124 resulted in performance slightly lower than HFC-152a, yet still superior to that of HFC-32.

Table-4(c): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K

Performance Parameters using *different ecofriendly refrigerants*	HFC-152a	HFC-245fa	HFC-32	HFC-134a	R123	R124	R12
First law Efficiency (COP $_{VCRS}$)	7.091	7.227	6.658	7.026	7.241	7.123	7.045
Exergy Destruction Ratio(EDR_{VCRS})	1.373	1.329	1.527	1.395	1.324	1.363	1.388
Exergetic Efficiency	0.4214	0.4294	0.3957	0.4175	0.4303	0.4233	0.4187
Exergy of Fuel "kW"	29.61	29.06	31.54	29.89	29.0	29.48	29.81
Exergy of product "kW"	12.48	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3754	0.3775	0.3517	0.3618	0.3851	0.3677	0.3688
Total Exergy Destruction (%)	62.46	62.25	64.83	63.82	61.49	63.23	63.12
Exergy Destruction in condenser(%)	36.95	36.41	38.18	35.52	37.12	35.95	36.02
Exergy Destruction in evaporator(%)	18.17	19.03	17.16	18.99	18.15	18.89	18.49
Exergy Destruction in valves(%)	4.989	4.70	6.325	6.310	4.308	5.735	5.852

Exergy Destruction in sub-cooler(%)	2.344	2.10	3.163	2.996	1.916	2.674	2.753
System total Exergy Destruction (%)	62.46	62.25	64.83	63.82	61.49	63.23	36.88
Rational Exergetic efficiency (%)	37.54	37.75	35.17	36.18	38.51	36.77	14.38
First compressor work (kW)	14.47	14.0	15.39	14.17	14.22	13.99	8.765
Second compressor work (kW)	8.761	8.541	9.295	8.697	8.61	8.592	6.663
Third compressor work (kW)	6.388	6.523	6.852	7.023	6.174	6.898	0.7147
Total compressor work (kW)	29.61	29.06	31.54	29.89	29.0	29.48	0.5080
Mass flow rate in evaporator-1 (kg/sec)	0.3522	0.5299	0.3423	0.5470	0.5935	0.6790	0.4597
Mass flow rate in evaporator-2 (kg/sec)	0.2495	0.3758	0.2495	0.3920	0.4173	0.4849	1.682
Mass flow rate in evaporator-3 (kg/sec)	0.2172	0.3405	0.2180	0.3773	0.3545	0.4621	1.507
Mass flow rate in condenser (kg/sec)	0.8188	1.246	0.8050	1.317	1.365	1.626	0.3988
EDR_{VCRS} (by second Method)	1.482	1.449	1.639	1.395	1.429	1.494	1.711
Exergetic Efficiency(by second Method)	0.4029	0.4083	0.3790	0.4175	0.4112	0.4009	0.3688
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	1.663	1.649	1.844	1.529	1.597	1.721	0.6452
Exergetic Efficiency(by third Method)	0.3754	0.3775	0.3517	0.3955	0.3851	0.3675	7.045
Second law efficiency(COP/$COP_{\_Carnot}$)	0.6494	0.6618	0.6097	0.6434	0.6631	0.6525	1.388

The ideal thermodynamic performance of the modified vapor compression refrigeration system (System-2), which incorporates multiple evaporators, individual compressors, and multiple expansion valves, was assessed using various ultra-low GWP ecofriendly refrigerants under the assumption of 100% isentropic efficiency for all three compressors. Performance indicators—including first-law efficiency (COP), exergy efficiency, and exergy destruction across components—are detailed in Table 4(d).

Among the refrigerants analyzed, R-515a delivered the highest performance based on both energy and exergy evaluations, while R-32 exhibited the lowest efficiency. The performance of System-2 using HFC-152a was marginally lower than HFC-245fa but outperformed HFC-134a. Additionally, HCFC-124 demonstrated slightly lower performance than HFC-152a, yet was still more effective than HFC-32.

Table-4(d): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K

Performance Parameters using R1234ze in given table-1(b)	R-450a	R-513a	R-515a	R454b
First law Efficiency (COP $_{VCRS}$)	6.826	6.937	7.018	6.452
Exergy Destruction Ratio(EDR_{VCRS})	1.465	1.425	1.398	1.608
Exergetic Efficiency	0.4057	0.4122	0.4170	0.3834
Exergy of Fuel “kW”	30.76	30.27	29.92	32.55
Exergy of product “kW”	12.48	12.48	12.48	12.48
Rational Efficiency	0.3451	0.3506	0.3602	0.3362
Total Exergy Destruction (%)	65.49	64.94	63.98	66.98
Exergy Destruction in condenser(%)	34.47	34.47	34.47	34.47
Exergy Destruction in evaporator(%)	21.28	19.35	18.4	16.41
Exergy Destruction in valves(%)	6.753	7.383	6.131	6.659
Exergy Destruction in sub-cooler(%)	2.988	3.519	2.97	3.561
System total Exergy Destructionin (%)	65.49	64.94	63.98	66.98
Rational Exergetic efficiency (%)	34.51	35.06	36.02	33.62
Second law efficiency(COP/$COP_{\_Carnot}$)	0.6251	0.6353	0.6427	0.5908
First compressor work (kW)	14.48	14.07	14.09	15.62
Second compressor work (kW)	8.869	8.707	8.681	9.423
Third compressor work (kW)	7.415	7.496	7.153	7.506
Total compressor work (kW)	30.76	30.27	29.92	32.55
Mass flow rate in evaporator-1 (kg/sec)	0.5835	0.6202	0.6107	0.4079
Mass flow rate in evaporator-2 (kg/sec)	0.4155	0.4478	0.4375	0.2888
Mass flow rate in evaporator-3 (kg/sec)	0.4118	0.4590	0.4279	0.2753
Mass flow rate in condenser (kg/sec)	1.411	1.527	1.476	0.972
Exergy Destruction Ratio (EDR_{VCRS}) (second Method)	1.614	1.575	1.534	1.731
Exergetic Efficiency (second Method)	0.3825	0.3885	0.3946	0.3661
Exergy Destruction Ratio (EDR_{VCRS}) (third Method)	1.898	1.852	1.776	1.975
Exergetic Efficiency (using third Method)	0.3451	0.3506	0.3602	0.3362

The ideal thermodynamic performance of the modified vapor compression refrigeration system (System-3), featuring multiple evaporators, individual compressors, and multiple expansion valves, was analyzed using various ultra-low GWP ecofriendly refrigerants. This evaluation was conducted under the assumption of 80% isentropic efficiency for all three compressors. The results—including first-law efficiency (COP), exergy efficiency, and component-wise exergy destruction—are presented in Tables 5(a) through 5(d). Among the refrigerants examined, HFO-1234ze (Z) demonstrated the highest overall performance in terms of both energy and exergy metrics, while HFO-1234yf exhibited the lowest. The actual thermodynamic performance of System-3 using HCFO-1233zd(E) was found to be slightly lower than that of HFO-1234ze(Z), yet superior to that of HCFO-1224yd(Z). In turn, HCFO-1224yd(Z) outperformed HFO-1336mzz(Z), making the latter the least effective among the selected HCFOs. Nevertheless, HFO-1336mzz(Z) showed better thermodynamic characteristics than several other ecofriendly ultra-low GWP refrigerants. Notably, the electrical energy requirement (interpreted as exergy input or fuel exergy) was observed to be highest when operating the system with HFO-1234yf.

