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Thermodynamic analysis of three-stage cascaded refrigeration systems using ultra-low GWP eco-friendly HCFO & HFO refrigerants

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Abstract

The technological problems include decreasing greenhouse gas emissions by reducing energy consumption, given the expansion of global energy consumption, and the need to achieve low temperatures. This includes optimizing cold production processes and using environmentally friendly refrigerants (GWP < 150) in refrigeration. The goal of this work is to identify the most reliable approach to optimizing a three-stage cascade vapor-compression refrigeration system. To achieve temperatures between −115 °C and −140 °C, groups are chosen and utilized. To find the ideal operating point that minimizes energy consumption and enables comparison of optimization techniques, energy, exergetic, and environmental analyses are also used. It was found that HCFO-1233zd(E) in the high-temperature cycle, HFO-1336mzz(Z) in the medium-temperature cycle, and HFO-1225ye(Z) give better thermodynamic performance at ultra-low temperatures (below 120 °C) than a conventional three-stage cascaded VCR system.

1. Introduction

The current world's population depends heavily on the refrigeration sector. There are refrigeration systems practically everywhere. Both the food business and air conditioning will require more refrigeration as a result of global warming. Given that most systems require electricity to function, this area's energy usage will rise even more. By 2050, the refrigeration industry's electricity usage is expected to four-fold. According to data from the same source, this industry today accounts for about 20% of the world's electricity output. Refrigeration systems are crucial, and it's because of them that we have to deal with global warming. However, it's crucial to note that these systems themselves contribute to global warming through the use of synthetic fluids and the CO2 emissions that result from producing the electricity required to run these systems. This needs to be fixed right now. First, there are existing rules in place to limit the manufacturing and use of fluorocarbons (CFC, HFC, HCFC, etc.), but research is still needed to identify substitute fluids with minimal environmental impact (GWP must be less than 150) [1]. The usage of HFOs &HCFOs are encouraged by their greater perspective. lowering electricity use by diversifying refrigeration systems and advancing technology. creating systems that use less electricity or improving the energy efficiency of already-existing systems. This technique, which involves optimizing a vapor compression system that uses natural refrigerants to produce extremely low temperatures (below −80 °C), may be placed precisely. In certain industries and cutting-edge technological domains that need highly pure oxygen and nitrogen, which are produced using cryogenic technologies, refrigeration at these temperatures is crucial. In the medical field, very low temperatures are crucial for procedures like cryotherapy and bio-conservation, which expose patients to extremely low temperatures (-80 °C to -140 °C). Multi-stage cascade refrigeration systems are typically used for refrigeration at extremely low temperatures. Additionally, the use of appropriate refrigerants with boiling points much lower than the intended evaporation temperature is necessary to produce ultra-low temperatures.

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Although most research on cascade refrigeration machines focuses on two-stage systems with temperatures over −50 °C, the study of ultra-low temperature refrigeration fills a significant research gap in this field [1,2]. In contrast, there is little literature on three-stage cascade systems, especially when it comes to creating temperatures below −120 °C. Using R1150 for the low-temperature cycle, R41 and R170 for the medium-temperature cycle, and R290, R161, R717, R1234yf, R1234ze, R1270, R152a, and R32 for the high-temperature cycles, 32 refrigerant combinations were tested in a three-stage cascade configuration. They identified the ideal operating conditions for each cycle and recommended R1150/R41/R717, R1150/R41/R152a, R1150/R41/R161, R1150/R170/R717, R1150/R170/R152a, and R1150/R170/R161. Using 1-butene for the low-temperature cycle, Heptane, Tans-2-butene, and Toluene for the medium-temperature cycle, and m-Xylene for the high-temperature cycle and thermodynamic (energy and exergy) analysis of three-stage cascade vapour compression refrigeration systems for hydrocarbon refrigerants. for calculating COP, total compressor work, exergy efficiency, total exergy destruction, mass flow rate and compressor discharge temperatures, and component exergy destruction. It was proposed that different hydrocarbon refrigerants on TCRS provide higher COP and exergy efficiency at different evaporator temperatures. At an evaporator temperature of -100 °C, the greatest COP and energy efficiency were determined to be 0.5931 and 54.4%, respectively [3]. The optimization of a three-stage cascade cycle evaporation temperatures between -120 °C and -90 °C. Between −120 °C and −110 °C, the 1-butene/Heptane/m-Xylene group performed best, while between −100 °C and −90 °C, the 1-butene/Toluene/m-Xylene group performed best. Because compressor outlet temperatures stayed below 120 °C, hydrocarbon refrigerants utilized in three-stage cascade systems did not show any lubricating or stability problems. They showed that two-stage cascade systems worked better than three-stage cascade systems at temperatures between −80 °C and −120 °C. However, three-stage cascade systems were better at evaporating temperatures below −120º. A three-stage cascade refrigeration system with a flash bottle that uses m-Xylene, Toluene, and 1-butene in the high, medium, and low temperature sub-cycles was recently examined [4].

