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RESEARCH PAPER

Thermal (energy-exergy) performances of modified VCRS with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves with back pressure valves using low GWP

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Abstract

This work investigates the thermodynamic performance of low-GWP, eco-friendly hydrochlorofluoroolefin (HCFO) refrigerants, which are increasingly adopted due to their very short atmospheric lifetimes. HCFO-1233zd(E), with an ODP < 0.0004, and HCFO-1224yd(Z), with an ODP < 0.00023, were evaluated in a vapour compression refrigeration (VCR) system incorporating multiple evaporators at different temperatures, a single compressor, a sub-cooler, and multiple expansion valves. Detailed energy–exergy analysis (coefficient of performance) and second-law analysis (exergetic efficiency) were performed to determine thermodynamic behaviour and to minimize compressor power consumption. The results show that HCFO-1224yd(Z) exhibits slightly lower COP and exergetic efficiency than HCFO-1233zd(E), yet both outperform many HFO and HFO-blended refrigerants. Numerical simulations were conducted to identify the minimum electrical energy consumption for six different evaporator loading conditions in the multi-evaporator VCR system, revealing an optimum at loading condition V when using HFO-1234ze(E) and HFO-1234yf. Additionally, the influence of seven evaporator temperature settings at the optimum loading was examined in terms of exergetic efficiency, second-law efficiency, and relative COP for HFO refrigerants. Comparative analysis was also carried out for HFOs, HCFOs, low-GWP HFCs and HCFCs, and HFO/HFC blends, providing comprehensive insight into their suitability as next-generation sustainable refrigerants.

1. Introduction

Systems based on vapor compression technology for heating, air conditioning, and refrigeration have worked with a wide range of refrigerants in the past. Given the fact that they have specific thermophysical and safety features suitable for certain applications, these fluids are crucial to the operation and design of refrigeration systems. Hydrofluorocarbons (HFCs) are among these refrigerants and are widely utilized all over the world. Due to their high global warming potential (GWP) or high permanence in the atmosphere, they significantly contribute to the greenhouse effect. For instance, R134a is one of the most often utilized as a working fluid HFC refrigerants in HACR because of its high efficiency. However, it is a fluid that significantly contributes to the greenhouse effect because of its high GWP of 1300.

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Primarily as a result of growing global warming, various agreements and regulations have been established in recent decades to lessen the environmental damage produced by refrigerants. Regarding this, the European Union intends to phase out 79% of HFC refrigerants by the end of 2030 by limiting their use if they have global warming potential values exceeding 150 refrigeration and air conditioning. In addition to the aforementioned, internationally speaking, the Kigali Amendment, which called for a decrease of 80 to 85% in HFC consumption and production by the middle of the twenty-first century, was passed in 2016. The roadmap for the implementation of this amendment was established in Mexico by the Ministry of the environment and natural resources, and it defines alternative refrigerants in domestic refrigeration applications such as the use of R600a (a hydrocarbon (HC)), and HFO-1234yf (hydrofluoroolefin), as alternatives to medium GWP ecofriendly HFC-134a. Thus, the refrigeration industries have been forced to make significant changes towards the development and use of environmentally friendly refrigerants. In this sense, synthetic fluids such as HFOs have been considered as viable refrigerants to replace R134a. Hydro chloro fluoro olefins (HCFOs) are a new refrigerants group that contains fluorine and chlorine; this group has a relatively low GWP and a negligible ODP. HCFOs have been promoted as chiller-suitable refrigerants with a very short atmospheric lifetime. HCFO-1233zd(E), which has an ODP < 0.0004. Another refrigerant from the same group still under investigation is HCFO-1224yz(Z). However, the thermodynamic performances using HCFO-1224yz(Z) is slightly lower than using HCFO-1233zd(E) [2]. The change in evaporator and condenser temperatures of two stage vapour compression refrigeration plant using R22 add considerable effect on plant irreversibility [3] and suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator**.** The effect of using a suction line heat exchanger on the performance of an R-134a automotive air-conditioning system with a 40 °C condenser temperature. The study reported a 5–10% improvement in the system COP and concluded that HFO-1234yf as a replacement for R-134a because it provides similar thermodynamic properties but with a lower heat of vaporization. Accordingly, it offers a lower capacity for the same compressor size, which makes it suitable for the suction line heat exchanger. The suction line heat exchanger was applied to R-134a and HFO-1234yf systems as a solution for the capacity loss when using HFO-1234yf, which improved the system cooling capacity by 2–10%; the COP of the system was not stressed enough in this study, as the main objective was to study the cooling capacity [4]. Based on the literature it was observed that researchers have not gone through detailed first & second law (energy-exergy) analysis in terms of coefficient of performance and second law analysis in term of exergetic efficiency, second law efficiency and relative COP and to find out minimum electrical energy consumption by the compressor in the vapour compression refrigeration system with multiple evaporators at different temperatures using single compressor with sub cooler and multiple expansion valves.

2. Results and Discussion

The input numerical values have been taken to validate thermal model were shown in table 1. It was found that results obtained from thermal model well matched results as shown in table-1 respectively.

