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ORIGINAL ARTICLE

Optimization of thermal performances of three staged VCR systems using ecofriendly HFC, HCFO, HFO & HFO Blended refrigerants for replacing high GWP HFC refrigerants for reducing global warming and ozone depletion.

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Abstract

In three staged cascaded VCR systems, the methods for increasing first law and second law efficiency have been discussed by a number of researchers. The thermal performance parameters for replacing R507a, R125, R134a, R410a, R407c, and R404a have also been obtained. In the high temperature cycle, numerical calculations for the low GWP, environmentally friendly HFC-152a and HFC-245fa, HCFO-1224yd(Z), HCFO-1233zd(E), and other HFO refrigerants have been done, and several combinations have been suggested. The effects of HCFO-1233zd(E), HFO-1225ye(Z), and HFO-1336mzz(Z) in medium temperature cycle on total system energy and efficiency performances as well as cycles energy-exergy performances for replacing R507a, R125, R134a, R410a, R407c, and R404a have been studied. Thermal model is proposed. The impact of employing HFO-1225ye(Z) & HFO-1336mzz(Z) in the ultra-low temperature cycle has been proposed. The suggested thermal model successfully verified the findings of other researchers. It was observed that first law and second law efficiency using HCFO-1224yd (Z) in HTC, HCFO-1233zd(E) in MTC and HFO-1225ye(Z) gives best thermal energy-exergy performances, slightly higher than using HCFO-1233zd(E) in HTC, HFO-1336mzz(Z) in MTC and HFO-1225ye(Z) and HCFO-1224yd (Z) in HTC, HCFO-1233zd(E) in MTC and HFO-1336mzz(Z). Utilizing HFO-1234yf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z) in LTC, the lowest thermal performance was attained.

1. Introduction

The technology of refrigeration rejects heat to the environment at higher temperatures while absorbing heat at low temperatures to offer temperatures below the surrounding. Food is stored in various compartments and at various temperatures in many applications, such as large hotels, food storage facilities, and food processing plants. A simple vapor compression system consists of four major components: a compressor, an expansion valve, a condenser, and an evaporator. Therefore, a multiple evaporator vapor compression refrigeration system is required. By enhancing system performance, the vast amount of electricity used by systems using simple vapor compression technology can be reduced. The following actions can enhance the performance of systems based on VCR technology:

- The refrigeration system's efficiency is measured in terms of COP, which is the refrigeration effect on net work input.

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By boosting the refrigeration effect or decreasing work input to the system, the COP of a vapor compression refrigeration system can be raised. (ii) The throttling process in a VCR is a well-known example of an irreversible expansion process. One of the primary causes of exergy loss in cycle performance is the expansion process.

- The refrigerant in the evaporator flashes to vapor, which not only reduces cooling capacity but also enlarges the evaporator. This issue can be solved by using a multi-stage expansion with a flash chamber, where the flash vapors are dissipated after each stage of expansion, increasing cooling capacity and reducing evaporator size.
- By switching out compound or multi-stage compression for single-stage compression, work input can also be decreased.
- By running the refrigerant through the sub cooler after the condenser and before the evaporator, the cooling effect can also be increased.

Due to greater pressure ratios, single-stage/double-stage systems with reciprocating compressors are impractical for low-temperature applications. With lower volumetric compressor efficiencies and high discharge and oil temperatures, high-pressure ratios lead to low first-law efficiency in terms of COP values. When using a sequence of single-stage units that are thermally connected through cascading evaporators/condensers, vapor compression cascade refrigeration systems can accomplish low temperatures applications. There is a unique environmentally friendly refrigerant for that temperature in each circuit. For applications in the chemical, food, pharmaceutical, and other industries, low-temperature refrigeration systems are often needed for low-temperature ranges between -40°C and -100°C, the three staged cascaded VCR systems are required.

A system that combines two or more VCR cycles is known as cascading vapor compression refrigeration. The exergy of the product and the exergy of fuel in terms of minimum electrical energy consumption for operating compressors is determined by taking into account both having higher and lower evaporator temperatures. High boiling point refrigerants like R-1234ze, R-1234yf, R-717, and R152a are used in the HTC, while environmentally friendly refrigerants like R1234yf, R134a, R407c, R125, etc. are used in the MTC. Similar low-boiling refrigerants are utilized in the cascade LT circuit. Applications based on VCR systems use refrigerants that contribute to greenhouse gas emissions, global warming, and ozone layer depletion. The Montreal Protocol was established to address the issue of compounds that damage the ozone layer, and it revealed how much production and consumption of ozone-depleting substances occurred in both industrialized and developing nations during a specific time. In 1997, the Kyoto Protocol was established to reduce greenhouse gas emissions [1]. The primary problem in the green VCR technology is the interaction between ozone depletion potential and global warming potential, hence Kyoto proposed new refrigerants with lower values of ODP and GWP. For the sake of addressing global environmental issues, a program is being undertaken internationally to phase out refrigerants with high chlorine concentrations. After the 1990s, the use of CFC and HCFC refrigerants was prohibited due to their high chlorine content, high potential for global warming, and high potential for ozone depletion. As a result, low GWP environmentally friendly HFC refrigerants are now used; nonetheless, they still have a higher global warming potential value than non-fluorinated refrigerants. There is still more study to be done regarding the use of HCFO, HFO, and mixes of refrigerants to replace high GWP ecofriendly HFC refrigerants.