Using low global warming potential refrigerants, the energy and exergy analysis was carried out of a subcritical cascade refrigeration system and discovered a 13% increase in the COP [5]. It was discovered that Hydrocarbon R-600a provides the best thermodynamic first and second law performances with the lowest exergy destruction ratio in the ultra-low temperature range between -110°C and -130°C when using environmentally friendly HFO refrigerants in the medium temperature range (up to -50°C) using Low GWP ecofriendly R245fa in the intermediate temperature cycle up to -95°C and R600a, R290 in the ultra-low temperature of a cascade refrigeration system. Compared to R290, the thermodynamic first and second law performances of R32 and ethylene are almost identical. Because most hydrocarbons are combustible, using them can be promising if the right safety precautions are taken [6]. In comparison to R1224yd(Z), R1234ze(E), and R1243zf used in intermediate temperature for R1234ze(Z) /R1234ze(E) & R1243zf, R1233zd(E) in a high-temperature cycle using R600a, R290, and R32 and Ethylene in ultra-low temperature ranges between -110°C and -130°C, R1230°C. R134a in the high-temperature circuit and R1234yf in the low-temperature cycle, however, showed the lowest performance. When the thermodynamic performance of cascade vapor compression refrigeration systems was evaluated between HFC-134a and HFO-1234yf, it was discovered that HFO-1236mzz(z) and R1225ye(Z) performed similarly to R134a when employed in an intermediate temperature cycle up to -50°C of evaporator temperature. Regulation (EU) No 517/2014 strongly advises using HFO refrigerant with zero ozone-depleting potential (ODP) and low global warming potential (GWP), such as R1234yf, to mitigate climate change risk, environmental impact, and deterioration. For a vapor compression refrigeration cycle, refrigerant R1234yf may be an option. However, R1234yf's GWP and ODP ratings are 4 and 0, respectively, indicating the refrigerant's eco-friendliness. Using environmentally friendly refrigerants, an energy analysis of cascade refrigeration systems with three and four stages for low-temperature applications was carried out . Using R1234yf and R1234ze in the high temperature circuits and primarily thirteen environmentally friendly refrigerants in the intermediate circuits and ethane, it was found that the effect of performance parameters (i.e., approaches, condenser temperature, and temperature variations in the evaporators) on the thermal performances in terms of second law efficiency of the system (exergetic efficiency) and exergy destruction ratio (EDR) and first law efficiency (i.e., overall coefficient of performance). The optimal R1234ze-R134a-R410a ethane combination was shown to have superior thermal performance compared to R1234yf-R134a-R410a ethane [7]. Eco-friendly refrigeration systems are becoming more and more popular as a solution to energy and environmental issues. This study proposes using natural refrigerants such ammonia, carbon dioxide, and hydrocarbons in a two-stage cascade vapour compression refrigeration system for a sustainable environment instead of the currently most popular refrigerant, R-134a, in light of global warming. Thermodynamic performances in terms of COP, exergetic efficiency, and system exergy destruction ratio (EDR) for very low-temperature application using ethane in low-temperature circuits and R1234ze and R1234yf in higher-temperature circuits. It was found that using R1234ze, which has an ultra-low global warming potential (of GWP=6), produces better thermal performance than R1234yf (of GWP=6) in the higher temperature circuit of a four-stage cascade refrigeration system. In the first intermediate temperature circuit, R134a does not significantly increase thermodynamic performance when compared to R410a. When utilizing R600a in the low-temperature evaporator circuit, the second law efficiency performs better than when using R290 and R404a refrigerant in the lower temperature circuit (LTC) [8]. A few hydrofluorocarbons and hydrocarbon-based refrigerants have been suggested as alternatives by numerous investigators due to their low GWP and zero ODP. Of the two, pure hydrocarbon refrigerants are a fascinating choice. The primary drawback of using hydrocarbon refrigerants is that they are flammable. Although the use of flammable refrigerants was previously forbidden, current laws permit the use of flammable fluids with appropriate safety precautions, therefore this problem can be avoided. Hydrocarbon-based refrigerants have a number of advantages over chlorofluorocarbon-based refrigerants, notwithstanding the flammability problem. Using HFO+HFC mixes in HTC and LTC cycles, a thermodynamic analysis of cascaded vapour compression refrigeration systems and basic vapour compression refrigeration systems. R.S. Mishra [12,13,14,15,16] conducted

2. Results and Discussion

The following cascaded three-stage vapour-compression refrigeration system has been considered for numerical computation in ultra-low-temperature applications. System-1: cascaded vapor compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -20 °C, HFO-1336mzz (Z) in MTC at evaporator temperature of -80 °C, and HFO1225ye (Z) in LTC at evaporator temperature of -125 °C.

System-2: Cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -20oC and 1225ye (Z) in MTC at evaporator temperature of -80oC and HFO-1336mzz (Z) in LTC at evaporator temperature of -125ºC

The numerical computation was carried out for the two cascaded, three-stage vapour-compression refrigeration systems using energy-exergy analysis, and the results are shown in Tables 1 and Table 2, respectively.

2.1 Effect of HTC condenser temperature on thermal performances of cascaded VCRS

For variation of HTC condenser temperature, It was found that by decreasing HTC condenser temperature from 60ºC to 30ºC, the First law (energy) efficiency and second law (exergy) efficiency in increases in both systems respectively.

Table 1: Effect of HTC condenser temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30ºC and HFO-1336mzz (Z) in MTC in MTC of -80ºC and and R1225ye (Z) in LTC

HTC condenser temperature (ºC)	60ºC	55ºC	50ºC	45ºC	40ºC	35ºC	30ºC
Cascade First law Efficiency ($COP_{Cascade}$)	0.3223	0.3387	0.3552	0.3717	0.3886	0.4057	0.4231
System Exergy Destruction Ratio $_{cascade}$	2.064	1.916	1.781	1.656	1.541	1.434	1.334
Exergetic Efficiency_$_{cascade}$	0.3031	0.3429	0.3596	0.3764	0.3935	0.4108	0.4284
Exergy of Fuel “kW”	543.0	516.7	492.7	470.7	450.3	431.3	413.6
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 2: Effect of HTC condenser temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30ºC and R1225ye (Z) in MTC in MTC of -80ºC and and HFO-1336mzz (Z) in LTC