Table 1: Validation of results obtained from model

Performance Parameters	Model	Ref.[5]
First Law Efficiency (COP)	4.80	5.232
Work done by compressor “kW”	43.76	40.14
Mass flow rate in first evaporator(kg/min)	28.11	28.18
Mass flow rate in first evaporator (kg/ min)	44.694	44.82
Mass flow rate in first evaporator (kg/ min)	29.394	29.55
Compressor efficiency	100%	100%

The results presented in Tables 1(b) and 2(c) clearly demonstrate the significant effects of sub-cooling on the thermodynamic performance of a vapour compression refrigeration (VCR) system operating with multiple evaporators at different temperatures using R-12 as the working refrigerant with a 100% compressor efficiency assumption. Table 1(b) reveals that introducing sub-cooling markedly enhances system behaviour, as evidenced by an increase in the first-law efficiency (COP) from 4.809 to 5.232, representing an improvement of approximately 8.8%. This improvement occurs because sub-cooling increases the refrigerating effect through a higher enthalpy difference at the evaporator inlet without altering the mass flow rate in the first and second evaporators, both of which remain constant. Additionally, the compressor work decreases from 43.67 kW to 40.14 kW, a reduction of about 8.08%, indicating better energy utilization. The most noticeable change is observed in the mass flow rate of the third evaporator, which increases significantly by about 29.26%, suggesting that sub-cooling enables a greater proportion of the refrigerant to expand through the lower-temperature evaporator, permitting improved load distribution and enhanced system stability.

Table 2 further strengthens the conclusion by examining detailed energy and exergy performance under specific evaporator heat loads and temperature conditions. With sub-cooling, the COP increases from 4.163 to 4.530, confirming the improvement in cooling effectiveness relative to power input. Compressor work again decreases, dropping from 50.44 kW to 46.36 kW, highlighting lower electrical energy consumption. Beyond first-law advantages, exergy analysis reveals substantial improvements: the exergy destruction ratio decreases from 1.932 to 1.618, indicating reduced thermodynamic irreversibility, while system exergy efficiency improves from 0.3422 to 0.3820. Second-law efficiency also rises from 0.4255 to 0.4730, and relative COP increases from 0.6565 to 0.7248, collectively showing that sub-cooling enhances both energy quality and system effectiveness. Mass flow rates in the first and second evaporators remain unchanged, but changes in the third evaporator’s mass flow behaviour reflect altered refrigerating capacities produced by sub-cooling. The condenser mass flow rate decreases from 1.854 to 1.708 kg/s, implying reduced refrigerant circulation requirements. Overall, both tables confirm that sub-cooling significantly enhances first-law and second-law performance, reduces compressor energy demand, minimizes system irreversibility, and provides improved operational stability in multi-evaporator VCR systems.

Table 1(b): Effect of sub cooling on thermodynamic performances of vapour compression refrigeration systems with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves using R-12 refrigerant. for 100% compressor efficiency

Performance Parameters	With sub cooling	Without subcooling	% difference
First Law Efficiency (COP)	5.232	4.809	8.796
Work done by compressor "kW"	40.14	43.67	-8.083
Mass flow rate in first evaporator (kg/ min)	28.18	28.18	0.0 %
Mass flow rate in second evaporator (kg/ min)	44.82	44.82	0.0 %
Mass flow rate in first evaporator (kg/ min)	29.55	38.196	29.259%

Table 2: Effect of sub cooling on thermodynamic performances of vapour compression refrigeration systems with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves using R-12 refrigerant for 100% isentropic compressor efficiency for input data :$Q_{\_eva1}$=105 kW, $Q_{\_eva2}$=70 kW, $Q_{\_eva3}$=35 kW, $T_{\_eva1}$ =263 K, $T_{\_eva2}$ =278 K, $T_{\_eva3}$ =283 K, $T_{\_Cond}$=313 K, $T_{\_Subcooled\ fluid\ out\ at\ condenser\ outlet}$ =303 K, and Compressor Efficiency=100%)

Performance Parameters	With sub cooling	Without sub cooling
First Law Efficiency (COP)	4.530	4.163
Work done by compressor "kW"	46.36	50.44
Exergy Destruction Ratio	1.618	1.932
System exergy Efficiency	0.3820	0.3422
Exergy of fuel kW	46.36	50.44
Exergy of Product kW	17.71	17.71
Second Law efficiency	0.4730	0.4255
Relative_COP	0.7248	0.6565
Mass flow rate in first evaporator (kg/sec)	0.7364	0.7364
Mass flow rate in second evaporator (kg/ sec)	0.4849	0.4849
Effective mass flow rate in second evaporator (kg/ sec)	0.5087	0.5087
Mass flow rate in third evaporator (kg/sec)	0.2751	0.2985
Effective mass flow rate in third evaporator (kg/ sec)	0.4631	0.6086
Mass flow rate in condenser (kg/ sec)	1.708	1.854

The results from Tables 2, 3, 4, and 5 collectively show that sub-cooling plays a crucial role in enhancing the performance of vapour compression refrigeration systems equipped with multiple evaporators, a single compressor, and multiple expansion valves. For R-12 (Table 2), sub-cooling increases the COP from 4.163 to 4.530 and reduces compressor work from 50.44 kW to 46.36 kW, demonstrating an improvement in both system efficiency and energy consumption. Exergy destruction decreases from 1.932 to 1.618, while system exergy efficiency rises from 0.3422 to 0.3820, indicating reduced thermodynamic irreversibility. Second-law efficiency also improves significantly (0.4255 to 0.4730), and relative COP increases from 0.6565 to 0.7248.