Table-5(a): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression with individual expansion valves with flash chambers using ecofriendly refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using different ecofriendly refrigerants	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	R12
First law Efficiency (COP $_{System}$)	7.371	7.204	7.228	7.205	7.047
Exergy Destruction Ratio(EDR$_{System}$)	1.283	1.336	1.328	1.336	1.388
Exergetic Efficiency $_{System}$	0.4380	0.4281	0.4275	0.4281	0.4188
Exergy of Fuel $_{System}$ “kW”	28.49	29.15	29.05	29.15	29.8
Exergy of product $_{System}$ “kW”	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3955	0.3765	0.3806	0.373	0.3688
Total Exergy Destruction (%)	60.45	62.35	61.94	62.70	63.12
Exergy Destruction in condenser (%)	38.05	36.55	36.86	36.4	35.95
Exergy Destruction in evaporator (%)	16.65	18.98	18.78	19.33	18.5
Exergy Destruction in valves (%)	3.895	4.714	4.366	4.862	5.884
Exergy Destruction in sub-cooler(%)	1.851	2.116	1.924	2.112	2.769
Total Exergy Destruction (%)	60.45	62.35	61.94	62.70	63.12
Rational Efficiency (%)	39.55	37.65	38.06	37.30	36.88
First compressor work (kW)	1.898	1.96	1.958	1.961	1.982
Second compressor work (kW)	3.156	3.247	3.243	3.248	3.291
Third compressor work (kW)	23.44	23.94	23.85	23.94	24.53
Total compressor work (kW)	28.49	29.15	29.05	29.05	29.8
Mass flow rate in evaporator-1 (kg/sec)	0.4887	0.6175	0.5282	0.5990	0.7147
Mass flow rate in evaporator-2 (kg/sec)	0.8345	1.055	0.9018	1.023	1.226
Mass flow rate in evaporator-3 (kg/sec)	1.124	1.449	1.230	1.414	1.692
Exergy Destruction Ratio(EDR$_{VCRS}$) (second Method)	1.380	1.457	1.4442	1.464	1.507
Exergetic Efficiency(using second Method)	0.4202	0.4071	0.4095	0.4058	0.3989
Exergy Destruction Ratio(EDR$_{VCRS}$) (third method)	1.528	1.656	1.627	1.681	1.711
Exergetic Efficiency(using third Method)	0.3955	0.3765	0.3806	0.3730	0.3688
Second law efficiency(COP/COP_Carnot)	0.6750	0.6591	0.6619	0.6598	0.6454

Table-5(b): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression with individual expansion valves with flash chambers using HFO refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using ecofriendly refrigerants	HFO-1234 Ze(E)	HFO-1225 ye(Z)	HFO-1243zf	HFO-1234yf
First law Efficiency (COP $_{System}$)	7.082	7.014	6.898	6.909
Exergy Destruction Ratio(EDR$_{System}$)	1.376	1.399	1.440	1.436
Exergetic Efficiency $_{System}$	0.4209	0.4168	0.4099	0.4106
Exergy of Fuel $_{System}$ “kW”	29.45	29.940	30.45	30.39
Exergy of product $_{System}$ “kW”	12.48	12.48	12.48	12.48

Rational Efficiency	0.3613	0.3765	0.3525	0.3450
Total Exergy Destruction (%)	63.87	62.35	64.75	65.50
Exergy Destruction in condenser(%)	35.47	35.02	34.49	34.12
Exergy Destruction in evaporator(%)	18.96	19.44	20.55	19.81
Exergy Destruction in valves(%)	6.402	6.693	6.676	7.833
Exergy Destruction in sub-cooler(%)	3.035	3.161	3.030	3.741
Total system Exergy Destruction (%)	63.87	64.31	64.75	65.5
Rational Efficiency(%)	36.13	35.69	35.25	34.5
First compressor work (kW)	1.964	1.983	2.035	1.995
Second compressor work (kW)	3.261	3.292	3.371	3.316
Third compressor work (kW)	24.43	24.66	25.04	25.08
Total compressor work (kW)	29.45	29.940	30.45	30.39
Mass flow rate in evaporator-1 (kg/sec)	0.5915	0.6945	0.5425	0.6693
Mass flow rate in evaporator-2 (kg/sec)	1.016	1.193	0.9323	1.156
Mass flow rate in evaporator-3 (kg/sec)	1.437	1.691	1.311	1.666
Exergy Destruction Ratio(EDR_{VCRS}) (using second Method)	1.518	1.543	1.58	1.595
Exergetic Efficiency(using second Method)	0.3972	0.3933	0.3877	0.3853
Exergy Destruction Ratio(EDR_{VCRS}) (using third Method)	1.768	1.802	1.837	1.899
Exergetic Efficiency(using third Method)	0.3613	0.3569	0.3525	0.3450
Second law efficiency	0.6485	0.6424	0.6317	0.6327

Table-5(c): Effect of different different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression with individual expansion valves with flash chambers using HFC refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using R1234ze in given table-1(b)	HFC-152a	HFC-245fa	HFC-32	HFC-134a	R124	R123
First law Efficiency (COP_{VCRS})	7.103	7.227	6.726	7.027	7.123	7.240
Exergy Destruction Ratio(EDR_{VCRS})	1.369	1.329	1.502	1.395	1.362	1.324
Exergetic Efficiency	0.4221	0.4294	0.3997	0.4176	0.4233	0.4303
Exergy of Fuel “kW”	29.57	29.06	31.22	29.89	29.48	29.01
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3759	0.3775	0.3549	0.3617	0.3675	0.3850
Total Exergy Destruction (%)	62.41	62.25	64.51	63.83	63.25	61.5
Exergy Destruction in condenser(%)	36.75	36.41	37.24	35.47	35.96	37.11
Exergy Destruction in evaporator(%)	18.22	19.03	17.38	19.01	18.89	18.15
Exergy Destruction in valves(%)	5.042	4.699	6.522	6.339	5.732	4.313
Exergy Destruction in sub-cooler(%)	2.371	2.099	3.267	3.011	2.673	1.918
System total Exergy Destruction (%)	62.41	62.25	64.51	63.83	63.25	61.5
Rational Exergetic efficiency (%)	37.59	37.75	35.49	36.17	36.75	38.5
First compressor work (kW)	1.973	1.951	2.009	1.982	1.963	1.956
Second compressor work (kW)	3.272	3.232	3.342	3.290	3.258	3.240
Third compressor work (kW)	24.32	23.88	25.87	24.61	24.25	23.81
Total compressor work (kW)	29.57	29.06	31.22	29.89	29.48	29.01
Mass flow rate in evaporator-1 (kg/sec)	0.3522	0.5299	0.3423	0.5470	0.6790	0.5935
Mass flow rate in evaporator-2 (kg/sec)	0.6043	0.9057	0.5928	0.9413	1.164	1.012
Mass flow rate in evaporator-3 (kg/sec)	0.8268	1.245	0.8231	1.323	1.625	1.367
EDR_{VCRS} (second method)	1.479	1.449	1.614	1.529	1.494	1.429
Exergetic Efficiency(using second Method)	0.4034	0.4083	0.3826	0.3955	0.4009	0.4116
Exergy Destruction Ratio(EDR_{VCRS}) (third method)	1.660	1.649	1.818	1.765	1.721	1.597
Exergetic Efficiency(using third Method)	0.3759	0.3775	0.3549	0.3617	0.3675	0.385
Second law Efficiency	0.6504	0.6618	0.6160	0.6435	0.6523	0.6630

Table-5(d): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporator individual compressors with multiple expansion valves using HFO blended refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K

Performance Parameters using R1234ze in given table-1(b)	R-450a	R-515a	R454b	R454c
First law Efficiency (COP $_{VCRS}$)	6.781	7.084	6.418	5.572
Exergy Destruction Ratio(EDR$_{VCRS}$)	1.481	1.398	1.622	2.020
Exergetic Efficiency	0.4030	0.4171	0.3814	0.3311
Exergy of Fuel "kW"	30.97	29.92	32.72	37.69
Exergy of product "kW"	12.48	12.48	12.48	12.48
Rational Efficiency	0.3434	0.3602	0.3347	0.2723
Total Exergy Destruction (%)	65.66	63.98	66.53	72.77
Exergy Destruction in condenser(%)	34.47	36.49	39.23	37.51
Exergy Destruction in evaporator(%)	21.31	18.40	16.60	23.67
Exergy Destruction in valves(%)	6.89	6.125	7.065	8.302
Exergy Destruction in sub-cooler(%)	2.99	2.967	3.646	3.246
System total Exergy Destruction (%)	65.66	63.98	66.53	72.77
Rational Exergetic efficiency (%)	34.34	36.02	33.47	27.23
Second law efficiency(COP/COP$_{_Carnot}$)	0.6210	0.6427	0.5878	0.5102
First compressor work (kW)	2.022	1.983	2.046	2.108
Second compressor work (kW)	3.356	3.292	3.404	3.509
Third compressor work (kW)	25.59	24.65	27.27	32.07
Total compressor work (kW)	30.97	29.92	32.72	37.69
Mass flow rate in evaporator-1 (kg/sec)	0.5863	0.6107	0.4112	0.5682
Mass flow rate in evaporator-2 (kg/sec)	1.007	1.048	0.7115	0.9811
Mass flow rate in evaporator-3 (kg/sec)	1.421	1.474	1.0	1.403
Exergy Destruction Ratio(EDR$_{VCRS}$) (using second method)	1.629	1.534	1.744	2.198
Exergetic Efficiency(using second Method)	0.3803	0.3946	0.3644	0.3127
Exergy Destruction Ratio(EDR$_{VCRS}$) (using third method)	1.912	1.776	1.988	2.672
Exergetic Efficiency (using third method)	0.3434	0.3602	0.3347	0.3989

The ideal thermodynamic performance of the modified vapor compression refrigeration system (System-4), operating with multiple evaporators, individual compressors, and multiple expansion valves, was evaluated using various ultra-low GWP ecofriendly refrigerants. The analysis assumed 80% isentropic efficiency for all three compressors. The comparative results—including coefficient of performance (COP), exergy efficiency, and exergy destruction across system components—are detailed in Tables 6(a) through 6(d). Among the studied refrigerants, HFO-1234ze(Z) exhibited the best performance in terms of both first and second law efficiencies, while HFO-1234yf showed the lowest overall thermodynamic performance. System-4, when using HCFO-1233zd (E), demonstrated slightly lower performance than with HFO-1234ze (Z), but outperformed HCFO-1224yd (Z). Furthermore, the thermodynamic performance of HCFO-1224yd (Z) remained superior to that of HFO-1336mzz (Z). Among the selected hydrofluoroolefins, HFO-1336mzz (Z) displayed better performance compared to several other ultra-low GWP alternatives. Notably, the system's electrical energy demand (i.e., exergy input or fuel equivalent) was highest when HFO-1234yf was employed.