HTC condenser temperature (ºC)	60ºC	55ºC	50ºC	45ºC	40ºC	35ºC	30ºC
Cascade First law Efficiency ($COP_{Cascade}$)	0.3192	0.3354	0.3516	0.3680	0.3847	0.4015	0.4187
System Exergy Destruction Ratio $_{cascade}$	2.095	1.945	1.809	1.684	1.568	1.460	1.359
Exergetic Efficiency_$_{cascade}$	0.3231	0.3395	0.3560	0.3726	0.3895	0.4065	0.4239
Exergy of Fuel “kW”	548.3	521.8	497.7	475.5	455.0	435.9	418.0
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

2.2 Effect of HTC evaporator temperature on thermal performances of cascaded VCRS

Table 3 and Table 4 show a similar trend in the thermal and exergetic performance of the cascaded vapour-compression refrigeration system as the HTC evaporator temperature increases from −30°C to 0°C. In Table 3, the cascade COP initially increases from 0.3489 at −30°C to a maximum of 0.3516 at −20°C, representing an improvement of about 0.77%, after which it continuously decreases to 0.3371 at 0°C. Thus, the optimum HTC evaporator temperature is approximately −20°C. The same trend is observed for exergetic efficiency, which rises from 0.3533 to 0.3560 (≈0.76% increase) between −30°C and −20°C and then falls to 0.3413 at 0°C (≈4.13% below the maximum value). Conversely, the system exergy destruction ratio decreases from 1.830 at −30°C to a minimum of 1.809 at −20°C, followed by an increase to 1.930 at 0°C. This indicates that the system experiences its lowest irreversibility around −20°C. The exergy of fuel follows the opposite trend: it decreases from 501.5 kW to 497.7 kW between −30°C and −20°C, a reduction of 3.8 kW (0.76%), and subsequently increases to 519.1 kW at 0°C, whereas the exergy of product remains constant at 177.2 kW. The increase in HTC evaporator temperature initially reduces the compression burden and improves system performance, but beyond approximately −20°C the thermodynamic balance between the cascade stages deteriorates, resulting in higher exergy destruction and increased exergy input requirement.

Table 4 exhibits the same qualitative behaviour but with slightly improved performance compared with Table 3. The cascade COP increases from 0.3527 at −30°C to 0.3552 at −20°C, corresponding to an increase of approximately 0.71%, and then decreases to 0.3415 at 0°C, which is about 3.86% lower than the maximum COP. Similarly, the exergetic efficiency improves from 0.3571 to 0.3596 between −30°C and −20°C (≈0.70% increase) before declining to 0.3458 at 0°C. The exergy destruction ratio decreases from 1.800 to 1.781, a reduction of 0.019 (≈1.06%), and subsequently increases to 1.892 at 0°C. The exergy of fuel decreases from 496.2 kW at −30°C to 492.7 kW at −20°C, saving 3.5 kW (≈0.71%), and then rises to 512.4 kW at 0°C, while the product exergy remains fixed at 177.2 kW. Comparing both tables, Table 4 provides consistently higher COP and exergetic efficiency and lower exergy destruction ratio than Table 3 at every investigated temperature. At the optimum temperature of −20°C, the COP improves from 0.3516 to 0.3552 (≈1.02%), while exergetic efficiency increases from 0.3560 to 0.3596 (≈1.01%) and exergy destruction ratio decreases from 1.809 to 1.781 (≈1.55%). Hence, −20°C can be identified as the thermodynamically optimum HTC evaporator temperature, providing the best balance between energy efficiency, exergy efficiency, and irreversibility for the investigated cascaded system.

Table 3: Effect of HTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC in MTC of -80°C and and R1225ye (Z) in LTC

HTC evaporator temperature (°C)	-30°C	-25°C	-20°C	-15°C	-10°C	-5°C	0°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.3489	0.3511	0.3516	0.3506	0.3479	0.3434	0.3371
System Exergy Destruction Ratio $_{cascade}$	1.830	1.813	1.809	1.817	1.839	1.876	1.930
Exergetic Efficiency_ $_{cascade}$	0.3533	0.3554	0.3560	0.3550	0.3522	0.3477	0.3413
Exergy of Fuel “kW”	501.5	498.5	497.7	499.20	503.10	509.6	519.10
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 4: Effect of HTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC in MTC of -80°C and and R1225ye (Z) in LTC

HTC evaporator temperature (°C)	-30°C	-25°C	-20°C	-15°C	-10°C	-5°C	0°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.3527	0.3547	0.3552	0.3541	0.3515	0.3474	0.3415
System Exergy Destruction Ratio $_{cascade}$	1.80	1.785	1.781	1.789	1.809	1.843	1.892
Exergetic Efficiency_ $_{cascade}$	0.3571	0.3591	0.3596	0.3586	0.3559	0.3517	0.3458
Exergy of Fuel “kW”	496.2	493.4	492.7	494.2	0.497.8	503.8	512.4
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

2.3 Effect of MTC evaporator temperature on thermal performance of cascaded VCRS

Tables 5 and 6 demonstrate the influence of MTC evaporator temperature on the first-law and second-law performance of the three-stage cascaded vapour-compression refrigeration system. In Table 5, when the MTC evaporator temperature is increased from −80°C to −75°C, the cascade COP increases from 0.3516 to 0.3524, corresponding to an improvement of approximately 0.23%. However, a further increase in temperature causes a gradual deterioration in COP, reaching 0.3359 at −50°C. Thus, the maximum COP of 0.3524 is obtained at −75°C. The same behaviour is reflected in the exergetic efficiency, which increases from 0.3560 at −80°C to 0.3568 at −75°C, followed by a decline to 0.3438 at −50°C. In contrast, the system exergy destruction ratio initially decreases from 1.809 to 1.803, indicating reduced irreversibility, but subsequently increases to 1.909 at −50°C. The exergy of fuel also follows an approximately inverse trend with performance: it decreases from 497.7 kW at −80°C to 496.6 kW at −75°C, before increasing progressively to 515.4 kW at −50°C. Since the exergy of product remains constant at 177.2 kW, the variation in exergetic performance is primarily associated with changes in the required exergy input and system irreversibilities. These results indicate that a relatively low MTC evaporator temperature is necessary to maintain favourable thermodynamic matching between the MTC and LTC stages.