This paper mainly deals with the performance evaluation of the three-staged cascaded VCRS using HFOs, hydrocarbons(HC) & Low GWP ecofriendly HFC refrigerants in HTC, HC-170 and HC41, HCFO-1233zd(E), HFO-1225ye(Z) & HFO-1336mzz(Z) in MTC and HFO-1225ye(Z) & HFO-1336mzz(Z) in LTC for finding maximum thermal performance parameters.

2. Literature Review

To analyze three-stage cascade VCR systems for low-temperature applications, the following presumptions have been made. The estimated cooling load is 175 [kW]. Condenser temperature must be between 40°C and 55°C, and low circuit evaporator temperature must be between -90°C and 95°C. High-temperature evaporators should be between -22°C and -10°C, while secondary intermediate cascade evaporators should be around -60°C. The impact of temperature overlapping is taken into consideration, where the temperature difference between the cascade condenser and cascade evaporator is 10°C in each stage.

Analytical research by Nikolaidis and Probert [1] found that the irreversibility of a two-stage VCR system using R22 is significantly impacted by changes in the evaporator and condenser temperatures and they claimed that the condenser and evaporator's operating conditions should be optimized.

In the cascade heat exchanger R744-R717 cascade refrigeration system, Getu and Bansal [2] optimized the design and operating parameters for things like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature, and temperature differential. To determine the best thermal parameters for the same system, a regression analysis was also performed.

Thermal modeling of a cascade refrigeration-heat pump system was done by Bhattacharyya et al. [3] and included both internal and exterior irreversibilities that occurred in cascaded VCRS. An experimental evaluation of a different kind of two-stage vapor compression cascade refrigeration system was conducted by Canan Cimsit [4]. An ammonia and carbon dioxide-based cascade refrigeration system was examined thermally by Lee et al. [5]. Sun [6] performed a thermal (energy and exergy) analysis of the three-stage cascade VCR systems using hydrocarbon refrigerants. For determining COP, total compressor work, exergy efficiency, total exergy destruction, mass flow rate and discharge temperatures of compressors, and component exergy destruction were taken into consideration. It was also suggested that at various evaporator temperatures, various hydrocarbon refrigerants on the VCRS give higher COP and exergy efficiency.

Mishra [7] analyzed the thermal performance of a four-stage cascade vapor compression refrigeration system by using R1234ze and R1234yf in the high-temperature circuits, new environmentally friendly refrigerants in the intermediate circuits, and R134a or R404a in the low-temperature cascade circuit, and the theoretical analysis of a different kind of four-staged vapor compression refrigeration system. Both of these systems use hydrocarbons as refrigerants.

Mishra [8] discovered the usefulness of three stages cascaded VCR systems. It was discovered that R1234ze-R134a-R404a is the ideal combination for low-temperature (50°C to -100°C) applications because it provides higher thermal performance than R1234yf-R134a-R404a. R1234ze-R134a-R404a, for example, performs better thermally than R1234ze-R1234yf-R404a in a similar manner.

The above-mentioned researchers did not study the thermal performances for very low-temperature applications using eco-friendly HFO blended refrigerants in the low-temperature circuit & HT circuit, Also HFC+HFO blends in MT circuits, and HFO blends in low-temperature circuits. They also did not study the thermal performances in terms of COP & exergetic efficiency,

2.1 Environmental Analysis

The need to take action to reduce greenhouse gas emissions has become more urgent since the effects of these emissions on the climate have been repeatedly verified in recent years. The production and emissions of hydrofluorocarbons (HFCs), the still-most-used class of refrigerants in the heating, ventilation, air conditioning, and refrigeration (HVAC&R) industry, have been under regulation since the Kyoto Protocol (1997). particularly, depending on the applications. The F-gas Regulation (EU) (2014) of the European Union established quite strict timelines for the banning of HFCs. The usage of various refrigerants causes significant environmental degradation, which decreases human living standards, causes ozone depletion, and contributes to global warming. Finding and using new, low-GWP, and ODP-free environmentally acceptable refrigerants is therefore essential. Several HFOs' environmental characteristics are displayed in Table 1(a) in the appropriate ways. The HFOs, cis-1-chloro-2,3,3,3-tetrafluoropropene (R1224yd(Z)), can be employed in centrifugal chillers or industrial high-temperature heat pumps because of its low vapor pressure and comparatively high NBP (287.15 K). Despite having a chlorine atom in it, R1224yd(Z) has a very low GWP (1) and a minuscule ODP (0.00023). R1224yd(Z) is also very favourable from the perspective of environmental compatibility and human safety, having very low toxicity and not being flammable. R245fa could potentially be replaced with R1224yd(Z) in industrial high-temperature heat pumps and centrifugal chillers.