Table-6(a): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR system (system-4) using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers using ecofriendly refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using *different ecofriendly refrigerants*	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	HFO-1234 Ze(E)	HFO-1243 zf	R12
First law Efficiency (COP $_{System}$)	7.114	6.965	7.004	6.947	6.80	6.636	6.818
Exergy Destruction Ratio(EDR$_{System}$)	1.346	1.416	1.403	1.422	1.475	1.536	1.468
Exergetic Efficiency $_{System}$	0.4263	0.4139	0.4162	0.4128	0.4041	0.3944	0.4052
Exergy of Fuel $_{System}$ "kW"	29.27	30.15	29.98	30.23	30.88	31.64	30.80
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.4444	0.421	0.43	0.4333	0.4334	0.4237	0.4322
Total Exergy Destruction (%)	55.56	56.56	56.51	56.67	56.66	57.63	56.78

Exergy Destruction in condenser(%)	37.15	36.48	35.86	35.26	34.23	33.35	34.93
Exergy Destruction in evaporator(%)	12.06	13.35	13.46	13.32	12.49	14.5	13.07
Exergy Destruction in valves(%)	6.329	7.717	7.189	8.093	9.941	10.03	8.784
Exergy Destruction in sub-cooler(%)	1.808	2.055	1.871	2.046	2.929	2.930	2.691
First compressor work (kW)	2.199	2.347	2.319	2.381	2.44	2.496	2.367
Second compressor work (kW)	3.559	3.759	3.72	3.80	3.89	3.984	3.804
Third compressor work (kW)	23.51	24.04	23.95	24.05	24.55	25.16	24.63
Total compressor work (kW)	29.27	30.15	29.98	30.23	30.88	31.64	30.80
Mass flow rate in evaporator-1 (kg/sec)	0.5663	0.7396	0.6256	0.7273	0.7346	0.6652	0.8534
Mass flow rate in evaporator-2 (kg/sec)	0.9408	1.221	1.034	1.196	1.212	1.102	1.417
Mass flow rate in evaporator-3 (kg/sec)	1.128	1.455	1.235	1.421	1.444	1.317	1.699
Exergy Destruction Ratio(EDR_{VCRS}) (second method)	1.346	1.416	1.403	1.422	1.475	1.536	1.468
Exergetic Efficiency (second method)	0.4263	0.4139	0.4162	0.4128	0.4041	0.3944	0.4052
Exergy Destruction Ratio(EDR_{VCRS}) (third method)	1.25	1.302	1.299	1.308	1.307	1.360	1.314
Exergetic Efficiency(third method)	0.4444	0.4344	0.4349	0.4333	0.4334	0.4237	04322
Second law efficiency (COP/COP_Carnot)	0.6570	0.6378	0.6414	0.6362	0.6227	0.6077	0.6244

Table-6(b): Effect of different ecofriendly refrigerants on the ideal thermodynamic performances of Modified VCR system (system-4) using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers using ecofriendly refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters *different ecofriendly refrigerants*	HFC-152a	HFC-245fa	HFC-32	HFC-134a
First law Efficiency (COP $_{VCRS}$)	6.893	6.987	6.528	6.767
Exergy Destruction Ratio(EDR_{VCRS})	1.441	1.408	1.578	1.487
Exergetic Efficiency	0.4096	0.4152	0.3879	0.4021
Exergy of Fuel “kW”	30.47	30.05	32.17	31.03
Exergy of product “kW”	12.48	12.48	12.48	12.48
Rational Efficiency(%)	0.433	0.4356	0.421	0.4313
Total Exergy Destruction (%)	56.7	56.44	57.9	56.87
Exergy Destruction in condenser(%)	35.8	35.35	36.28	34.32
Exergy Destruction in evaporator(%)	13.2	13.39	12.51	12.92
Exergy Destruction in valves(%)	7.702	7.698	9.108	9.624
Exergy Destruction in sub-cooler(%)	2.309	2.038	3.183	2.913
System total Exergy Destruction (%)	56.7	56.44	57.9	56.87
Rational Exergetic efficiency (%)	43.30	42.1	42.1	43.13
First compressor work (kW)	2.318	2.336	2.368	2.423
Second compressor work (kW)	3.735	3.742	3.83	3.879
Third compressor work (kW)	24.41	23.98	25.97	24.73
Total compressor work (kW)	30.97	30.05	32.17	31.03
Mass flow rate in evaporator-1 (kg/sec)	0.4139	0.6346	0.4035	0.6688
Mass flow rate in evaporator-2 (kg/sec)	0.6898	1.049	0.6794	1.110
Mass flow rate in evaporator-3 (kg/sec)	0.8299	1.251	0.8264	1.329

Table-6(c): Effect of different load conditions on the ideal thermodynamic performances of Modified VCR system(system-4) using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers *using ecofriendly refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)*

Performance Parameters using R1234ze in given table-1(b)	HFO-1225ye(Z)	HFO-1234yf	R-450a	R-515a	R454b	R454c
First law Efficiency (COP $_{VCRS}$)	6.733	6.597	6.521	6.747	6.209	5.372
Exergy Destruction Ratio(EDR_{VCRS})	1.499	1.551	1.581	1.490	1.710	2.132
Exergetic Efficiency	0.4001	0.3921	0.3875	0.4010	0.3690	0.3192
Exergy of Fuel “kW”	31.19	31.83	32.21	31.12	33.82	39.09

Exergy of product "kW"	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.4306	0.428	0.4164	0.4296	0.4042	0.3512
Exergy Destruction in condenser(%)	33.79	32.78	33.31	35.26	38.12	36.37
Exergy Destruction in evaporator(%)	12.91	12.65	14.76	12.22	11.55	17.15
Exergy Destruction in valves(%)	10.25	11.78	10.28	9.563	9.911	11.36
Exergy Destruction in sub-cooler(%)	3.05	3.594	2.890	2.866	3.543	3.148
System total Exergy Destruction (%)	56.94	57.2	58.36	57.04	59.58	64.88
Rational Exergetic efficiency (%)	43.06	42.8	41.64	42.96	40.42	35.12
First compressor work (kW)	2.465	2.548	2.497	2.447	2.461	2.628
Second compressor work (kW)	3.934	4.05	3.988	3.907	3.969	4.207
Third compressor work (kW)	24.79	23.23	25.72	24.77	27.39	32.26
Total compressor work (kW)	31.19	31.83	32.21	31.12	33.82	39.09
Mass flow rate in evaporator-1 (kg/sec)	0.8633	0.8547	0.7242	0.7536	0.4946	0.7083
Mass flow rate in evaporator-2 (kg/sec)	1.426	1.408	1.197	1.243	0.8295	1.176
Mass flow rate in evaporator-3 (kg/sec)	1.70	1.676	1.428	1.482	1.005	1.411
Exergy Destruction Ratio(EDR_{VCRS}) (second method)	1.499	1.551	1.581	1.490	1.710	2.132
Exergetic Efficiency (by second method)	0.4001	0.3921	0.3875	0.4010	0.3690	0.3192
Exergy Destruction Ratio(EDR_{VCRS}) (by third method)	1.322	1.336	1.402	1.328	1.474	1.848
Exergetic Efficiency (by third method)	0.4306	0.428	0.4164	0.4296	0.4042	0.3512
Second law efficiency (COP/COP_{Carnot})	0.6166	0.6042	0.5971	0.6179	0.5686	0.4915