A distinctly stronger and more systematic response is observed in Table 6. Here, increasing the MTC evaporator temperature from −80°C to −65°C improves the cascade COP from 0.3552 to 0.3596, representing an increase of approximately 1.24%. The COP subsequently decreases to 0.3529 at −50°C, establishing −65°C as the optimum MTC evaporator temperature for this configuration. The exergetic efficiency exhibits an almost identical trend, increasing from 0.3596 at −80°C to a maximum of 0.3641 at −65°C, an improvement of approximately 1.25%, and then decreasing to 0.3573 at −50°C. Importantly, the exergy destruction ratio decreases substantially from 1.781 to 1.746, a reduction of approximately 1.96%, between −80°C and −65°C, demonstrating that the system operates with lower irreversibility at the optimum condition. Simultaneously, the exergy of fuel decreases from 492.7 kW to 486.6 kW, representing a saving of 6.1 kW or approximately 1.24%. Beyond −65°C, fuel exergy increases again to 495.8 kW at −50°C, accompanied by increasing exergy destruction.

Table 5: Effect of MTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC in MTC of -80°C and and R1225ye (Z) in LTC

MTC evaporator temperature (°C)	-80°C	-75°C	-70°C	-65°C	-60°C	-55°C	-50°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.3516	0.3524	0.3520	0.3505	0.3480	0.3449	0.3359
System Exergy Destruction Ratio $_{cascade}$	1.809	1.803	1.806	1.818	1.838	1.869	1.909
Exergetic Efficiency $_{cascade}$	0.3560	0.3568	0.3564	0.3549	0.3523	0.3486	0.3438
Exergy of Fuel “kW”	497.7	496.6	497.1	499.2	502.9	508.3	515.40
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 6: Effect of MTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration Msystem using R1233zd (E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC in MTC of -80°C and and R1225ye (Z) in LTC

MTC evaporator temperature (°C)	-80°C	-75°C	-70°C	-65°C	-60°C	-55°C	-50°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.3552	0.3579	0.3594	0.3596	0.3586	0.3564	0.3529
System Exergy Destruction Ratio $_{cascade}$	1.781	1.760	1.748	1.746	1.754	1.771	1.798
Exergetic Efficiency $_{cascade}$	0.3596	0.3624	0.3639	0.3641	0.3631	0.3609	0.3573
Exergy of Fuel “kW”	492.7	489.0	486.9	486.6	488.0	491.0	495.8
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Comparing both tables reveals that Table 6 provides superior overall performance: at −65°C, its COP (0.3596) is about 2.60% higher than the corresponding COP in Table 5 (0.3505), while its exergetic efficiency (0.3641) is about 2.59% higher than 0.3549. Therefore, the results clearly establish that the MTC evaporator temperature has an optimum intermediate range rather than a simple monotonic effect, with −65°C in Table 6 providing the best compromise between energy efficiency, exergy efficiency, and irreversibility.

2.4 Effect of LTC evaporator temperature on thermal performances of cascaded VCRS

Tables 7 and 8 illustrate the effect of LTC evaporator temperature on the thermodynamic performance of the cascaded vapour-compression refrigeration system. Unlike the HTC and MTC temperature variations discussed earlier, the LTC evaporator temperature produces a strong and nearly monotonic improvement in COP as the temperature rises from −140°C to −115°C. In Table 7, the cascade COP increases dramatically from 0.2371 at −140°C to 0.4243 at −115°C, representing an improvement of approximately 78.99%. The largest incremental improvement occurs between −140°C and −135°C, where COP increases by 0.0624, or approximately 26.32%. Thereafter, COP continues to rise, reaching 0.3552 at −125°C, 0.3843 at −120°C, and finally 0.4243 at −115°C. This behaviour can be attributed to the reduction in the temperature lift of the LTC compressor when the evaporating temperature is increased. The second-law parameters support this interpretation. The exergy destruction ratio decreases continuously from 1.955 to 1.727, corresponding to a reduction of approximately 11.66%, while exergetic efficiency improves from 0.3384 to 0.3667, an increase of approximately 8.36%. Furthermore, the exergy of fuel decreases substantially from 640.8 kW to 422.4 kW, giving a reduction of 218.4 kW or 34.08%. The exergy of product also decreases from 216.9 to 154.9 kW; therefore, the improvement in exergetic efficiency is primarily associated with the much larger reduction in fuel exergy than in product exergy.

Table 8 follows the same fundamental trend but exhibits a somewhat different magnitude of response because the refrigerants used in the MTC and LTC stages are interchanged. The cascade COP rises from 0.2662 at −140°C to 0.4131 at −115°C, representing an overall improvement of approximately 55.18%. The COP increases successively through 0.2937, 0.3222, 0.3516 and 0.3820 as the LTC evaporator temperature is increased from −135°C to −120°C. Simultaneously, the system exergy destruction ratio decreases from 2.032 at −140°C to 1.734 at −115°C, corresponding to a reduction of approximately 14.67%. This reduction indicates that raising the LTC evaporating temperature considerably decreases the total irreversibility of the cascaded system. The exergetic efficiency also improves from 0.3298 to 0.3657, an increase of approximately 10.89%. Moreover, the exergy of fuel falls from 657.5 kW to 423.6 kW, representing a substantial reduction of 233.9 kW (35.57%). A comparison between Tables 7 and 8 reveals that Table 7 provides higher COP and exergetic efficiency throughout the investigated range, while Table 8 generally exhibits a higher exergy destruction ratio and fuel-exergy requirement. At −115°C, for example, Table 7 achieves a COP of 0.4243, compared with 0.4131 in Table 8, an advantage of approximately 2.71%; its exergetic efficiency is 0.3667 versus 0.3657, while the exergy destruction ratio is lower (1.727 versus 1.734). Thus, within the investigated range, −115°C gives the best performance, and no internal optimum is observed—the system performance continuously improves as the LTC evaporator temperature increases.