Table 3: Thermodynamic performances of vapour compression refrigeration systems with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves using HFO-1234yf refrigerant

Performance Parameters	With sub cooling	Without sub cooling
First Law Efficiency (COP)	4.348	3.848
Work done by compressor "kW"	48.29	54.58
Exergy Destruction Ratio	1.825	2.317
System exergy Efficiency	0.3539	0.3015
Exergy of fuel kW	48.29	54.58
Exergy of Product kW	17.09	16.48
Second Law efficiency	0.4408	0.3780
Relative_COP	0.6809	0.5907
Mass flow rate in first evaporator(kg/s)	0.6984	0.6984
Mass flow rate in second evaporator(kg/s)	0.4560	0.4560
Effective mass flow rate in second evaporator (kg/ s)	0.4861	0.4861
Mass flow rate in third evaporator (kg/ s)	0.2708	0.3047
Effective mass flow rate in third evaporator (kg/ sec)	0.5221	0.7361
Mass flow rate in condenser (kg/s)	1.707	1.921

Mass flow rates in the first and second evaporators remain constant, but the third evaporator shows a reduction in mass flow under sub-cooled conditions, meaning the refrigerating effect per unit mass increases. Similar trends are observed for HFO-1234yf in Table 3, where sub-cooling raises the COP from 3.848 to 4.348 and lowers compressor work from 54.58 to 48.29 kW. Exergy destruction is notably reduced (2.317 to 1.825), and the system exergy efficiency improves from 0.3015 to 0.3539. A substantial increase in second-law efficiency (0.3780 to 0.4408) and relative COP (0.5907 to 0.6809) further confirms the positive impact of sub-cooling on modern low-GWP refrigerants. For HFO-1234ze(E), Table 4 shows that sub-cooling increases the COP from 3.078 to 3.479 and decreases compressor work from 68.22 kW to 60.37 kW, while exergy destruction falls from 3.146 to 2.532 and system exergy efficiency increases from 0.2412 to 0.2832. Table 5, using the same refrigerant under a different expansion arrangement, illustrates an even greater enhancement—COP rises from 4.057 to 4.504, compressor work decreases from 51.76 to 46.63 kW, and exergy destruction reduces from 2.197 to 1.776. The second-law efficiency increases from 0.3932 to 0.4501 and relative COP from 0.6172 to 0.6994. The sub-cooling improves first-law performance, second-law performance, compressor energy consumption, and exergy efficiency across traditional (R-12) and next-generation low-GWP refrigerants (HFO-1234yf and HFO-1234ze(E)) in multi-evaporator VCR systems.

Table 4: *Effect of sub cooling on actual thermodynamic performances of vapour compression refrigeration systems with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves using HFO-1234ze(E) refrigerant for 100% compressor efficiency for input data :$Q_{\_eva1}$=105 kW, $Q_{\_eva2}$=70 kW, $Q_{\_eva3}$=35 kW, $T_{\_eva1}$ =263 K, $T_{\_eva2}$ =278 K, $T_{\_eva3}$ =283 K, $T_{\_Cond}$=313 K, $T_{\_Subcooled\ fluid\ out\ at\ condenser\ outlet}$ =303 K*

Performance Parameters	With sub cooling	Without sub cooling
First Law Efficiency (COP)	3.479	3.078
Work done by compressor “kW”	60.37	68.22
Exergy Destruction Ratio	2.532	3.146
System exergy Efficiency	0.2832	0.2412
Exergy of fuel kW	60.37	68.22
Exergy of Product kW	17.09	16.46
Second Law efficiency	0.3527	0.3024
Relative_COP	0.5455	0.4725
Mass flow rate in first evaporator (kg/s)	0.6984	0.6984
Effective mass flow rate in second evaporator (kg/ s)	0.4560	0.4560
Mass flow rate in second evaporator (kg/ s)	0.4861	0.4861
Mass flow rate in third evaporator (kg/ s)	0.2708	0.3047
Effective mass flow rate in third evaporator (kg/ s)	0.5221	0.7361
Mass flow rate in condenser (kg/s)	1.707	1.921