The actual thermodynamic performance of the modified vapor compression refrigeration system (System-1), which incorporates ultra-low GWP ecofriendly refrigerants and assumes 100% isentropic efficiency for all three compressors, has been analyzed in terms of COP (first law efficiency), exergy efficiency, and component-wise exergy destruction. The comparative results are presented in Tables 3(a) through 3(d). Based on Table 3(a), the highest thermodynamic performance—both in terms of energy and exergy efficiencies—was achieved using HFO-1234ze (Z), while HFO-1234yf exhibited the lowest performance among all selected refrigerants. Systems using HCFO-1233zd (E) and HCFO-1224yd (Z) demonstrated slightly lower performance compared to HFO-1234ze(Z), but surpassed HFO-1336mzz(Z), HFO-1243zf, and HFO-1225ye(Z). Among the HCFO group, HCFO-1233zd (E) delivered superior actual thermodynamic performance relative to HCFO-1224yd (Z) and other ultra-low GWP alternatives. The electrical energy requirement (fuel exergy input) was found to be lowest when HFO-1234ze (Z) was used, and highest with CFC-12, highlighting the environmental and energy efficiency advantage of HFO-1234ze (Z). According to Table 3(b), the actual performances of HFO-1234ze (E), HFO-1243zf, and HFO-1225ye (Z) were marginally lower than that of CFC-12. However, HFO-1234yf consistently exhibited the lowest COP and exergy efficiency, alongside the highest electrical power consumption.

Table-7(a): Effect of different ecofriendly refrigerants on the actual thermodynamic performances of Modified VCR system (system-1) using multiple evaporators at different temperatures with compound compression and individual expansion valves *using HFOs & HCFOs refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 80%)*

Performance Parameters using different ecofriendly refrigerants	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	R12
First law Efficiency (COP_{System})	4.320	4.162	4.206	4.140	4.058
Exergy Destruction Ratio(EDR_{System})	2.896	3.043	3.001	3.065	3.147
Exergetic Efficiency $_{System}$	0.2567	0.2473	0.2499	0.2460	0.2412
Exergy of Fuel $_{System}$ "kW"	48.61	50.46	49.93	50.73	51.75
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48	12.48
Rational Efficiency(%)	25.67	24.73	24.99	24.6	24.12
Total Exergy Destruction (%)	74.33	75.27	75.01	75.88	75.53
Exergy Destruction in compressors(%)	17.83	18.44	18.36	18.45	17.92
Exergy Destruction in condenser(%)	39.58	37.09	37.76	36.75	37.0
Exergy Destruction in evaporator(%)	7.272	7.979	8.083	7.935	7.779
Exergy Destruction in valves(%)	7.506	9.232	8.517	9.695	10.18
Exergy Destruction in sub-cooler(%)	2.146	2.531	2.287	2.571	3.003

Relative COP (COP/COP_Carnot)	0.7912	0.7622	0.7703	0.7582	0.7433
First compressor work (kW)	26.58	27.7	27.38	27.89	27.37
Second compressor work (kW)	15.41	15.96	15.79	16.02	16.37
Third compressor work (kW)	6.622	6.809	6.753	6.821	7.002
Mass flow rate in evaporator-1 (kg/sec)	0.6060	0.8054	0.6762	0.7966	0.9289
Mass flow rate in evaporator-2 (kg/sec)	0.3973	0.5238	0.4407	0.5159	0.6078
Mass flow rate in evaporator-3 (kg/sec)	0.1954	0.2557	0.2155	0.2507	0.2985
Total Mass flow rate in condenser (kg/sec)	1.199	1.585	1.332	1.563	1.835
Exergetic Efficiency(by second Method)	0.3956	0.3811	0.3852	0.3791	0.3716
Exergetic Efficiency(by third Method)	0.2623	0.2537	0.2558	0.2525	0.2412
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	2.812	2.941	2.909	2.961	3.022

Table-7(b): Effect of different ecofriendly refrigerants on the actual thermodynamic performances of Modified VCR system(system-1) using multiple evaporators at different temperatures with compound compression and individual expansion valves using HFO refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 80%)

Performance Parameters using *different ecofriendly refrigerants*	HFO-1243zf	HFO-1234ze(E)	HFO-1225ye(Z)	HFO-1234yf	R12
First law Efficiency (COP $_{VCRS}$)	3.918	3.996	3.945	3.822	4.058
Exergy Destruction Ratio(EDR_{VCRS})	3.295	3.211	3.261	3.403	3.147
Exergetic Efficiency	0.2328	0.2375	0.2347	0.2271	0.2412
Exergy of Fuel “kW”	53.60	52.55	53.17	54.94	51.75
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.2328	0.2375	0.2347	0.2271	0.2412
Total Exergy Destruction (%)	76.72	76.25	76.53	77.29	75.53
Exergy Destruction in compressor (%)	18.19	18.42	18.40	18.43	17.92
Exergy Destruction in condenser(%)	34.98	35.22	34.78	33.34	37.0
Exergy Destruction in evaporator(%)	8.413	7.34	7.57	7.328	7.779
Exergy Destruction in valves(%)	11.76	11.83	12.21	14.02	10.18
Exergy Destruction in sub-cooler(%)	3.374	3.436	3.579	4.168	3.003
System total Exergy Destruction (%)	76.72	76.25	76.53	77.29	24.12
Rational Exergetic efficiency (%)	23.28	23.75	23.47	22.71	75.53
Second law efficiency(COP/COP_$_{Carnot}$)	0.7176	0.7319	0.7233	0.70	0.7433
First compressor work (kW)	29.48	28.91	29.26	30.30	27.37
Second compressor work (kW)	16.92	16.58	16.78	17.31	16.37
Third compressor work (kW)	7.198	7.055	7.135	7.337	7.002
Total system(three compressors) work (kW)	53.6	52.55	53.17	54.94	51.75
Mass flow rate in evaporator-1 (kg/sec)	0.7359	0.8167	0.9626	0.9682	0.9289
Mass flow rate in evaporator-2 (kg/sec)	0.4797	0.5302	0.6269	0.6269	0.6078
Mass flow rate in evaporator-3 (kg/sec)	0.2347	0.2585	0.3051	0.3047	0.2985
Mass flow rate in condenser (kg/sec)	1.45	1.605	1.893	1.90	1.835

The actual thermodynamic performance of the modified vapor compression refrigeration (VCR) systems using low-GWP ecofriendly refrigerants was evaluated under the condition of 100% isentropic efficiency for all three compressors. Performance indicators, including the coefficient of performance (COP), exergy efficiency, and component-wise exergy destruction, are presented in Table 3(b). Among all evaluated refrigerants, HCFC-123 exhibited the highest first and second law efficiencies, while HFC-32 demonstrated the lowest performance. The system performance with HFC-152a was found to be slightly lower than that of HFC-245fa but marginally better than HFC-134a. Further evaluation under a reduced isentropic efficiency condition of 80% is presented in Table 3(c). Under this more realistic operational assumption, the highest thermodynamic performance was recorded with refrigerant R-515a, while the lowest was observed using R-454c. For this configuration, the performance of the system using R-450a was slightly below that of R-513a, but superior to that using R-454b.

Table-7(c): Effect of different ecofriendly refrigerants on the actual thermodynamic performances Modified VCR system (system-1) using multiple evaporators at different temperatures with compound compression and individual expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K