Table 7: Effect of LTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC in MTC of -80°C and and R1225ye (Z) inLTC

LTC evaporator temperature (°C)	-140°C	-135°C	-130°C	-125°C	-120°C	-115°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.2371	0.2995	0.3069	0.3552	0.3843	0.4243
System Exergy Destruction Ratio $_{cascade}$	1.955	1.883	1.825	1.781	1.748	1.727
Exergetic Efficiency$__{cascade}$	0.3384	0.3469	0.3540	0.3596	0.3639	0.3667
Exergy of Fuel “kW”	640.8	584.3	535.3	492.7	455.4	422.4
Exergy of Product “kW”	216.9	2.2.7	189.5	177.2	165.7	154.9

Table 8: Effect of LTC evaporator temperature on thermal performances of cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -30°C and R1225ye (Z) in MTC of -80°C and HFO-1336mzz (Z) inLTC

LTC evaporator temperature (°C)	-140°C	-135°C	-130°C	-125°C	-120°C	-115°C
Cascade First law Efficiency ($COP_{Cascade}$)	0.2662	0.2937	0.3222	0.3516	0.3820	0.4131
System Exergy Destruction Ratio $_{cascade}$	2.032	1.940	1.867	1.809	1.765	1.734
Exergetic Efficiency$__{cascade}$	0.3298	0.3401	0.3488	0.3560	0.3616	0.3657
Exergy of Fuel “kW”	657.5	595.9	543.2	497.7	458.2	423.6
Exergy of Product “kW”	216.9	202.7	189.5	177.2	165.7	154.9

2.5 Effect of Temperature Overlapping (Approach) on Thermal Performance of Three-Stage Cascaded VCRS

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Tables 9 and 10 investigate the influence of the temperature overlap between the MTC condenser and HTC evaporator, while simultaneously varying the LTC temperature overlap from 0 to 15°C. The results demonstrate that both overlap temperatures have a pronounced effect on the overall thermodynamic performance of the cascaded refrigeration system. In Table 9, when the MTC overlap is maintained at 0°C, increasing the LTC overlap from 0 to 15°C causes the cascade COP to decrease systematically from 0.488 to 0.4075, corresponding to a reduction of approximately 16.50%. At the same time, the exergy destruction ratio increases from 1.024 to

1.424, an increase of about 39.06%, while exergetic efficiency falls from 0.494 to 0.4126, representing a decrease of approximately 16.48%. The exergy of fuel increases from 358.6 to 429.5 kW, or approximately 19.76%, whereas the exergy of product remains constant at 177.2 kW. This clearly indicates that increasing the LTC temperature overlap introduces additional thermodynamic losses and increases the required exergy input. A similar trend is observed when the MTC overlap is increased to 5°C. At zero LTC overlap, COP decreases from 0.488 to 0.4619, a reduction of 5.35%, while the exergy destruction ratio increases from 1.024 to 1.138 (≈11.13%). Table 10 presents the corresponding results for larger MTC overlaps of 10°C and 15°C. For an MTC overlap of 10°C, increasing the LTC overlap from 0 to 15°C reduces COP from 0.4371 to 0.3671, corresponding to a substantial reduction of approximately 16.02%. During the same change, the exergy destruction ratio rises from 1.260 to 1.691, an increase of approximately 34.05%, and exergetic efficiency decreases from 0.4425 to 0.3716, a reduction of about 16.02%. The exergy of fuel simultaneously rises from 400.4 to 476.8 kW, or approximately 19.08%. When the MTC overlap is further increased to 15°C, COP falls from 0.4131 to 0.3479, a reduction of approximately 15.79%, while the exergy destruction ratio increases from 1.391 to 1.839, representing an increase of approximately 32.21%. The corresponding exergetic efficiency decreases from 0.4183 to 0.3522 (≈15.80%). Thus, Tables 9 and 10 collectively establish an important result: increasing either MTC or LTC temperature overlap deteriorates system performance. The best condition among these cases occurs at 0°C MTC overlap and 0°C LTC overlap, where COP = 0.488, exergetic efficiency = 0.494, and exergy destruction ratio = 1.024. Increasing the MTC overlap from 0 to 15°C at zero LTC overlap reduces COP from 0.488 to 0.4131, approximately 15.35%, while increasing the exergy destruction ratio from 1.024 to 1.391, approximately 35.84%.

Table 9: Effect of LTC evaporator temperature on thermal performances of cascaded VCRS using HCFO1233zd (E) in HTC at condenser temperature of 40°C & evaporator temperature of -20°C and HFO-1336mzz (Z) in MTC of -80°C and HFO1225ye (Z)) in LTC of -125°C

MTC temperature overlapping ($T_{\_MTC\_Cond}$- $T_{\_HTC\_EVA}$) (°C)	0	0	0	0	5	5	5	5
LTC temperature overlapping (°C)	0	5	10	15	0	5	10	15
Cascade First law Efficiency ($COP_{Cascade}$)	0.488	0.4589	0.432	0.4075	0.4619	0.4349	0.410	0.3870
System Exergy Destruction Ratio $_{cascade}$	1.024	1.152	1.283	1.424	1.138	1.271	1.409	1.553
Exergetic Efficiency $_{\_cascade}$	0.494	0.4646	0.437	0.4126	0.4677	0.4403	0.4151	0.3917
Exergy of Fuel “kW”	358.6	381.3	404.9	429.5	378.8	420.4	426.9	452.3
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 10: Effect of LTC evaporator temperature on thermal performances of cascaded VCRS using R1233zd (E) in HTC at condenser temperature of 40°C & evaporator temperature of -20°C and HFO-1336mzz (Z) in MTC of -80°C and HFO1225ye (Z) in LTC of -125°C