Table 6 presents the load distribution profile for a vapour compression refrigeration system equipped with multiple evaporators, a single compressor, and multiple expansion valves, operating with environment-friendly refrigerants and maintaining an isentropic efficiency of 80% for the first compressor. The table outlines six different operating scenarios (I–VI), each representing a unique combination of cooling loads distributed across the three evaporators. In every case, the first evaporator handles either 105 kW, 70 kW, or 35 kW, depending on the load requirement of the specific mode. Similarly, the second evaporator alternates among 35 kW, 70 kW, and 105 kW, showing how load shifting can be used to balance system performance under varying refrigeration demands. The third evaporator follows a complementary distribution pattern, receiving 70 kW, 35 kW, or 105 kW to ensure that the total refrigeration capacity adapts to the changing thermal conditions. These varying load combinations demonstrate the flexibility of multi-evaporator systems in handling diverse temperature zones or product cooling requirements simultaneously. By redistributing the loads across the three evaporators, the system can optimize energy usage, maintain temperature stability across different cooling chambers, and adjust performance according to the real-time cooling demand of each section. This structured presentation of load variation also helps in analyzing compressor work, refrigerant mass flow rates, and overall COP under different load-sharing scenarios. Overall, Table 6 highlights how multi-evaporator VCR systems can dynamically manage cooling loads to achieve higher efficiency, operational flexibility, and environmentally sustainable performance.

Table 5: *Effect of sub cooling on actual thermodynamic performances of vapour compression refrigeration systems with multiple evaporators at the different temperatures with single compressor, with multiple expansion valves using HFO-1234ze(E) refrigerant for 100% compressor efficiency for input data :$Q_{\_eva1}$=105 kW, $Q_{\_eva2}$=70 kW, $Q_{\_eva3}$=35 kW, $T_{\_eva1}$ =263 K, $T_{\_eva2}$ =278 K, $T_{\_eva3}$ =283 K, $T_{\_Cond}$=313 K, $T_{\_Subcooled\ fluid\ out\ at\ condenser\ outlet}$ =303 K*

Performance Parameters	With sub cooling	Without sub cooling
First Law Efficiency (COP)	4.504	4.057
Work done by compressor “kW”	46.63	51.76
Exergy Destruction Ratio	1.776	2.197
System exergy Efficiency	0.3603	0.3128
Exergy of fuel kW	46.63	51.76
Exergy of Product kW	16.8	16.19
Second Law efficiency	0.4501	0.3932
Relative_COP	0.6994	0.6172
Mass flow rate in first evaporator (kg/sec)	0.6157	0.6157
Mass flow rate in second evaporator (kg/ sec)	0.4019	0.4019
Effective mass flow rate in second evaporator (kg/ sec)	0.4259	0.4259
Mass flow rate in third evaporator (kg/ sec)	0.2337	0.2585
Effective mass flow rate in third evaporator (kg/ sec)	0.4270	0.5827
Mass flow rate in condenser (kg/ sec)	1.469	1.624

Table 6: Load Profile of vapour compression refrigeration systems with multiple evaporators at the different Temperatures with single compressor, with multiple expansion valves using ecofriendly refrigerants for 80%isentropic efficiency of first compressor.

S.No.	Iput value	Unit	I	II	III	IV	V	VI
1	Cooling Load on First Evaporator($Q_{\_Eva\_1}$)	‘kW’	105	105	70	70	35	35
2	Cooling Load on second Evaporator($Q_{\_Eva\_2}$)	‘kW’	35	70	105	35	70	105
3	Cooling Load on second Evaporator($Q_{\_Eva\_3}$)	kW	70	35	35	105	105	70

Tables 7 and 8 examine how varying evaporator loading conditions influence the thermodynamic performance of multi-evaporator vapour compression refrigeration systems operating at three different evaporator temperatures—263 K, 273 K, and 278 K—with a single compressor, multiple expansion valves, and a subcooler. Both tables evaluate two low-GWP HFO refrigerants: HFO-1234ze(E) in Table 7 and HFO-1234yf in Table 8. Across all six operating conditions (I to VI), the results show a gradual increase in cooling load imbalance, which leads to corresponding variations in system efficiency, compressor work, exergy indicators, and mass flow distribution. For HFO-1234ze(E), the first-law efficiency (COP) ranges from 3.594 to 3.609, showing slight improvement as evaporator load shifts, while compressor work decreases marginally from 58.44 kW to 58.19 kW. However, increasing load asymmetry raises the exergy destruction ratio from 2.168 to 2.674, reducing system exergy efficiency from 0.3157 to 0.2722, indicating growing irreversibilities. Similar trends appear for HFO-1234yf, though with slightly lower COP values (3.467–3.485) and slightly higher compressor work (60.57–60.26 kW), reflecting its slightly inferior thermodynamic performance compared to HFO-1234ze(E). In both refrigerants, second-law efficiency declines steadily with unequal load distribution, and relative COP decreases, demonstrating efficiency loss under unbalanced evaporator operations. The mass flow rates through the three evaporators adjust according to their assigned cooling loads, with higher loads requiring higher mass flow, while the condenser mass flow decreases gradually across conditions due to reduced total refrigeration effect. Effective mass flow rates exhibit similar proportional trends, confirming correct energy and exergy distribution across the system. Overall, the tables highlight that although both refrigerants maintain stable performance, HFO-1234ze(E) consistently provides slightly higher COP, lower compressor work, and better exergy efficiency, especially under balanced loading. Increasing load imbalance increases irreversibility and decreases overall efficiency for both refrigerants, emphasizing the importance of balanced evaporator loading in multi-evaporator VCR systems.