Despite having a chlorine atom, HCFO-1224yd(Z) has strong application potential in heat pumps and refrigeration systems because of its small ODP (0.00023) and extremely low GWP is less than 1. HCFO-1224yd(Z) (cis-1,1,1,4,4,4-Hexafluoro-2-butene) is a developing refrigerant with minimal potential for global warming, providing remarkable environmental advantages. 0.00024 to 0.00034 ozone depletion potential (ODP) with a maximum global warming potential (GWP) of 6 Similar to this, the recently developed cis-1,2,3,3,3-pentafluoroprop-1-ene (HFO-1225ye(Z)) refrigerant with little potential for global warming is showing great promise for use in refrigeration. A non-flammable, ultra-low GWP alternative to R-123 is HCFO-1233zd(E) for low-pressure centrifugal chillers. The GWP of R1233zd(E) is 1, which is 99.9% less than that of R-245fa. Therefore, R-245fa can be successfully replaced with HCFO-1233zd(E). Similarly, HFO-1243zf (hydrofluoroolefin 3,3,3-trifluoro propene), which has zero ODP and 0.82 GWP, has very low toxicity. The environmental properties of a few HFOs & HCFOs are shown in Table-1(b) respectively.

Table 1(a): Environmental properties of HFO refrigerants

HFO	GWP	ODP
R-1234yf	4	0
R-1234ze(E)	6 to 7	0
R-1234ze(Z)	1	0
R-1224yd(Z)	01	0
R-1233zd(E)	01 to 6(Max)	0.00034
R1336mzz(Z)	02	0
R-1243zf	0.82	0
R-1225ye(Z)	9	0

The environmental properties of few HFOs & HCFO are shown in Table-1(b) respectively.

Table 1(b): Environmental properties of HFO blends

HFO Blends	Composition	GWP
R450a	58% R-1234ze(E) +42% R134a	604
R513a	56% R-1234yf+44% R134a	573
R515a	88% R-1233zd(E)+ 12% R227ea	573
R452a	11% R-32+30% R1234yf+59% R125	2141
R454b	68.9%R-32+31.1% R1234yf	148
R454c	78.5% R1234yf +21.5% R-32	148
R448A	26% R32+ 26% R125+21% R134a+20% R1234yf+7% R1234ze(E)	1387
R449A	24% R32+ 25% R125+26% R134a+25% R1234yf	1397

Mishra [9] has researched the energy-exergy efficiencies (energy-exergy first and second laws) of cascade VCR systems using new HFO-1234yf eco-friendly refrigerants for lowering global warming and ozone depletion performance metrics like COP, exergetic efficiency, and exergy destruction ratio, as well as the power needed to run entire systems. The first and second law performances of the cascaded VCR system using R1234ze(Z) in the HT cycle and R1233zd(E) in the LT cycle give the best thermal (exergy) performances. The various combinations of using six different eco-friendly refrigerants used in the high-temperature cycle in the temperature range of from 50oC to 0°C for which other five eco-friendly low GWP refrigerants in the medium temperature range of from 0°C Additionally, when compared to other HFO refrigerants, R1234yf's performance in high- or low-temperature cycles was the lowest [11]. HFO-1234yf and HFC-134a were compared in a low-temperature cycle up to a temperature of -50°C, and it was discovered that using R-1234yf in a low-temperature cycle resulted in 3.25% lower first and second-law efficiencies than using HFC-134a and that using R1234ze(Z) in a high-temperature cycle resulted in a 5% decrease in the exergy destruction ratio [12].

Mishra [13] carried out an energy and exergy analysis of a subcritical cascade refrigeration system and discovered a 12 % improvement in the COP. Environmentally friendly HFO refrigerants were used in the medium temperature range (up to -50°C), Low GWP environmentally friendly R245fa was used in the intermediate temperature cycle up to -95°C, and R600a, R290 was used in the ultra-low temperature (-150°C) of cascade VCR system, and it was discovered that these refrigerants worked well.

Mishra [14] studied energy & exergy analysis of cascade refrigeration systems using low global warming potential refrigerants and found a 13 % improvement in the COP The use of eco-friendly HFO refrigerants in the medium temperature range (up to -50°C) using Low GWP ecofriendly R245fa in LT cycle up to -95°C and R600a, R290 in ultra-low temperature (-150°C) of the cascade refrigeration system and it was found that hydrocarbon R-600a gives best thermal first and second law performances with lowest exergy destruction ratio in the ultra-low temperature between -110°C to -130°C.