MTC temperature overlapping ($T_{\_MTC\_Cond}$- $T_{\_HTC\_EVA}$) (°C)	10	10	10	10	15	15	15	15
LTC temperature overlapping (°C)	0	5	10	15	0	5	10	15
Cascade First law Efficiency ($COP_{Cascade}$)	0.4371	0.4119	0.3886	0.3671	0.4131	0.3897	0.3860	0.3479
System Exergy Destruction Ratio $_{cascade}$	1.260	1.398	1.541	1.691	1.391	1.534	1.684	1.839
Exergetic Efficiency $_{\_cascade}$	0.4425	0.4170	0.3935	0.3716	0.4183	0.3946	0.3726	0.3522
Exergy of Fuel “kW”	400.4	424.9	450.3	476.8	423.6	449.10	475.5	503.2
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 11: Effect of LTC evaporator temperature on thermal performances of cascaded VCRS using R1233zd (E) in HTC at condenser temperature of 40°C & evaporator temperature of -20°C and R1225ye (Z) in MTC of -80°C and HFO-1336mzz (Z) inLTC of -125°C

MTC temperature overlapping ($T_{\_MTC\_Cond}$- $T_{\_HTC\_EVA}$) (°C)	0	0	0	0	5	5	5	5
LTC temperature overlapping (°C)	0	5	10	15	0	5	10	15
Cascade First law Efficiency ($COP_{Cascade}$)	0.4855	0.4552	0.4273	0.4016	0.4599	0.4316	0.4056	0.3816
System Exergy Destruction Ratio $_{cascade}$	1.034	1.170	1.311	1.459	1.148	1.288	1.435	1.588
Exergetic Efficiency $_{\_cascade}$	0.4915	0.4609	0.4327	0.4066	0.4656	0.4370	0.4107	0.3863
Exergy of Fuel “kW”	360.5	380.5	409.5	435.7	380.6	405.4	431.4	458.6
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 12: Effect of LTC evaporator temperature on thermal performances of cascaded VCRS using R1233zd (E) in HTC at condenser temperature of 40°C & evaporator temperature of -20°C and R1225ye (Z) in MTC of -80°C and HFO-1336mzz (Z) in LTC of -125°C

MTC temperature overlapping ($T_{\_MTC\_Cond}$- $T_{\_HTC\_EVA}$) (°C)	10	10	10	10	15	15	15	15
LTC temperature overlapping (°C)	0	5	10	15	0	5	10	15
Cascade First law Efficiency ($COP_{Cascade}$)	0.4352	0.4089	0.3847	0.3622	0.4114	0.3869	0.3643	0.3433
System Exergy Destruction Ratio $_{cascade}$	1.269	1.415	1.568	1.727	1.401	1.553	1.711	1.877
Exergetic Efficiency $_{\_cascade}$	0.4406	0.4140	0.3895	0.3667	0.4165	0.3917	0.3688	0.3476
Exergy of Fuel “kW”	402.1	428.0	455.0	483.2	425.4	452.3	480.4	509.8
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Tables 11 and 12 illustrate the effect of MTC and LTC temperature overlap on the thermal and exergy performance of the three-stage cascaded vapour compression refrigeration system using R1233zd(E) in the HTC, R1225ye(Z) in the MTC, and HFO-1336mzz(Z) in the LTC, with the HTC condenser temperature of 40°C, HTC evaporator temperature of −20°C, MTC evaporator temperature of −80°C, and LTC evaporator temperature of −125°C. The results clearly show that increasing the LTC temperature overlap from 0°C to 15°C continuously deteriorates system performance at every MTC overlap condition. In Table 11, at an MTC overlap of 0°C, the cascade COP decreases from 0.4855 to 0.4016, while the exergetic efficiency decreases from 0.4915 to 0.4066 and the exergy destruction ratio increases from 1.034 to 1.459 as the LTC overlap increases from 0°C to 15°C. Similarly, at an MTC overlap of 5°C, the COP decreases from 0.4599 to 0.3816, whereas the exergy destruction ratio increases from 1.148 to 1.588. The same trend becomes more pronounced in Table 12: at an MTC overlap of 10°C, increasing LTC overlap from 0°C to 15°C reduces the COP from 0.4352 to 0.3622 and exergetic efficiency from 0.4406 to 0.3667, while increasing the exergy destruction ratio from 1.269 to 1.727. At an MTC overlap of 15°C, the COP further decreases from 0.4114 to 0.3433, and the exergy destruction ratio rises from 1.401 to 1.877. The exergy of fuel follows the opposite trend, increasing from 360.5 kW to 435.7 kW in Table 11 and from 402.1 kW to 483.2 kW in Table 12 as LTC overlap increases from 0°C to 15°C at the respective MTC overlap levels, whereas the exergy of product remains constant at 177.2 kW. Overall, the optimum condition is obtained at 0°C MTC overlap and 0°C LTC overlap, where the system achieves the maximum COP of 0.4855, maximum exergetic efficiency of 0.4915, minimum exergy destruction ratio of 1.034, and minimum exergy of fuel of 360.5 kW. Thus, increasing either MTC or LTC temperature overlap adversely affects both first-law and second-law performance, with the effect of LTC overlap being particularly significant.