Table 7: Effect of evaporators loading conditions on thermodynamic performances of vapour compression refrigeration systems using multiple evaporators at the different temperatures with single compressor, multiple expansion valves and subcooler using low GWP ecofriendly HFO -1234ze(E) refrigerant (for first evaporator temperature is 263K, second evaporator temperature is 273K,, third evaporator temperature is 278K,Condenser temperature is 313K, Sub cooled condenser fluid temperature out 303K,)

Performance Parameters	I	II	III	IV	V	VI
First Law Efficiency (COP)	3.594	3.596	3.599	3.604	3.609	3.606
Work done by compressor “kW”	58.44	58.4	58.36	58.28	58.19	58.23
Exergy Destruction Ratio	2.168	2.240	2.321	2.485	2.674	2.580
System exergy Efficiency	0.3157	0.3087	0.3011	0.2870	0.2722	0.2793
Exergy of fuel kW	58.44	58.4	58.36	58.28	58.19	58.23
Exergy of Product kW	18.45	18.02	17.57	16.72	15.84	16.27
Second Law efficiency	0.3884	0.3811	0.3733	0.3587	0.3435	0.3509
Relative_COP	0.5888	0.5813	0.5733	0.5582	0.5424	0.5501
Mass flow rate in first evaporator (kg/sec)	0.5923	0.5923	0.3949	0.3949	0.1974	0.1974
Mass flow rate in second evaporator (kg/ sec)	0.3943	0.1972	0.5915	0.1972	0.3943	0.5915
Effective mass flow rate in second evaporator (kg/ sec)	0.4168	0.2196	0.6064	0.2121	0.4018	0.5990
Mass flow rate in third evaporator (kg/ sec)	0.2391	0.4782	0.2391	0.7173	0.7173	0.4782
Effective mass flow rate in third evaporator (kg/ sec)	0.4775	0.670	0.4757	0.8607	0.8589	0.6663
Mass flow rate in condenser (kg/ sec)	1.487	1.482	1.477	1.468	1.458	1.463

Table 8: Effect of evaporators loading conditions on thermodynamic performances of vapour compression refrigeration systems using multiple evaporators at the different temperatures with single compressor, multiple expansion valves and subcooler using low GWP ecofriendly HFO -1234yf refrigerant (for first evaporator temperature is 263K, second evaporator temperature is 273K,, third evaporator temperature is 278K, Condenser temperature is 313K, Sub cooled condenser fluid temperature out 303K,)

Performance Parameters	I	II	III	IV	V	VI
First Law Efficiency (COP)	3.467	3.470	3.473	3.479	3.485	3.482
Work done by compressor “kW”	60.57	60.52	60.47	60.37	60.26	60.31
Exergy Destruction Ratio	2.253	2.317	2.389	2.534	2.698	2.617
System exergy Efficiency	0.3074	0.3015	0.2951	0.2830	0.2704	0.2765
Exergy of fuel kW	60.57	60.52	60.47	60.37	60.26	60.31
Exergy of Product kW	18.62	18.25	17.84	17.08	16.29	16.68
Second Law efficiency	0.3777	0.3715	0.3649	0.3525	0.3395	0.3458
Relative_COP	0.5712	0.5649	0.5581	0.5454	0.5321	0.5385
Mass flow rate in first evaporator(kg/sec)	0.6695	0.6695	0.4463	0.4463	0.2232	0.2232
Mass flow rate in second evaporator (kg/ sec)	0.4462	0.2231	0.6693	0.2231	0.4462	0.6693
Effective mass flow rate in second evaporator (kg/ sec)	0.4740	0.2509	0.6878	0.2416	0.4555	0.6786
Mass flow rate in third evaporator (kg/ sec)	0.2776	0.5552	0.2776	0.8328	0.8328	0.5552
Effective mass flow rate in third evaporator (kg/ sec)	0.5862	0.8036	0.5837	1.018	1.016	0.7986
Mass flow rate in condenser(kg/ sec)	1.730	1.724	1.718	1.706	1.695	1.70

Tables 9, 10, and 11 collectively analyze how varying the temperature profile of three evaporators influences the thermodynamic behavior of a vapour compression refrigeration system equipped with a single compressor, multiple expansion valves, and a subcooler. Table 9 outlines seven temperature combinations, showing gradual increases in evaporator temperatures—from 263 K to 273 K for the first evaporator, 273 K to 278 K for the second, and 278 K to 283 K for the third. Tables 10 and 11 then evaluate the system's performance at these temperature conditions using two low-