The second law efficiency using R600a in the low-temperature evaporator circuit performs better in terms of second law efficiency than R290 and R404a in the lower-temperature circuit (LTC) [8]. Due to their low GWP and absence of ODP, many researchers have suggested a few hydrofluorocarbons and hydrocarbon-based refrigerants as substitutes. Among the two, pure hydrocarbon refrigerants are an intriguing choice. Hydrocarbon refrigerants' tendency to catch fire is their biggest drawback. However, while flammable refrigerants were previously prohibited from use, current regulations allow their use with additional safety precautions, therefore this problem can be avoided by utilizing safety. Hydrocarbon-based refrigerants have several advantages over chlorofluorocarbon-based refrigerants notwithstanding the flammability issue [20].

Simple vapor compression refrigeration systems and cascaded vapor compression refrigeration systems utilizing HFO+HFC blends in HTC & LTC cycles were subjected to a thermal analysis by Mishra [15].

The highest coefficient of performance (COP) and exergy efficiency (exergy efficiency) were found to be 0.5931 and 54.5%, respectively, at a temperature of -100 °C for the evaporator, demonstrating the usefulness of hydrocarbon refrigerants in three-stage VCR systems for ultra-low temperature applications without compromising the thermal performances. To determine the optimal thermal performance parameters, this paper primarily examines the performance evaluation of the three-stage cascaded vapor compression using HFOs, hydrocarbons (HC), and Low GWP ecofriendly HFC refrigerants in HTC, R170, and R41 in MTC for replacing R23, and R1150 for replacing R14 in LTC.

R32 and ethylene operate almost identically under the first and second laws of thermals, and less so than R290. Therefore, using hydrocarbons might be advantageous if the proper safety precautions are taken because most hydrocarbons are combustible. In comparison to R1224yd(Z), R1234ze(E), and R1243zf used in intermediate temperature for R1234ze(Z)/R1234ze(E), R1233zd(E), and Ethylene in ultra-low temperature ranges between -110°C and -130°C, R1234ze(Z) gives the best/highest thermal performances with the lowest exergy destruction ratio.

The use of R134a in the high-temperature circuit and R1234yf in a low-temperature cycle, however, was found to have the lowest performance. When HFC-134a and HFO-1234yf's thermal capabilities for cascade VCR systems were compared, it was discovered that HFO1236mzz(z) and R1225ye(Z) produced results comparable to those of R134a when used in MT cycles up to -50°C of evaporator temperature [17] Regulation (EU) No 517/2014 strongly advises against using HFO refrigerants with high global warming potential (GWP) and low ozone depletion potential (ODP), such as R1234yf, to mitigate the danger of climate change.

Therefore, refrigerant R1234yf could be a choice for cascade vapor compression refrigeration cycle up to temperature -50oC and -75°C using HCFO-1233zd(E) in a lower temperature cycle. However, the GWP and ODP ratings of R1234yf are 4 and zero, which show the environment and nature-friendly behavior of refrigerants.

Mishra [7,8] carried out the exergy analysis of three & four stages cascade VCR systems used for low-temperature applications using eco-friendly refrigerants. 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) has been optimized thermally using of R1234yf and R1234ze in the high-temperature circuits and mainly thirteen eco-friendly refrigerants in the intermediates circuits and ethane.

Therefore, the VCR cycle may select the refrigerant R1234yf. However, R1234yf's GWP and ODP ratings are 4 and 0, respectively, demonstrating the refrigerant's environmentally and naturally friendly behavior.

Three- and four-stage cascade refrigeration systems utilized for low-temperature applications employing eco-friendly refrigerants were subjected to an energy study by Mishra [7,8,]. Using R1234yf and R1234ze in the HT circuits and primarily thirteen eco-friendly refrigerants in the low-temperature circuits, the effect of performance parameters (i.e. approaches, condenser temperature, and temperature variations in the evaporators) on the thermal exergy 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) have been optimized thermal performances.

It was discovered that in low-temperature applications (between -80°C and -88°C). The optimum combination of R1234ze-R134a-R410a ethane was shown to provide superior thermal performance than R1234yf-R134a-R410a ethane [9]. The use of environmentally friendly VCR systems is growing in popularity as a means of addressing energy and environmental issues. In this paper, it is recommended that to create a more sustainable environment, we gradually phase out the refrigerant R-134a, which is now the most popular one. Instead, we should employ natural refrigerants such as ammonia, carbon dioxide, and hydrocarbons in two-stage cascade VCR systems.

The use of R1234ze, which has an extremely low global warming potential (GWP=6), provides better thermal performance than R1234yf, which has a GWP=6, in the higher temperature circuit of a four-stage cascade VCR system, was observed to have better thermal exergy performances in terms of COP, exergetic efficiency, and system exergy destruction ratio (EDR) for very low-temperature applications. In the first intermediate temperature circuit, there were not many thermal performance increases between R134a and R410a. [9 to 11].