2.6 Effect of ecofriendly Refrigerants on thermal performance of cascaded VCRS for ultra-low-temperature applications

The effects of eco-friendly refrigerants on the thermal energy and exergy performance of the three-stage cascaded vapour compression refrigeration system were evaluated, and the results are presented in Tables 13 and 14, respectively. The analysis was performed at a condenser temperature of 50°C, HTC evaporator temperature of −20°C, MTC evaporator temperature of −80°C, and LTC evaporator temperature of −125°C, with a compressor efficiency of 0.80 for each stage and an LTC cooling load of 175 kW. The results indicate that the combination of HCFO-1233zd(E) in the HTC, R1336mzz(Z) in the MTC, and R1225ye(Z) in the LTC provides the highest first-law and second-law performance among the eco-friendly refrigerant combinations investigated. In contrast, the combinations employing HFO-1234yf in the HTC exhibit the lowest thermodynamic performance under the specified operating conditions. The calculated results were further compared with those of the conventional three-stage cascaded vapour compression refrigeration system employing CFC refrigerants, namely R12 in the HTC, R22 in the MTC, and R13 in the LTC, under the same cooling load and temperature conditions. As presented in Table 13, among the HFO-based eco-friendly combinations, the maximum cascade COP of 0.3360 is obtained for the HFO-1234ze(E)/R1336mzz(Z)/R1225ye(Z) combination, followed by 0.3348 for HFO-1243zf/R1336mzz(Z)/R1225ye(Z) and 0.3327 for HFO-1234ze(E)/R1225ye(Z)/R1336mzz(Z). The HFO-1234yf-based combinations exhibit the lowest COP values of 0.3207 and 0.3175, respectively. The corresponding cascade exergetic efficiency ranges from 0.3215 to 0.3402, with the maximum value of 0.3402 obtained for HFO-1234ze(E)/R1336mzz(Z)/R1225ye(Z). The minimum system exergy destruction ratio of 1.940 is also obtained for this combination, whereas the maximum value of 2.11 is observed for HFO-1234yf/R1225ye(Z)/R1336mzz(Z). The exergy of fuel varies from 520.9 to 551.1 kW, while the exergy of product remains constant at 177.2 kW. For comparison, the conventional R12/R22/R13 system exhibits a COP of 0.3452, an exergetic efficiency of 0.3495, and an exergy destruction ratio of 1.861. Table 14 demonstrates that several alternative low-GWP refrigerant combinations provide improved thermodynamic performance. The HCFO-1233zd(E)/R1336mzz(Z)/ R1225ye(Z) combination provides the best overall eco-friendly performance, with a cascade COP of 0.3552, exergetic efficiency of 0.3596, and exergy destruction ratio of 1.781. The corresponding exergy of fuel is 492.7 kW, while the exergy of product remains constant at 177.2 kW. Compared with the conventional R12/R22/R13 system, this combination improves the COP by approximately 2.9% and the exergetic efficiency by approximately 2.9%, while reducing the exergy destruction ratio by approximately 4.3%. Among the hydrocarbon-based combinations, R600a/R290/propylene achieves a COP of 0.3413, whereas R290/R600a/propylene gives a COP of 0.3357.

Table 13: Effect of Ecofriendly low GWP Refrigerants on thermal performance of cascaded VCRS at condenser temperature of 50ºC, HTC compressor efficiency = 0.80, MTC compressor efficiency = 0.80, LTC compressor efficiency = 0.80, Cooling Load at LTC evaporator=175kW.

HTC Ecofriendly low GWP Refrigerants at evaporator temperature of -20ºC	HFO-1234 ze(E)	HFO-1234 ze(E)	HFO-1243zf	HFO-1243zf	HFO-1234yf	HFO-1234yf	R12
MTC Ecofriendly low GWP Refrigerants at evaporator temperature of -80ºC	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R-22
LTC Ecofriendly low GWP Refrigerants at evaporator temperature of 125ºC	R1225 ye(Z)	R1336 Mzz (Z)	R1225y e(Z)	R1336 Mzz (Z)	R1225ye(Z)	R1336 Mzz (Z)	R13
Cascade First law Efficiency ($COP_{Cascade}$)	0.3360	0.3327	0.3348	0.3315	0.3207	0.3175	0.3452
System Exergy Destruction Ratio $_{cascade}$	1.940	1.969	1.950	1.979	2.08	2.11	1.861
Exergetic Efficiency$_{_cascade}$	0.3402	0.3368	0.3390	0.3357	0.3247	0.3215	0.3495
Exergy of Fuel “kW”	520.9	526.1	522.6	527.8	545.7	551.10	507.0
Exergy of Product “kW”	177.2	177.2	177.2	177.2	177.2	177.2	177.2

Table 14: Effect of eco-friendly low-GWP refrigerants on thermal performance of cascaded VCRS at condenser temperature of 50°C, HTC compressor efficiency = 0.80, MTC compressor efficiency = 0.80, LTC compressor efficiency = 0.80, Cooling Load at LTC evaporator=175kW.

HTC Ecofriendly low GWP Refrigerants at evaporator temperature of -20°C	HCFO-1233 zd(E)	HCFO-1233 zd(E)	R290	R600a	R290	R600a	R12
MTC Ecofriendly low GWP Refrigerants at evaporator temperature of -80°C	R1336 mzz(Z)	R1225 ye(Z)	R600a	R290	R600a	R290	R-22
LTC Ecofriendly low GWP Refrigerants at evaporator temperature of 125°C	R1225ye(Z)	R1336 mzz(Z)	Propylene	Propylene	Ethylene	Ethylene	R13
Cascade First law Efficiency ($COP_{Cascade}$)	0.3552	0.3516	0.3357	0.3413	0.3286	0.3340	0.3452
System Exergy Destruction Ratio $_{cascade}$	1.781	1.809	1.942	1.893	2.006	1.957	1.861
Exergetic Efficiency_$_{cascade}$	0.3596	0.3560	0.3399	0.3456	0.3327	0.3382	0.3495
Exergy of Fuel "kW"	492.7	497.7	521.2	512.7	532.6	523.9	507.0
Exergy of Product "kW"	177.2	177.2	177.2	177.2	177.2	177.2	177.2