GWP refrigerants: HFO-1234ze(E) and HFO-1234yf, respectively. A consistent trend emerges in both tables: raising evaporator temperatures significantly improves thermodynamic performance. For HFO-1234ze(E), the COP increases from 3.609 (Case I) to 4.893 (Case VII) as evaporator temperatures rise, while compressor work drops sharply from 58.19 kW to 42.92 kW, demonstrating the reduction in compression ratio and required energy input. The second-law efficiency also improves in the higher-temperature cases, increasing from 0.3435 to 0.3470, although intermediate states show fluctuations due to changes in exergy destruction. Similar patterns are observed for HFO-1234yf, where the COP rises from 3.485 to 4.746, and compressor work decreases from 60.26 kW to 44.25 kW, showing a comparable efficiency enhancement with temperature increase. However, at all conditions, HFO-1234ze(E) provides slightly better performance due to its more favorable thermodynamic properties. Exergy destruction ratios in both refrigerants decrease significantly at elevated evaporator temperatures, indicating lower irreversibility and improved system quality. Mass flow rates across evaporators also adjust in response to temperature shifts, with higher evaporator temperatures reducing refrigerant circulation due to lower required enthalpy lift.

Table 9: Temperature profile of vapour compression refrigeration systems with multiple evaporators at the different Temperatures with single compressor, with multiple expansion valves using ecofriendly refrigerants for 80%isentropic efficiency of first compressor.

S. No.	Input value	I	II	III	IV	V	VI	VII
1	Temperature of first Evaporator(K)	263	263	263	268	268	268	273
2	Temperature of second Evaporator(K)	273	273	278	273	273	278	278
3	Temperature of second Evaporator(K)	278	283	283	278	283	283	283

Table 10: Effect of evaporators temperature conditions on thermodynamic performances of vapour compression refrigeration systems using multiple evaporators at the different temperatures with single compressor, multiple expansion valves and subcooler using low GWP ecofriendly HFO -1234ze(E) refrigerant (f*or first evaporator load is 35kW, second evaporator load is 70kW,, third evaporator load is 105kW,Condenser temperature is 313K, Sub cooled condenser fluid temperature out 303K,)*

Performance Parameters	I	II	III	IV	V	VI	VII
First Law Efficiency (COP)	3.609	3.619	3.624	4.170	4.180	4.186	4.893
Work done by compressor “kW”	58.19	58.03	57.95	50.37	50.24	50.17	42.92
Exergy Destruction Ratio	2.674	3.104	3.368	2.431	2.862	3.137	2.930
System exergy Efficiency	0.2722	0.2437	0.2289	0.2915	0.2589	0.2419	0.2545
Exergy of fuel kW	58.19	58.030	57.95	50.37	50.24	50.17	42.92
Exergy of Product kW	15.84	14.14	13.27	14.68	13.01	12.13	10.92
Exergy Destruction Ratio	1.911	2.184	2.346	1.681	1.946	2.09	1.882
Second Law efficiency	0.3435	0.3141	0.2989	0.3730	0.3394	0.3217	0.3470
Relative_COP	0.5424	0.5121	0.4964	0.6017	0.5669	0.5486	0.6107
Mass flow rate in first evaporator (kg/sec)	0.1974	0.1974	0.2052	0.1936	0.1936	0.2011	0.1972
Mass flow rate in second evaporator (kg/ sec)	0.3943	0.410	0.4019	0.1972	0.410	0.4019	0.4019
Effective mass flow rate in second evaporator (kg/ sec)	0.4018	0.4256	0.4099	0.4017	0.4253	0.4097	0.4096
Mass flow rate in third evaporator (kg/ sec)	0.2391	0.7010	0.7010	0.7173	0.7010	0.7010	0.7010
Effective mass flow rate in third evaporator (kg/ sec)	0.8589	0.8166	0.8152	0.8579	0.8159	0.8144	0.8136
Mass flow rate in condenser (kg/ sec)	1.458	1.440	1.430	1.453	1.435	1.425	1.420

Table 11: Effect of evaporators loading conditions on thermodynamic performances of vapour compression refrigeration systems using multiple evaporators at the different temperatures with single compressor, multiple expansion valves and subcooler using low GWP ecofriendly HFO -1234yf refrigerant (f*or first evaporator load is 35kW, second evaporator load is 70kW,, third evaporator load is 105kW, Condenser temperature is 313K, Sub cooled condenser fluid temperature out 303K,)*

Performance Parameters	I	II	III	IV	V	VI	VII
First Law Efficiency (COP)	3.485	3.498	3.504	4.033	4.046	4.053	4.746
Work done by compressor “kW”	60.26	60.04	59.93	52.07	51.90	51.81	44.25
Exergy Destruction Ratio	2.698	3.083	3.307	2.488	2.880	3.117	2.961
System exergy Efficiency	0.2704	0.2449	0.2322	0.2867	0.2577	0.2429	0.2524
Exergy of fuel kW	60.26	60.04	59.93	52.07	51.90	51.81	44.25
Exergy of Product kW	16.29	14.71	13.92	14.93	13.38	12.59	11.17
Second Law efficiency	0.3395	0.3133	0.3003	0.3658	0.3359	0.3207	0.3424
Relative_COP	0.5321	0.5052	0.4918	0.5872	0.5565	0.5408	0.5985
Mass flow rate in first evaporator(kg/sec)	0.2232	0.2232	0.2328	0.2186	0.2186	0.2278	0.2231
Mass flow rate in second evaporator (kg/ sec)	0.4462	0.4658	0.4560	0.4462	0.4658	0.4560	0.4560
Effective mass flow rate in second evaporator (kg/ sec)	0.4555	0.4853	0.4660	0.4553	0.4849	0.4658	0.4656
Mass flow rate in third evaporator (kg/ sec)	0.8328	0.8123	0.8123	0.8328	0.8123	0.8123	0.8123
Effective mass flow rate in third evaporator (kg/ sec)	1.016	0.9626	0.9606	1.015	0.9616	0.9595	0.9584
Mass flow rate in condenser(kg/ sec)	1.695	1.671	1.659	1.689	1.665	1.653	1.647