Performance Parameters	HFC-152a	HFC-245fa	HFC-32	HFC-134a	R123	R124	R12
First law Efficiency (COP_{VCRS})	4.118	4.173	3.79	3.993	4.237	4.063	4.058
Exergy Destruction Ratio(EDR_{VCRS})	3.086	3.033	3.440	3.214	2.972	3.141	3.147
Exergetic Efficiency	0.2447	0.2480	0.2252	0.2373	0.2518	0.2415	0.2412
Exergy of Fuel “kW”	50.99	50.33	55.41	52.59	49.56	51.68	51.75
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.2447	0.2480	0.2252	0.2889	0.2518	0.2415	24.12
Total Exergy Destruction (%)	75.53	75.2	77.48	76.27	74.82	75.85	75.53
Exergy Destruction in compressors(%)	17.54	18.42	16.44	18.01	18.23	18.4	17.92
Exergy Destruction in condenser(%)	38.54	37.08	40.38	35.97	38.27	36.08	37.0
Exergy Destruction in evaporator(%)	7.887	7.994	7.264	7.627	7.974	7.592	7.779
Exergy Destruction in valves(%)	8.946	9.194	10.09	11.32	8.121	10.72	10.18
Exergy Destruction in sub-cooler(%)	2.612	2.515	3.296	3.342	2.217	3.061	3.003
System total Exergy Destruction (%)	75.53	75.20	77.48	76.27	74.82	75.85	75.53
Rational Exergetic efficiency (%)	24.47	24.80	22.52	23.73	25.81	24.15	24.47
First compressor work (kW)	27.94	27.62	30.37	28.89	27.15	28.4	27.37
Second compressor work (kW)	16.16	15.91	17.53	16.61	15.69	16.32	16.37
Third compressor work (kW)	6.912	6.796	7.502	7.085	6.722	6.958	7.002
Total compressor work (kW)	50.99	50.33	55.41	52.59	49.56	51.68	51.75
Mass flow rate in evaporator-1 (kg/sec)	0.4468	0.6908	0.4376	0.7378	0.7458	0.9129	0.9289
Mass flow rate in evaporator-2 (kg/sec)	0.2936	0.4497	0.2907	0.4821	0.4867	0.5936	0.6078
Mass flow rate in evaporator-3 (kg/sec)	0.1448	0.2197	0.1450	0.2364	0.2383	0.2897	0.2985
Mass flow rate in condenser (kg/sec)	0.8852	1.360	0.8733	1.456	1.471	1.796	1.835
Exergetic Efficiency(by second Method)	0.3771	0.3821	0.3471	0.3657	0.3880	0.3721	0.3716

Table-7(d): Effect of different ecofriendly refrigerants on the actual thermodynamic performances of Modified VCR system (system-1) using multiple evaporators at different temperatures with compound compression of multiple expansion valves *using HFO blended refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K*

Performance Parameters	R-450a	R-513a	R-515a	R454b	R454c	R12
First law Efficiency (COP_{VCRS})	3.854	3.881	3.973	3.633	3.251	4.058
Exergy Destruction Ratio (EDR_{VCRS})	3.366	3.336	3.236	3.632	4.177	3.147
Exergetic Efficiency	0.2290	0.2307	0.2361	0.2159	0.1932	0.2412
Exergy of Fuel “kW”	54.49	54.10	52.86	57.81	64.6	51.75
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.2290	0.2307	0.2361	0.2159	0.1932	0.2412
Total Exergy Destruction (%)	77.1	76.93	76.39	78.41	80.68	75.53
Exergy Destruction in compressors(%)	18.20	18.28	18.40	16.84	17.47	17.92
Exergy Destruction in condenser(%)	34.8	34.33	36.06	43.15	35.94	37.0
Exergy Destruction in evaporator(%)	8.726	7.379	7.196	6.756	10.38	7.779
Exergy Destruction in valves(%)	12.03	13.08	11.38	11.30	13.27	10.18
Exergy Destruction in sub-cooler(%)	3.35	3.872	3.349	3.758	3.622	3.003
System total Exergy Destruction (%)	77.1	76.93	76.39	78.41	80.68	75.53
Rational Exergetic efficiency (%)	22.90	23.07	23.61	21.59	19.32	24.47
Second law efficiency($COP/COP_{\_Carnot}$)	0.7068	0.7109	0.7276	0.6654	0.5954	0.7433
Exergy Efficiency(by second Method)	0.3529	0.3554	0.3638	0.3327	0.2977	24.47
First compressor work (kW)	29.95	29.79	29.07	31.66	35.26	27.37
Second compressor work (kW)	17.21	17.07	16.69	18.3	20.49	16.37
Third compressor work (kW)	7.334	7.251	7.104	7.847	8.854	7.002
Mass flow rate in evaporator-1 (kg/sec)	0.8033	0.8728	0.8349	0.5435	0.7932	0.9289
Mass flow rate in evaporator-2 (kg/sec)	0.5223	0.5675	0.5421	0.3593	0.5180	0.6078
Mass flow rate in evaporator-3 (kg/sec)	0.2449	0.2770	0.2643	0.1783	0.2540	0.2985
Mass flow rate in condenser(kg/sec)	1.581	1.717	1.641	1.081	1.565	1.835

The actual thermodynamic performance of the modified vapor compression refrigeration (VCR) systems using ultra-low GWP ecofriendly refrigerants was assessed at 80% isentropic efficiency for all three compressors. Key performance metrics—namely the coefficient of performance (COP), exergy efficiency, and component-wise exergy destruction—are summarized in Table 7(e). Among all refrigerants studied, HFO-1234ze (Z) demonstrated the highest first and second law efficiencies, whereas HFO-1234yf exhibited the lowest performance.

System-6.5 operating with HCFO-1233zd (E) showed slightly lower thermodynamic performance than HFO-1234ze(Z), but outperformed HCFO-1224yd(Z). In turn, the system using HCFO-1224yd (Z) performed marginally better than that using HFO-1336mzz (Z). Within the group of evaluated HFO refrigerants, HFO-1336mzz (Z) offered superior performance relative to several other ultra-low GWP alternatives.

Additionally, the electrical energy consumption (representing the exergy of the input fuel) increased with certain refrigerants, reaching its maximum when HFO-1234yf was used.

Table-7(e): Effect of different ecofriendly refrigerants on actual thermodynamic performances of vapour compression refrigeration system (system-3) using multiple evaporator individual compressors with multiple expansion valves using HFOs and HCFOs refrigerants using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using *different ecofriendly refrigerants*	HFO-1234 Ze(Z)	HCFO-1224 yd(Z)	HCFO-1233 zd(E)	HFO-1336 mzz(Z)	HFO-1243 Zf	HFO-1234 Ze(E)	R1225 ye(Z)	HFO-1234 yf	R12
First law Efficiency (COP_{VCRS})	5.866	5.733	5.752	5.698	5.443	5.577	5.522	5.413	5.608
Exergy Destruction Ratio(EDR_{VCRS})	1.869	1.935	1.935	2.119	2.265	2.187	2.218	2.283	2.001
Exergetic Efficiency	0.3486	0.3486	0.3418	0.3206	0.3062	0.3138	0.3109	0.3046	0.3332
Exergy of Fuel “kW”	35.8	36.63	36.51	36.86	38.59	37.65	38.03	38.8	37.45
Exergy of product “kW”	12.48	12.48	12.48	12.48	12.48	12.48	12.48	12.48	12.48
EDR_{VCRS} (by second Method)	1.966	2.339	2.040	2.067	2.186	2.11	2.137	2.186	2.12
Exergetic Efficiency (by 2^{nd} Method)	0.3372	0.2995	0.3290	0.3261	0.3139	0.3215	0.3187	0.3138	0.3205
Second law efficiency($COP/COP_{\_Carnot}$)	0.5372	0.5229	0.5267	0.5218	0.4996	0.5107	0.5057	0.4984	
EDR_{VCRS} (by third Method)	2.177	1.956	2.303	1.964	2.025	1.957	1.9771	1.993	2.408
Exergetic Efficiency(by third Method)	0.3147	0.3383	0.3028	0.3374	0.3306	0.3381	0.3359	33.41	0.2934
System total Exergy Destruction (%)	68.53	66.17	69.72	66.26	66.94	66.21	66.41	66.59	70.66
First compressor work (kW)	2.372	1.956	2.447	1.984	2.08	2.033	2.054	2.123	2.478
Second compressor work (kW)	3.956	4.689	4.064	4.739	4.968	4.852	4.906	5.05	4.125
Third compressor work (kW)	29.47	30.13	30.0	30.13	31.54	30.77	31.07	31.63	30.85
Total compressor work (kW)	35.8	36.77	36.51	38.86	38.59	37.65	38.03	38.8	37.41

The actual thermodynamic performance of the modified vapor compression refrigeration (VCR) systems (System-4) utilizing ultra-low GWP ecofriendly refrigerants was evaluated at 80% isentropic efficiency for all three compressors. The key parameters assessed—coefficient of performance (COP), exergy efficiency, and component-wise exergy destruction—are presented in Table 7(f). Among the refrigerants examined, HFO-1234ze (Z) delivered the highest performance according to both the first and second laws of thermodynamics, while HFO-1234yf showed the lowest. System-4 using HCFO-1233zd (E) exhibited slightly lower performance than HFO-1234ze (Z) but outperformed HCFO-1224yd (Z). Meanwhile, HCFO-1224yd (Z) yielded marginally better results than HFO-1336mzz (Z). Among the tested HFO refrigerants, HFO-1336mzz (Z) demonstrated relatively better performance than several other ultra-low GWP alternatives. Furthermore, the electrical power required to operate the system (reflecting the exergy of fuel input) increased across refrigerants, peaking when HFO-1234yf was used. Table 8(a) presents a comparative analysis of the ideal first-law thermodynamic performance across four modified vapor compression refrigeration (VCR) systems. Among these, System-3—which integrates multiple evaporators, compound compression (multiple compressors), multiple expansion valves, and intercooling at the condenser outlet—demonstrated the highest thermodynamic performance, accompanied by the lowest total electrical energy consumption across all three compressors.