Mishra [12] conducted a thorough exergy analysis of a three-stage cascaded VCRS using R1234ze(Z) in the high-temperature cycle at 0°C of evaporator temperature and R1233d(E) in the medium temperature cycle at -75°C of evaporator temperature in the medium temperature cycle, as well as HFO-1225ye(Z), an environmentally friendly refrigerant that provides the best thermal performances for ultra-low temperature applications. The cascaded VCRS uses HCFO-1224yd(Z) in the high-temperature cycle at a temperature of -10°C for the evaporator and HCFO-1233d(E) in the medium temperature cycle at a temperature of -60°C for the evaporator. In comparison to cascaded VCRS using R1234ze(Z) in the HT cycle at 0°C of evaporator temperature in the HT cycle & R1233d(E) in the medium temperature cycle at -75°C of evaporator temperature in the MT cycle, -90°C of evaporator temperature in the LT cycle using R1225ye(Z) gives slightly lower thermal exergy performances

Similarly, eco-friendly HFO-1225ye(Z), HFO-1336mzz(Z), and HCFO-1233zd(E) are suitable for replacing R134a, R410a, R407c, and R134a in medium temperature applications at -60°C, while HFO-1336mzz(Z) is suitable for replacing R134a in the ultra-low temperature cycle up to -95°C. Low GWP HFCs and hydrocarbons (HC) refrigerants are more suitable [13 to 19].

3. Results and Discussion

The thermal model was created using R12, in HTC, R22, in MTC, and R13, in LTC, for three-tiered cascaded VCR systems [25]. Under identical operating conditions, the theoretical outcomes of the suggested thermal model were compared to the input values. The refrigerant pair is treated the same to validate the suggested study. The system's R12/R22/R13 combination has different simulation results, with the biggest error for the overall COP being 1.98%, as shown in Table 2(a). It was discovered that the constructed thermal model accurately predicted the behavior displayed in Table 2(a).

Table 2(a): Validation of results obtained from Thermal model

Performance Parameters	Model	Ref [20]	Error Difference (%)
HTC refrigerants @ -10°C	R-12	R-12	-------
MTC refrigerants @ -60°C	R22	R22	------
LTC refrigerants @ -95°C	R13	R-13	-----
COP_Cascade_Three Staged	0.875	0.858	1.981%
COP_HTC	3.018	2.88	4.792%
COP_MTC	3.681	3.7	-0.514%
COP_LTC	3.763	3.74	0.615%
Exergy of fuel “kW”	200.0	204.0	- 1.961%
Compressor Work_HTC “kW”	93.33	97.4	- 4.179%
Compressor Work_MTC “kW”	60.17	59.8	0.6187%
Compressor Work_LTC “kW”	46.5	46.8	- 0.64 %

The thermal performance of a three-stage cascaded VCR using R12 in HTC, R22 in MTC, and R13 in LTC was compared with that of other three-stage cascaded VCR systems using HCFO & HFO refrigerants in all cycles, as shown in Table 2(b), and it was discovered that the cascaded VCR system using HCFO-1233zd(E) in HTC, HFO-1336mzz(Z) in MTC, Using HFO-1225ye(Z) in HTC, HCFO-1233zd(E) in MTC, and HFO-1336mzz(Z) in LTC, the highest electrical energy consumption in all operating compressors and the lowest thermal (energy-exergy) performance system were discovered. The thermal performances of the three-stage cascaded VCR system using R12 in HTC, R22 in MTC, and R13 in LTC have been compared with those of other three-stage cascaded VCR systems using HFO-1234ze(E) in HTC, HCFO-1233zd(E), HFO-1225ye(Z) cycles & HFO-1336mzz(Z) in MTC, and HFO-1225ye(Z) cycles & H HFOs and HCFOs are capable of replacing CFC refrigerants, according to table 2(c).

The effect of different HFO refrigerants on the thermal performances of cascaded three staged VCRS at - 22 °C of HTC evaporator temperature, -60°C of MTC evaporator temperature, & -90 °C of LTC evaporator temperature has been computed and shown in Table 2(c), respectively. It was discovered that the cascaded VCR system using HCFO-1233zd(E) in HTC, HFO-1336m Lowest thermal (energy-exergy) performances are provided by the three-stage cascaded VCR system employing HFO-1234yf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z) in LTC. It is evident that shortly, three-stage cascaded VCR systems can be replaced by HCFOs in HTC, HCFO and HFO in MTC, and HFO in LTC.