Tables 12, 13, and 14 collectively examine the influence of a wide range of eco-friendly HFO, blended, and traditional refrigerants on the thermodynamic behavior of a compound-compression vapour compression refrigeration system equipped with three evaporators (105 kW, 70 kW, and 35 kW), multiple expansion valves, and a flash intercooler. Table 12 compares several next-generation HFO refrigerants, showing that R-1233zd(E) provides the highest COP (3.734) and lowest compressor work (56.24 kW), indicating superior energy efficiency among the tested HFOs. R-1243zf and R-1225ye(Z) exhibit slightly higher exergy destruction and energy input, while R-1234yf shows the lowest COP (3.467) and highest compressor work (60.57 kW), reflecting higher irreversibility and greater compression ratio. Despite variations, system exergy efficiency remains in a narrow band (0.3059–0.3165), with R-1233zd(E) again achieving the best overall thermodynamic performance. Mass flow rates across evaporators and condenser reveal refrigerant-specific density and thermophysical behavior, with R-1225ye(Z) requiring the highest total mass circulation (1.746 kg/s).

Table 13 extends the comparison to modern low-GWP blends (R450A, R515A, R513A, R454b, R454C) and baseline refrigerants such as R134a. R454b stands out with the highest second-law efficiency (0.4091), highest exergy product (21.76 kW), and lowest exergy destruction ratio (1.936), indicating excellent thermodynamic quality despite its moderate COP (3.287). R134a, although an older refrigerant, performs competitively with a COP of 3.576 and good exergy characteristics. Conversely, R454C exhibits the lowest COP (2.95) and high compressor work (71.19 kW), highlighting its higher irreversibility.

Table 12: Effect of using HFO refrigerants on thermodynamic performances of vapour compression refrigeration systems using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R-1233 zd(E)	R-1224 yd(Z)	HFO-1336 mzz(Z)	R-1243 zf	R-1225 ye(Z)	R1234 ze(E)	R1234 yf
First Law Efficiency (COP)	3.734	3.707	3.681	3.499	3.557	3.594	3.467
Work done by compressor “kW”	56.24	56.64	57.05	60.01	59.04	58.44	60.57
Exergy Destruction Ratio	2.16	2.177	2.269	2.184	2.180	2.168	2.253
System exergy Efficiency	0.3165	0.3148	0.3059	0.3141	0.3145	0.3157	0.3074
Exergy of fuel kW	56.24	56.64	57.05	60.01	59.04	58.44	60.57
Exergy of Product kW	17.80	17.83	17.45	18.85	18.57	18.45	18.62
Second Law efficiency	0.3916	0.3893	0.3797	0.3851	0.3865	0.3884	0.3777
Relative_COP	0.5992	0.5956	0.5841	0.5806	0.5850	0.5888	0.5712
Mass flow rate in first evaporator(kg/sec)	0.5309	0.6213	0.6044	0.5420	0.6949	0.5923	0.6695
Mass flow rate in second evaporator (kg/ sec)	0.3521	0.4117	0.3993	0.3617	0.4630	0.3943	0.4462
Effective mass flow rate in second evaporator (kg/ sec)	0.3685	0.4316	0.4204	0.3807	0.4889	0.4168	0.4740
Mass flow rate in third evaporator (kg/ sec)	0.2042	0.2410	0.2361	0.2173	0.2812	0.2391	0.2776
Effective mass flow rate in third evaporator (kg/ sec)	0.3667	0.4444	0.4498	0.4218	0.5624	0.4775	0.5862
Mass flow rate in condenser (kg/ sec)	1.266	1.497	1.475	1.344	1.746	1.487	1.730

Table 13: Effect of using HFO refrigerants on thermodynamic performances (Exergy Destruction in components and Rational exergetic efficiency) of vapour compression refrigeration systems using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)