In contrast, System-1, which employs multiple evaporators with individual compressors and expansion valves along with condenser-side intercooling, exhibited the lowest thermodynamic efficiency and the highest electrical energy demand. System-2, also configured with multiple evaporators and individual compressors and expansion valves, performed slightly below System-3 in terms of efficiency but better than System-1.

Table-7(f): Effect of different load conditions on the ideal thermodynamic performances of Modified VCR systems using multiple evaporators at different temperatures with compound compression of multiple expansion valves with flash chambers (system-4) using ecofriendly refrigerants using (Q_{eva1}=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiencies= 80%)

Performance Parameters using R1234ze in given table-1(b)	R-1234 ze(Z)	R-1224 yd(Z)	R1233 zd(E)	R1336 mzz(Z)	R1243 zf	R-1234 ze(E)	R1225 ye(Z)	R-1234 yf
First law Efficiency (COP $_{VCRS}$)	5.706	5.538	5.569	5.524	5.275	5.406	5.352	5.243
Exergy Destruction Ratio(EDR_{VCRS})	1.949	2.038	2.022	2.046	2.190	2.113	2.144	2.209
Exergetic Efficiency	03391	0.3291	0.3310	0.3283	0.3135	0.3212	0.3181	0.3116
Exergy of Fuel "kW"	36.8	37.92	37.71	38.02	39.81	38.85	39.24	40.05
Exergy of product "kW"	12.48	12.48	12.48	12.48	12.48	12.48	12.48	12.48
Rational Efficiency	0.3538	0.3456	0.3460	0.3446	0.3372	0.3404	0.3425	0.3402
Total Exergy Destruction (%)	64.62	65.44	65.40	65.54	66.28	65.96	65.75	65.96
Exergy Destruction in compressor (%)	19.08	19.46	19.41	19.48	19.32	19.47	19.45	19.48
Exergy Destruction in condenser(%)	30.88	29.19	29.54	29.0	27.61	28.19	27.85	27.02
Exergy Destruction in evaporator(%)	9.607	10.62	10.70	10.59	11.33	9.93	10.26	10.05
Exergy Destruction in valves(%)	5.057	6.166	5.744	6.465	8.013	7.943	8.188	9.049
Exergy Destruction in sub-cooler(%)	1.448	1.645	1.498	1.639	2.347	2.346	2.443	2.878
System total Exergy Destruction (%)	64.62	65.44	65.40	65.54	66.28	65.53	65.75	65.96
Rational Exergetic efficiency (%)	35.38	34.56	34.60	34.46	33.72	34.47	34.25	34.02
First compressor work (kW)	2.748	2.934	2.977	2.899	3.12	3.049	3.081	3.185
Second compressor work (kW)	4.462	4.715	4.765	4.665	4.998	4.880	4.934	5.08
Third compressor work (kW)	29.59	30.27	30.28	30.14	31.69	30.92	31.22	31.79
Total compressor work (kW)	36.8	37.92	38.2	37.71	39.81	38.85	39.24	40.06
Mass flow rate in evaporator-1 (kg/sec)	0.5663	0.7696	0.6256	0.7273	0.6652	0.7396	0.8633	0.8547
Mass flow rate in evaporator-2 (kg/sec)	0.9437	1.225	1.038	1.20	1.106	1.216	1.431	1.413
Mass flow rate in evaporator-3 (kg/sec)	1.136	1.466	1.243	1.431	1.327	1.455	1.713	1.689
EDR_{VCRS} (by IInd method)	1.906	1.988	1.976	1.996	2.114	2.04	2.067	2.112
Exergetic Efficiency (second method)	0.3442	0.3346	0.3360	0.3338	0.3211	0.3289	0.3260	0.3208
EDR_{VCRS} (third method)	1.948	2.038	2.021	2.046	2.189	2.113	2.144	2.209
Exergetic Efficiency(third method)	0.3392	0.3291	0.3310	0.3283	0.3136	0.3212	0.3181	0.3116
Relative COP (COP/COP$_{Carnot}$)	0.5226	0.5072	0.510	0.5058	0.4831	0.495	0.4901	0.4801

The maximum exergy destruction was identified in System-4, whereas the minimum occurred in System-1. Across all systems, the condenser emerged as the component contributing to the highest percentage of exergy destruction, while the subcooler exhibited the least. Comparative evaluation of Systems 2, 3, and 4 revealed that the third compressor in each configuration consumed the most electrical energy, while the first compressor had the least consumption. Additionally, the mass flow rate was highest in the third evaporator and lowest in the first. Finally, exergetic efficiency was computed using three distinct methods for all four systems. Results indicated that System-3 consistently achieved the highest exergy efficiency while requiring the least exergy input in the form of electrical energy.

Table-8(a): Comparison of ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporators multiple compressors, multiple expansion valves using HFO-1234ze(Z) refrigerant using (Q_{eva1}=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using eco friendly HFO1234ze(Z)	(Ideal) System-1	(Ideal) System-2	(Ideal) System-3	(Ideal) System-4
First law Efficiency (COP $_{System}$)	5.40	7.366	7.371	7.174
Exergy Destruction Ratio(EDR_{System})	2.116	1.285	1.283	1.346
Exergetic Efficiency $_{System}$	0.3209	0.4377	0.4380	0.4263
Exergy of Fuel $_{System}$ "kW"	38.89	28.51	24.89	29.27
Exergy of product $_{System}$ "kW"	12.48	12.48	12.48	12.48
Rational Efficiency(%)	32.09	39.54	39.55	44.44
Total Exergy Destruction (%)	67.96	60.46	60.45	55.56
Exergy Destruction in condenser(%)	46.76	38.11	38.05	37.15
Exergy Destruction in evaporator(%)	9.09	16.63	16.65	12.06
Exergy Destruction in valves(%)	9.382	3.872	3.895	6.329
Exergy Destruction in sub-cooler (%)	2.633	1.840	1.851	1.808

Total Exergy Destruction in system (%)	67.96	60.46	60.45	60.45
Rational exergetic efficiency Efficiency (%)	32.04	39.54	31.63	39.55
Second law efficiency (COP/COP_Carnot)	0.3297	0.4199	0.4202	0.4263
Exergy Destruction Ratio(EDR_{VCRS})	2.033	1.381	2.161	1.346
First compressor work (kW)	21.27	14.05	1.898	2.199
Second compressor work (kW)	12.33	8.497	3.156	3.559
Third compressor work (kW)	5.298	5.958	23.44	23.51
Total compressor work (kW)	38.89	28.51	24.89	29.27
Mass flow rate in evaporator-1 (kg/sec)	0.6060	0.4887	0.4887	0.5663
Mass flow rate in evaporator-2 (kg/sec)	0.3963	0.3435	0.834	0.9408
Mass flow rate in evaporator-3 (kg/sec)	0.1954	0.2859	1.125	1.128
Exergy Destruction Ratio(EDR_{VCRS})(by second Method)	2.116	1.529	1.528	1.250
Exergetic Efficiency(by second Method)	0.3209	0.3954	0.3955	0.4444

Table 8(b) presents a comparative assessment of the actual first-law thermodynamic performance for four modified vapor compression refrigeration (VCR) systems. Among the evaluated systems, System-3, which incorporates multiple evaporators, compound compression (with multiple compressors), multiple expansion valves, and intercooling at the condenser outlet, exhibited the best thermodynamic performance. It also registered the lowest electrical energy consumption across all three compressors. In contrast, System-1, consisting of multiple evaporators with individual compressors and expansion valves, along with intercooling, demonstrated the lowest actual thermodynamic efficiency and the highest total electrical power consumption among the systems. System-2, configured with multiple evaporators operating at different temperatures, individual compressors, individual expansion valves, and condenser-side intercooling, showed thermodynamic performance slightly inferior to System-3 but superior to System-1. The analysis also revealed that System-4 experienced the maximum exergy destruction, while System-1 showed the minimum exergy destruction. In all four systems, the condenser was identified as the component responsible for the highest percentage of exergy destruction, whereas the subcooler contributed the least. A detailed comparison among System-2, System-3, and System-4 revealed that the third compressor consistently incurred the highest electrical energy consumption, while the first compressor consumed the least. Additionally, the effective mass flow rate was observed to be highest in the third evaporator and lowest in the first evaporator across these systems.