2.7 Effect of ecofriendly Refrigerants on thermal performance of cascaded VCRS

Table 15 presents the effect of different eco-friendly/low-GWP refrigerant combinations on the first-law and second-law performance of the three-stage cascaded vapour compression refrigeration system operating at a condenser temperature of 50°C, HTC evaporator temperature of −20°C, MTC evaporator temperature of −60°C, and LTC evaporator temperature of −90°C. The compressor efficiency is maintained at 0.80 for all three stages, and the LTC cooling load is 175 kW. Among the eco-friendly combinations, the HCFO-1233zd(E)/HFO-1336mzz(Z)/HFO-1225ye(Z) combination gives a high cascade COP of 0.6084, while the second HCFO-1233zd(E)/HFO-1336mzz(Z)/HFO-1225ye(Z) arrangement gives the maximum COP of 0.6113. These values are substantially higher than those obtained with HFC-based combinations. For example, the HFC-152A/HFC-245fa/HFC-32 combination gives a COP of 0.5548, whereas the HFC-245fa/HFC-152A/HFC-32 combination gives 0.5899. The HFC-134a-based combinations show the lowest COP values of 0.5282 and 0.5316, indicating comparatively poorer first-law performance. The conventional R12/R22/R13 system gives a COP of 0.5865. Therefore, the best-performing eco-friendly combination with a COP of 0.6113 provides approximately 4.22% higher COP than the conventional system. The second-law analysis also confirms the superior performance of the HCFO/HFO combinations. The maximum cascade exergetic efficiency of 0.3838 is obtained for the combination having a COP of 0.6113, followed by 0.3820 for the other HCFO-1233zd(E)-based combination. In comparison, the conventional R12/R22/R13 system has an exergetic efficiency of 0.3683. Thus, the maximum eco-friendly combination improves the exergetic efficiency by approximately 4.21% relative to the conventional system. The system exergy destruction ratio further supports this observation, with the minimum value of 1.605 obtained for the best HCFO/HFO combination, compared with 1.715 for the conventional R12/R22/R13 system, corresponding to a reduction of approximately 6.41%. The exergy of fuel is also reduced from 298.4 kW for the conventional system to 286.3 kW for the best eco-friendly combination, while the exergy of product remains constant at 109.9 kW for all cases.

Table 15: Effect of eco-friendly low-GWP refrigerants on thermal performance of cascaded VCRS at condenser temperature of 50°C, HTC compressor efficiency = 0.80, MTC compressor efficiency = 0.80, LTC compressor efficiency = 0.80, Cooling Load at LTC evaporator=175kW.

HTC eco-friendly low-GWP refrigerants at evaporator temperature of -20°C	HCFO-1233 zd(E)	HCFO-1233 zd(E)	HFC-152A	HFC 245fa	HFC-134A	HFC-134A	R12
MTC Eco-friendly low GWP Refrigerants at evaporator temperature of -60°C	HFO1225 ye(Z)	HFO 1336 mzz(Z)	HFC 245fa	HFC-152A	HFC-407c	HFC-407c	R-22
LTC Ecofriendly low GWP Refrigerants at evaporator temperature of -90°C	HFO 1336 mzz(Z)	HFO 1225 ye(Z)	HFC 32	HFC 32	HFC	HFC-410A	R13
Cascade First law Efficiency ($COP_{Cascade}$)	0.6084	0.6113	0.5548	0.5899	0.5282	0.5316	0.5865
System Exergy Destruction Ratio $_{cascade}$	1.618	1.605	1.678	1.70	2.015	1.996	1.715
Exergetic Efficiency_$_{cascade}$	0.3820	0.3838	0.3735	0.3704	0.3317	0.3338	0.3683
Exergy of Fuel "kW"	287.7	286.3	294.2	296.7	331.6	329.3	298.4
Exergy of Product (kW"	109.9	109.9	109.9	109.9	109.9	109.9	109.9

3. Conclusions & Recommendations

The following conclusions were drawn from the present investigation

- In the three-staged cascaded vapor compression refrigeration systems for ultra-low temperature applications below (-120ºC) using eco-friendly refrigerants, HCFO-1233zd(E) in high temperature (HT) cycle, HFO-1336mzz(Z) in medium temperature (MT) cycle, and HFO-1225ye(Z) in lower temperature (LT) cycle. gives best thermodynamic performances than the the HCFO-1233zd(E) in high temperature (HT) cycle, HFO-1225ye(Z) in medium temperature (MT) cycle and HFO-1336mzz(Z) in lower temperature (LT) cycle.

- Both temperature overlap (Approach) variations significantly affect the thermodynamic performance. As temperature overlap increases, energy performance (COP) and exergy efficiency (second-law efficiency) decrease significantly.
- By increasing HTC evaporator temperature from -30 °C to -22 °C, the second law (exergy) efficiency increases to an optimum (maximum value), remains constant up to -20 °C in system -1, then decreases from -22 °C to -20 °C.
- By increasing the MTC evaporator temperature from -80 °C to -67 °C, the second-law (exergy) efficiency increases, reaches an optimum (maximum value), and remains constant up to -66 °C in system-1 and from -75 °C to -73 °C in system-2, then decreases.
- By decreasing the HTC condenser temperature from 60 °C to 30 °C, the second-law (exergy) efficiency increases in both systems.
- By increasing the LTC evaporator temperature from -140 °C to -108 °C, the second law (exergy) efficiency increases, reaches an optimum (maximum value), and remains constant up to -105 °C in system -1, and at -104 °C and -103 °C, then decreases.

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