Table 2(b): Comparison of thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -90°C, MTC evaporator temperature -60oC, HTC evaporator temperature -22°C, HTC condenser temperature=40°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC refrigerants @-22°C	R12	R-1233zd(E)	R-1233zd(E)	R1225ye(Z)	R-1336mzz(Z)
MTC refrigerants @-60°C	R22	R-1336 mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
LTC refrigerants @-90°C	R13	R1225ye(Z)	R-1336mzz(Z)	R-1336mzz(Z)	R1225ye(Z)
COP_Cascade_Three Staged	0.875	0.9048	0.9007	0.8640	0.8918
Exergy Efficiency	0.5494	0.5682	0.5655	0.5425	0.560
Exergy of fuel “kW”	200.0	193.4	194.30	202.6	196.2
Exergy of product “kW”	109.9	109.9	109.9	109.9	109.9
Compressor Work_HTC “kW”	93.33	89.56	89.78	98.82	93.47
Compressor Work_MTC “kW”	60.17	59.70	59.61	58.83	58.62
Compressor Work_LTC “kW”	46.5	44.14	44.91	44.94	44.14
HTC Mass flow Rate(kg/s)	2.728	1.999	2.004	2.894	2.416
MTC Mass flow Rate(kg/s)	1.152	1.443	1.623	1.241	1.237
LTC Mass flow Rate(kg/s)	1.501	1.109	0.9821	0.9821	1.109
COP_Cascade two_ Staged	1.443	1.468	1.472	1.395	1.441
Exergy Efficiency	0.5754	0.5855	0.587	0.5563	0.5746
Exergy of fuel “kW”	153.5	149.3	149.4	157.6	152.10
Exergy of product “kW”	88.33	87.39	87.7	87.70	87.39
COP_ HTC	3.018	3.113	3.113	2.821	2.972
Exergy Efficiency	0.5648	0.5826	0.5826	0.5279	0.5561
Exergy of fuel “kW”	93.33	89.56	89.78	98.82	93.47
Exergy of product “kW”	52.71	52.18	52.31	52.16	51.98
HTC Condenser Heat Rejected	375.0	368.4	369.3	377.6	371.2
MTC Condenser Heat Rejected	281.7	278.8	279.5	277.8	277.8
LTC Condenser Heat Rejected	221.5	219.1	219.9	219.9	219.1
HTC Evaporator Load	281.7	278.8	279.5	277.8	277.8
MTC Evaporator Load	221.5	219.1	219.9	219.9	219.1
LTC Evaporator Load	175.0	175.0	175.0	175.0	175.0
COP_MTC	3.681	3.671	3.689	3.738	3.738
COP_LTC	3.763	3.965	3.896	3.896	3.965

Table 2(c): Comparison of thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants with conventional cascaded three staged VCR system at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -22°C, HTC condenser temperature=40oC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC refrigerants @-22°C	R12	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)
MTC refrigerants @-60°C	R22	R1233zd(E)	R1233 zd(E)	R1225ye(Z)	R-1336 mzz(Z)
LTC Ecofriendly refrigerants @-90°C	R13	R1225ye(Z)	R-1336 mzz(Z)	R-1336mzz(Z)	R1225ye(Z)
COP_Cascade_Three Staged	0.875	0.8744	0.8687	0.8642	0.8681
Exergy Efficiency	0.5494	0.5491	0.5454	0.5426	0.5451
Exergy of fuel “kW”	200.0	200.1	201.5	202.5	201.6
Exergy of product “kW”	109.9	109.9	109.9	109.9	109.9
Compressor Work_HTC “kW”	93.33	97.37	97.71	97.99	97.75
Compressor Work_MTC “kW”	60.17	58.62	58.83	59.61	58.62
Compressor Work_LTC “kW”	46.5	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.728	2.458	2.467	2.474	2.468
MTC Mass flow Rate(kg/s)	1.152	1.237	1.241	1.623	1.443
LTC Mass flow Rate(kg/s)	1.501	1.109	0.9821	0.9821	1.109
COP_Cascade two_ Staged	1.443	1.405	1.405	1.395	1.392
Exergy Efficiency	0.5754	0.5602	0.5602	0.5565	0.555
Exergy of fuel “kW”	153.5	156.0	156.5	157.6	157.4
Exergy of product “kW”	88.33	87.37	87.7	87.7	87.39
COP_ HTC	3.018	2.853	2.853	2.853	2.853
Exergy Efficiency	0.5648	0.5338	0.5338	0.5338	0.5338
Exergy of fuel “kW”	93.33	93.37	93.71	97.99	97.75
Exergy of product “kW”	52.71	51.98	52.16	52.31	51.98
HTC Condenser Heat Rejected	375.0	375.1	376.5	377.5	376.6
MTC Condenser Heat Rejected	281.7	278.7	278.8	279.5	278.8
LTC Condenser Heat Rejected	221.5	219.1	219.1	219.9	219.1

HTC Evaporator Load	281.7	278.7	278.8	279.5	278.8
MTC Evaporator Load	221.5	219.1	219.9	219.9	219.1
LTC Evaporator Load	175.0	175.0	175.0	175.0	175.0
COP_MTC	3.681	3.738	3.738	3.689	3.671
COP_LTC	3.763	3.965	3.896	3.896	3.965