Table-8(b): Comparison of actual thermodynamic performances of vapour compression refrigeration systems using multiple evaporators multiple compressors, multiple expansion valves using HFO-1234ze (Z) refrigerant using (Q_{eva1}=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using eco friendly HFO1234ze(Z)	Actual System-1	Actual System-2	Actual System-3	Actual System-4
First law Efficiency (COP_{System})	4.32	5.893	5.866	5.706
Exergy Destruction Ratio(EDR_{System})	2.896	1.856	1.869	1.949
Exergetic Efficiency $_{System}$	0.2567	0.3502	0.3486	0.3391
Exergy of Fuel $_{System}$ “kW”	48.61	35.64	35.8	36.8
Exergy of product $_{System}$ “kW”	12.48	12.48	12.48	12.48
Rational Efficiency(%)	25.67	31.63	31.47	35.38
Total Exergy Destruction (%)	74.33	68.37	68.53	64.62
Exergy Destruction in compressors (%)	17.83	18.47	19.13	19.08
Exergy Destruction in condenser(%)	39.58	32.02	31.61	30.88
Exergy Destruction in evaporator(%)	7.272	13.31	13.26	9.607
Exergy Destruction in valves(%)	7.506	3.098	3.118	5.057
Exergy Destruction in sub-cooler (%)	2.146	1.472	1.482	1.448
Total Exergy Destruction in system (%)	74.33	68.37	68.53	64.62
Rational exergetic efficiency Efficiency (%)	25.67	31.63	31.47	35.38
Second law efficiency(COP/COP_Carnot)	0.3956	0.5396	0.5372	0.5226
Exergy Destruction Ratio(EDR_{VCRS})	2.89	1.962	2.177	1.949
First compressor work (kW)	26.58	17.57	2.372	2.748
Second compressor work (kW)	15.41	10.62	3.956	4.462
Third compressor work (kW)	6.622	7.448	29.47	29.59
Total compressor work (kW)	48.61	35.64	35.8	36.8
Mass flow rate in evaporator-1 (kg/sec)	0.6060	0.4887	0.4887	0.5663
Mass flow rate in evaporator-2 (kg/sec)	0.3973	0.3435	0.834	0.9408
Mass flow rate in evaporator-3 (kg/sec)	0.1954	0.2859	1.131	1.128
Exergy Destruction Ratio(EDR_{VCRS})(by second Method)	2.812	1.962	1.966	1.948
Exergetic Efficiency(by second Method)	0.2623	0.3387	0.3372	0.3392

Tables 9(a), 9(b), and 9(c) illustrate the thermodynamic and exergetic performance of a vapor compression refrigeration system under six distinct loading conditions for three system configurations—System-2, System-3, and System-4—each using the low-GWP refrigerant HFO-1234ze(Z). All configurations operate with three evaporators set at constant evaporating temperatures of 273 K, 278 K, and 283 K, respectively, and a fixed condenser temperature of 313 K with a subcooled liquid exiting at 303 K. By varying the cooling load distribution among the evaporators, different operational scenarios are simulated, and key performance indicators such as COP, exergy destruction, and efficiencies are evaluated.

In **System-2** (Table 9a), which operates under real compressor conditions, the coefficient of performance (COP) varies from 7.366 to 7.960 across the loading conditions, with the best performance observed under Loading Condition-6. The exergy destruction ratio (EDR) ranges between 1.285 and 1.601, while exergetic efficiency declines with increased imbalance in mass flow distribution, ranging from 0.3844 to 0.4377. The total compressor work fluctuates between 25.69 kW and 28.51 kW, depending on evaporator demand. The highest exergy destruction (64.17%) occurs in Loading Condition-5, corresponding to the lowest rational efficiency (35.83%). Second law efficiency improves as the system approaches ideal performance, with values spanning from 0.6745 to 0.7487.

System-3 (Table 9b), which assumes 100% isentropic efficiency in all compressors, exhibits slightly improved COP values compared to System-2, peaking at 8.176. Due to idealized compression, compressor work and the associated exergy of fuel are marginally reduced. While trends in exergetic efficiency and EDR remain similar to those in System-2, the overall exergy destruction across components such as the condenser, evaporators, expansion valves, and subcooler shows slight reductions. These improvements highlight the impact of isentropic efficiency on overall system performance and underscore the thermodynamic advantage of ideal compression assumptions.

Table-9(a): Effect of different loading conditions at different temperatures on the ideal thermodynamic performances of vapour compression refrigeration system(system-2) usingHFO-1234ze(Z) in the multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (T_{eva1}=273K, T_{eva2}=278K, T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K

Performance Parameters using different loading conditions at different temperatures	Loading Condition -1	Loading Condition -2	Loading Condition-3	Loading Condition-4	Loading Condition -5	Loading Condition-6
Q_{eva1} (kW)	105	105	70	70	35	35
Q_{eva2}(kW)	70	35	105	35	70	105
Q_{eva3}(kW)	35	70	35	105	105	70
First law Efficiency (COP_{System})	7.366	7.550	7.556	7.953	0.175	7.960
Exergy Destruction Ratio(EDR_{System})	1.285	1.349	1.362	1.506	1.601	1.509
Exergetic Efficiency $_{System}$	0.4377	0.4257	0.4257	0.3991	0.3844	0.3985
Exergy of Fuel $_{System}$ “kW”	28.51	27.82	27.79	26.4	25.69	26.38
Exergy of product $_{System}$ “kW”	12.48	11.84	11.82	10.557	9.874	10.51
EDR_{VCRS} (by second Method)	1.381	1.434	1.448	1.576	1.669	1.572
Exergetic Efficiency(by second Method)	0.4199	0.4108	0.4085	0.3882	0.3746	0.3888
Exergy Destruction in condenser(%)	38.11	38.94	38.97	40.76	41.75	40.78
Exergy Destruction in evaporator(%)	16.63	16.31	16.8	16.12	16.28	16.64
Exergy Destruction in valves(%)	3.872	3.924	3.929	4.040	4.106	4.046
Exergy Destruction in sub-cooler(%)	1.840	1.882	1.883	1.973	2.024	1.975
Total Exergy Destruction (%)	60.46	61.05	61.58	62.89	64.17	63.44
Rational Efficiency(%)	39.54	38.95	38.42	37.11	35.83	36.56
First compressor work (kW)	14.05	14.05	9.37	9.37	4.685	4.685
Second compressor work (kW)	8.497	4.413	12.47	4.303	8.277	12.36
Third compressor work (kW)	5.958	9.348	5.953	12.73	12.73	9.336
Total compressors work (kW)	28.51	27.82	27.79	26.40	25.69	26.38
Mass flow rate in evaporator-1 (kg/sec)	0.4887	0.4887	0.3258	0.3258	0.1629	0.1629
Mass flow rate in evaporator-2 (kg/sec)	0.3435	0.1784	0.5042	0.1740	0.3347	0.4998
Mass flow rate in evaporator-3 (kg/sec)	0.2859	0.4484	0.2856	0.6108	0.6105	0.4479
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	1.529	1.568	1.683	1.695	1.791	1.736
Exergetic Efficiency (by third Method)	0.3954	0.3895	0.3842	0.3711	0.3583	0.3656
Second law efficiency(COP/COP_{Carnot})	0.6745	0.6914	0.6919	0.7283	0.7487	0.7290
Rational Efficiency(by second Method)	0.4199	0.4108	0.4084	0.3882	0.38074	0.38535