Performance Parameters	R450a	R515A	R513A	R454b	R454C	R134A
First Law Efficiency (COP)	3.458	3.572	3.50	3.287	2.95	3.576
Work done by compressor “kW”	60.72	58.79	59.99	63.89	71.19	58.72
Exergy Destruction Ratio	2.248	2.204	2.165	1.936	2.634	2.083
System exergy Efficiency	0.3079	0.3121	0.3159	0.3406	0.2752	0.3243
Exergy of fuel kW	60.72	58.79	59.99	63.89	71.19	58.72
Exergy of Product kW	18.7	18.35	18.95	21.76	19.59	19.05
Second Law efficiency	0.3708	0.3843	0.3871	0.4091	0.3355	0.3971
Relative_COP	0.5711	0.5834	0.5827	0.5951	0.5008	0.5970
Mass flow rate in first evaporator(kg/s)	0.5868	0.6126	0.6187	0.4044	0.5649	0.5447
Mass flow rate in second evaporator (kg/s)	0.3909	0.4071	0.4135	0.2741	0.3788	0.3647
Effective mass flow rate in second evaporator (kg/s)	0.4125	0.4297	0.4377	0.2868	0.3999	0.3838
Mass flow rate in third evaporator (kg/ sec)	0.2360	0.2453	0.2539	0.1636	0.2318	0.2189
Effective mass flow rate in third evaporator (kg/s)	0.4646	0.4835	0.5181	0.3027	0.4653	0.4219
Mass flow rate in condenser(kg/s)	1.465	1.526	1.574	0.9939	1.430	1.350

Table 14 analyzes additional refrigerants including R-152a, R-245fa, R-32, R-124, and R-123. R-32 demonstrates the best second-law efficiency (0.4344) and highest exergy product (22.31 kW), suggesting strong performance despite its higher compressor work (61.48 kW). R-152a offers a high COP (3.656) and low exergy destruction (1.941), making it thermodynamically attractive. R-123 provides the highest COP (3.762) with relatively low compressor work (55.82 kW), indicating superior energy efficiency. Mass flow behaviour across Tables 12–14 reflects each refrigerant's vapor density and enthalpy characteristics, with lighter refrigerants requiring lower mass flow rates and denser refrigerants showing higher circulation. Overall, refrigerants such as R-1233zd(E), R-32, R-152a, and R454b emerge as the strongest performers, balancing COP, compressor work, and exergy efficiency, while high-mass-flow and high-irreversibility refrigerants show comparatively weaker thermodynamic behavior.

Table 14: Effect of using HFO refrigerants on thermodynamic performances (Exergy Destruction in components and Rational exergetic efficiency) of vapour compression refrigeration systems using multiple evaporators at the Different Temperatures with compound compression, multiple expansion valves and flash inter cooler using low GWP ecofriendly refrigerants (for *first evaporator load is 105 kW, second evaporator load is 70 kW, third evaporator load is 35 kW)*

Performance Parameters	R-152A	R245fa	R32	R124	R123
First Law Efficiency (COP)	3.656	3.719	3.416	3.640	3.762
Work done by compressor "kW"	57.45	56.46	61.48	57.7	55.82
Exergy Destruction Ratio	1.941	2.124	1.755	2.158	2.139
System exergy Efficiency	0.340	0.3201	0.3629	0.3166	0.3185
Exergy of fuel kW	57.45	56.46	61.48	57.7	55.82
Exergy of Product kW	19.53	18.07	22.31	18.27	17.78
Second Law efficiency	0.4147	0.3951	0.4344	0.3901	0.3942
Relative_COP	0.6196	0.6022	0.6282	0.5930	0.6034
Mass flow rate in first evaporator(kg/sec)	0.3503	0.5323	0.3352	0.6809	0.5970
Mass flow rate in second evaporator (kg/ sec)	0.2348	0.3533	0.2282	0.4527	0.3956
Effective mass flow rate in second evaporator (kg/ sec)	0.2449	0.3704	0.2378	0.4767	0.4126
Mass flow rate in third evaporator (kg/ sec)	0.1362	0.2070	0.1341	0.2702	0.2268
Effective mass flow rate in third evaporator (kg/ sec)	0.2391	0.3815	0.2361	0.5204	0.3945
Mass flow rate in condenser (kg/ sec)	0.8343	1.284	0.8091	1.678	1.404

3. Conclusions

Energetic and exergetic analysis of refrigeration system was carried out with different HFO refrigerants and following conclusion and recommendation are presented below:

- The thermal model demonstrated high validity, with COP (4.80 vs 5.23) and compressor work (43.76 vs 40.14 kW) closely matching reference values, confirming the accuracy of numerical predictions within approximately 9%.
- Sub-cooling significantly enhanced first-law performance across all refrigerants, increasing COP by 8–13% and lowering compressor work by 8–12%, indicating improved cooling efficiency and reduced energy consumption.
- Exergy destruction decreased by 10–20%, while system exergy efficiency and second-law efficiency improved consistently, showing reduced irreversibility and better thermodynamic quality of energy conversion.
- Mass-flow distribution in multi-evaporator systems became more efficient, with notable improvements in low-temperature evaporator performance and reduced condenser mass flow, demonstrating enhanced refrigerating effect per unit mass.
- Balanced evaporator loading delivered higher COP, lower exergy destruction, and superior system stability compared to imbalanced modes, highlighting the importance of optimal load distribution for maximum system efficiency.

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