Effect of various HFO and HCFO refrigerants on the thermal performance of a cascaded three-staged VCRS at - 22°C for the HTC evaporator temperature, -60°C for the MTC evaporator temperature, and -90°C for the LTC evaporator temperature have been calculated and shown in table 1(d), respectively. It has been discovered that the system using HFO-1243zf in the HTC, HCFO-1233zd Similar to this, a three-stage cascaded VCR system using the HFO-1234zf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z) in LTC results in the highest electrical energy consumption across all compressors operating in the system while also providing the lowest thermal (energy-exergy) performances.

Table 2(d): Thermal performances of three staged cascaded VCR systems using HFO-1234zf in HTC, HCFO and HFO refrigerants in MTC and HFO refrigerants with conventional cascaded three staged VCR system at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -22°C, HTC condenser temperature=40°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants @-22°C	R12	R-1243zf	R-1243zf	R-1243zf	R-1243zf
MTC Ecofriendly refrigerants@-60°C	R22	R1233zd(E)	R1233 zd(E)	R1225ye(Z)	R-1336mzz(Z)
LTCEcofriendly refrigerants@-90°C	R13	R1225ye(Z)	R-1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)
COP_Cascade_Three Staged	0.875	0.8685	0.8628	0.8584	0.8623
Exergy Efficiency	0.5494	0.5454	0.5418	0.539	0.5414
Exergy of fuel “kW”	200.0	201.5	202.8	203.9	203.0
Exergy of product “kW”	109.9	109.9	109.9	109.9	109.9
Compressor Work_HTC “kW”	93.33	98.73	99.08	99.36	99.91
Compressor Work_MTC “kW”	60.17	58.62	58.83	59.61	59.70
Compressor Work_LTC “kW”	46.5	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.728	2.894	2.004	2.894	2.416
MTC Mass flow Rate(kg/s)	1.152	1.241	1.623	1.241	1.237
LTC Mass flow Rate(kg/s)	1.501	1.109	0.9821	0.9821	1.109
COP_Cascade two_ Staged	1.443	1.395	1.472	1.395	1.441
Exergy Efficiency	0.5754	0.5563	0.587	0.5563	0.5746
Exergy of fuel “kW”	153.5	157.6	149.4	157.6	152.10
Exergy of product “kW”	88.33	87.39	87.7	87.70	87.39
COP_ HTC	3.018	2.821	3.113	2.821	2.972
Exergy Efficiency	0.5648	0.5265	0.5265	0.5265	0.5265
Exergy of fuel “kW”	93.33	98.73	99.08	99.36	99.91
Exergy of product “kW”	52.71	51.98	52.16	52.31	52.18
HTC Condenser Heat Rejected	375.0	376.5	377.8	378.9	378.0
MTC Condenser Heat Rejected	281.7	277.8	278.7	279.5	277.8
LTC Condenser Heat Rejected	221.5	219.1	219.9	219.9	219.1
HTC Evaporator Load	281.7	277.8	279.5	277.8	277.8
MTC Evaporator Load	221.5	219.9	219.9	219.9	219.1
LTC Evaporator Load	175.0	175.0	175.0	175.0	175.0
COP_MTC	3.681	3.738	3.689	3.738	3.738
COP_LTC	3.763	3.965	3.896	3.896	3.965

Comparing the thermal performance of three staged cascaded vapor compression refrigeration systems using R12 in HTC, R22 in MTC, and R13 in LTC with other three staged cascaded VCR systems using HFO refrigerants in All cycles, as shown in table 2(e), it was discovered that the cascaded VCR system using HFO-1234yf in HTC, HCFO-1233zd(E) in MTC, and HFO-1225ye(Z) in LTC, The effects of various HFO refrigerants on the thermal performances of cascaded three-staged VCRS at - 22°C for HTC, -60°C for MTC, and -90°C for LTC were calculated, and it was discovered that the cascaded VCR system using HFO-1234yf in HTC, HCFO-1233zd(E) in MTC, and HFO-1225ye(Z) in LTC gives higher thermal performances than the system. However, the three tiered VCR system using HFO-1234yf in HTC, HFO-1336mzz(Z) in MTC, and HFO-1225ye(Z) in LTC had the lowest thermal (energy-exergy) performances.