Table-9(b): Effect of different on the ideal thermodynamic performances of vapour compression refrigeration system (system-3) using ecofriendlyHFO-1234ze(Z) refrigerant in the multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze refrigerant using (Q_eva1=105 kW at T_{eva1}=273K, Q_{eva2}=70 kW at T_{eva2}=278K, Q_eva1=35 kW at T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using different loading conditions at different temperatures	Loading Condition-1	Loading Condition -2	Loading Condition -3	Loading Conditio n-4	Loading Conditio n-5	Loading Condition-6
Q_{eva1} (kW)	105	105	70	70	35	35
Q_{eva2}(kW)	70	35	105	35	70	105
Q_{eva3}(kW)	35	70	35	105	105	70
First law Efficiency (COP $_{System}$)	7.371	7.554	7.56	7.957	8.176	7.963
Exergy Destruction Ratio(EDR_{System})	1.283	1.348	1.351	1.505	1.601	1.508
Exergetic Efficiency $_{System}$	0.4380	0.4259	0.4254	0.3992	0.3845	0.3987
Exergy of Fuel $_{System}$ “kW”	28.49	27.8	27.78	26.39	25.68	26.37
Exergy of product $_{System}$ “kW”	12.48	11.84	11.82	10.54	9.874	10.51
Exergy Destruction in condenser (%)	38.05	38.88	38.91	40.71	41.72	40.74
Exergy Destruction in evaporator (%)	16.65	16.33	16.82	16.13	16.29	16.65
Exergy Destruction in valves (%)	3.895	6.395	3.95	4.058	4.119	4.061
Exergy Destruction in sub-cooler (%)	1.851	1.892	1.893	1.961	2.030	1.982
Total Exergy Destruction (%)	60.45	61.04	61.57	62.88	64.16	63.43
Rational Efficiency(%)	39.55	38.96	38.43	37.12	35.84	36.56
First compressor work (kW)	1.898	1.896	1.265	1.265	0.6326	0.6326
Second compressor work (kW)	3.156	2.532	3.145	1.896	1.885	2.509
Third compressor work (kW)	23.44	23.37	23.37	23.23	23.16	23.23
Total compressors work (kW)	28.49	27.8	27.78	26.39	25.68	26.37
Mass flow rate in evaporator-1 (kg/sec)	0.4887	0.4887	0.3258	0.3258	0.1629	0.1629
Mass flow rate in evaporator-2 (kg/sec)	0.8345	0.6694	0.8315	0.5013	0.4983	0.6634
Mass flow rate in evaporator-3 (kg/sec)	1.124	1.121	1.121	1.115	1.111	1.114
Exergy Destruction Ratio(EDR_{VCRS}) (by second Method)	1.380	1.433	1.447	1.575	1.601	1.591
Exergetic Efficiency (by second Method)	0.4202	0.4110	0.4086	0.3884	0.3747	0.3859
Exergy Destruction Ratio(EDR_{VCRS}) (by third Method)	1.529	1.567	1.602	1.694	1.790	1.735
Exergetic Efficiency(by third Method)	0.3955	0.3842	0.3842	0.3712	0.3584	0.3656
Second law efficiency(COP/$COP_{\_Carnot}$)	0.675	0.6918	0.6923	0.7286	0.7489	0.7290
Rational Efficiency	0.3955	0.3896	0.3843	0.3712	0.3584	0.3656

Table-9(c): Effect of different loading conditions at different temperatures on the ideal thermodynamic performances of vapour compression refrigeration system (system-4) using HFO-1234ze(Z) on the ideal thermodynamic performances of vapour compression refrigeration systems using multiple evaporator individual compressors with multiple expansion valves using HFO-1234ze(Z) refrigerant using (T_{eva1}=273K, T_{eva2}=278K, T_{eva3}=283K, T_{Cond}=313K, $T_{Subcooled\_Liquid}$=303K, compressors isentropic efficiency= 100%)

Performance Parameters using different loading conditions at different temperatures	Loading Condition-1	Loading Condition-2	Loading Condition-3	Loading Condition-4	Loading Condition-5	Loading Condition-6
Q_{eva1} (kW)	105	105	70	70	35	35
Q_{eva2}(kW)	70	35	105	35	70	105
Q_{eva3}(kW)	35	70	35	105	105	70
First law Efficiency (COP $_{System}$)	7.174	7.37	7.383	7.812	8.06	7.826
Exergy Destruction Ratio(EDR_{System})	1.346	1.406	1.407	1.551	1.639	1.552
Exergetic Efficiency $_{System}$	0.4263	0.4155	0.4155	0.3919	0.3790	0.3918
Exergy of Fuel $_{System}$ “kW”	29.27	28.49	28.44	26.88	26.05	26.83
Exergy of product $_{System}$ “kW”	12.48	11.84	11.82	10.54	9.874	10.51
Exergy Destruction Ratio(EDR_{VCRS})	1.303	1.362	1.407	1.502	1.586	1.502
Exergetic Efficiency	0.4342	0.4234	0.4233	0.3997	0.3867	0.3918
Exergy Destruction in condenser(%)	37.15	38.05	38.11	40.05	41.18	40.12
Exergy Destruction in evaporator(%)	12.08	12.39	12.41	13.09	13.48	13.12
Exergy Destruction in valves(%)	6.139	6.165	6.083	5.721	5.433	5.634

Exergy Destruction in sub-cooler(%)	1.716	1.851	1.854	1.949	2.004	1.952
Total Exergy Destruction (%)	56.96	56.6	56.6	58.86	60.10	58.87
Rational Efficiency(%)	43.04	43.4	43.40	41.14	39.9	41.13
First compressor work (kW)	2.199	2.199	1.466	1.466	0.7329	0.7329
Second compressor work (kW)	3.559	2.856	3.544	2.138	2.123	2.826
Third compressor work (kW)	23.517	23.44	23.43	23.28	23.20	23.27
Total compressors work (kW)	29.27	28.49	28.44	26.88	26.05	26.83
Mass flow rate in evaporator-1 (kg/sec)	0.5663	0.5663	0.3775	0.3775	0.1888	0.1888
Mass flow rate in evaporator-2 (kg/sec)	0.9408	0.7550	0.9369	0.5653	0.5614	0.7472
Mass flow rate in evaporator-3 (kg/sec)	1.128	1.124	1.124	1.117	1.113	1.117
Second law efficiency(COP/COP_$_{Carnot}$)	0.657	0.675	0.6761	0.7153	0.7381	0.7167
Rational Efficiency	0.4304	0.434	0.4340	0.4114	0.3990	0.4113

The rational efficiency reaches a maximum of 39.55% in Loading Condition-1 and declines with decreasing load. The second law efficiency continues to improve with load balancing and higher COPs. System-4 (Table 9c) also assumes 100% isentropic efficiency but presents a slight design variation. In this case, COP values are slightly lower than System-3, ranging from 7.174 to 8.060. Exergetic efficiency and rational efficiency follow similar trends as in previous systems but show higher values under balanced load distributions (e.g., 43.4% in Loading Condition-2). Exergy destruction is slightly lower across all components, particularly in the valves and subcooler. Mass flow rates vary depending on load but follow a consistent pattern across all three systems. Overall, the analysis highlights that better thermodynamic and exergetic performance is achieved under balanced load conditions, with higher COP, lower exergy destruction, and improved second law efficiency. The use of HFO-1234ze(Z) proves effective in all configurations, demonstrating environmentally friendly operation while maintaining competitive performance under varying operational demands.

3. Conclusions & Recommendation

Based on the thermodynamic analysis of four modified vapor compression refrigeration (VCR) systems using ultra-low GWP ecofriendly refrigerants, the following conclusions were drawn:

- Superior Performance with HFO-1234ze(Z): Among all tested refrigerants, HFO-1234ze(Z) exhibited the highest first- and second-law efficiencies (COP and exergy efficiency) across all four modified VCR systems. It also resulted in the lowest electrical energy consumption, making it the most energy-efficient and environmentally friendly option.
- Inferior Performance with HFO-1234yf: The lowest energy and exergy performances were observed when using HFO-1234yf, which also led to the highest electrical power consumption in all modified systems.
- Performance of HCFO-1224yd(Z): The use of HCFO-1224yd(Z) provided moderate thermodynamic performance, with energy and exergy efficiencies slightly lower than HCFO-1233zd(E) but higher than other ecofriendly refrigerants such as HFO-1336mzz(Z), R-1234ze(E), R-1225ye(Z), and R-1243zf in all system configurations.
- Performance of HFO-1336mzz(Z): While HFO-1336mzz(Z) performed worse than HCFO-1233zd(E) and HCFO-1224yd(Z), it still outperformed other ultra-low GWP refrigerants (R-1234ze(E), R-1225ye(Z), R-1243zf), indicating its viability in energy-conscious designs.
- System Comparison – Exergy of Fuel (Power Consumption): Among all systems, System-6 exhibited the lowest electrical energy consumption, whereas System-1 required the highest, indicating significant differences in exergy demand due to system configurations.
- Effect of Variable Cooling Load on COP: When subject to variable load conditions, the COP increased across all systems, reaching a peak at Load Condition-5, and subsequently decreased beyond that point.
- Effect on Electrical Energy Consumption: Electrical power consumption of all three compressors in the modified systems decreased up to Load Condition-5 and then increased, highlighting an optimal load condition for minimal energy input.
- Effect on Exergy Efficiency: Conversely, exergy efficiency decreased with increasing load, reaching a minimum at Load Condition-5, and then increased, indicating a trade-off between energy and exergy performances under varying loads.
- Component-Level Exergy Destruction: In the actual performance analysis at 80% compressor isentropic efficiency, the maximum exergy destruction consistently occurred in the condenser component across all systems, while other components such as subcoolers showed minimal exergy losses.

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