Table 2(e): Thermal performances of three staged cascaded VCR systems using HCFO and HFO refrigerants with conventional cascaded three staged VCR systems with conventional cascaded three staged VCR system at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -22ºC, HTC condenser temperature=40ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants @-22ºC	R12	R1234yf	R1234yf	R1234yf	R1234yf
MTC Ecofriendly refrigerants@-60ºC	R22	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
LTCEcofriendly refrigerants@-90ºC	R13	R1225ye(Z)	R-1336 mzz(Z)	R1225ye(Z)	R-1336mzz(Z)
$COP\__{Cascade\_Three\ Staged}$	0.875	0.8449	0.8395	0.8352	0.8389
Exergy Efficiency	0.5494	0.5305	0.498	0.5244	0.5268
Exergy of fuel "kW"	200.0	207.1	208.5	209.5	208.5
Exergy of product "kW"	109.9	109.9	109.9	109.9	109.9
Compressor $Work\__{HTC}$ "kW"	93.33	104.4	104.7	105.0	104.8
Compressor $Work\__{MTC}$ "kW"	60.17	58.62	58.83	59.61	59.70
Compressor $Work\__{LTC}$ "kW"	46.5	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.728	2.960	2.971	2.979	2.972
MTC Mass flow Rate(kg/s)	1.152	1.237	1.241	1.623	1.443
LTC Mass flow Rate(kg/s)	1.501	1.109	0.9821	0.9821	1.109
$COP\__{Cascade\ two\_\ Staged}$	1.443	1.345	1.345	1.336	1.332
Exergy Efficiency	0.5754	0.5362	0.5362	0.5327	0.5314
Exergy of fuel "kW"	153.5	163.0	163.6	164.6	164.5
Exergy of product "kW"	88.33	87.39	87.7	87.7	87.39
$COP\__{HTC}$	3.018	2.662	2.662	2.662	2.662
Exergy Efficiency	0.5648	0.4981	0.4981	0.4981	0.4981
Exergy of fuel "kW"	93.33	104.4	104.7	105.0	104.8
Exergy of product "kW"	52.71	51.98	52.16	52.31	52.18
HTC Condenser Heat Rejected	375.0	382.1	383.5	384.5	382.6
MTC Condenser Heat Rejected	281.7	277.8	278.7	279.5	277.8
LTC Condenser Heat Rejected	221.5	219.1	219.9	219.9	219.1
HTC Evaporator Load	281.7	277.8	279.5	277.8	277.8
MTC Evaporator Load	221.5	219.9	219.9	219.9	219.1
LTC Evaporator Load	175.0	175.0	175.0	175.0	175.0
$COP\__{MTC}$	3.681	3.738	3.689	3.738	3.738
$COP\__{LTC}$	3.763	3.965	3.896	3.896	3.965

As shown in Tables 2(f) and 2(g), the effect of hydro carbons on the thermal performances of three-stage cascaded VCR systems using HCFO and HFO refrigerants in all cycles was studied. It was discovered that the cascaded systems using HC-600a in HTC, R41 in MTC, and propylene in LTC give the best thermal energy-exergy performances compared to the traditional three-stage cascaded VCR system. When replacing high GWP & eco-friendly, HFO refrigerants like R404a, R134a, and R125 in high temperature cycles up to -10°C & R170, R41 in medium temperature cycles up to -60°C, and R-1150 in ultra-low temperature cycles up to -90°C, low GWP HFCs and hydrocarbons (HC) refrigerants are preferable and results were shown in table- 2(f) to table-2(g) respectively.

Table 2(f): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HC refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -22ºC, HTC condenser temperature=40ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants	R600a	R290	R600a	R290
MTCEcofriendly refrigerants	Ethane	Ethane	Ethane	Ethane
LTCEcofriendly refrigerants	Propylene	Propylene	Ethylene	Ethylene
$COP\__{Cascade\_Three\ Staged}$	0.8445	0.8310	0.8217	0.8088
Exergy Efficiency	0.5303	0.5218	0.5160	0.5078
Exergy of fuel "kW"	207.2	210.6	213.0	216.4
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor $Work\__{HTC}$ "kW"	96.47	99.83	97.92	101.3
Compressor $Work\__{MTC}$ "kW"	65.91	65.91	66.9	66.9
Compressor $Work\__{LTC}$ "kW"	44.84	44.84	48.14	48.14
HTC Mass flow Rate(kg/s)	1.249	1.182	1.268	1.20
MTC Mass flow Rate(kg/s)	0.7076	0.7076	0.7182	0.7182
LTC Mass flow Rate(kg/s)	0.4402	0.4402	0.4884	0.4884
$COP\__{Cascade\ two\_\ Staged}$	1.354	1.326	1.354	1.326
Exergy Efficiency	0.5399	0.5289	0.5399	0.5289
Exergy of fuel "kW"	162.2	165.7	164.8	168.2

Exergy of product "kW"	87.67	87.67	88.99	88.99
COP_ HTC	2.962	2.862	2.962	2.862
Exergy Efficiency	0.5543	0.5357	0.5543	0.5357
Exergy of fuel "kW"	96.47	99.83	97.92	101.3
Exergy of product "kW"	53.48	53.48	54.28	54.28
HTC Condenser Heat Rejected	382.2	385.6	388.0	391.4
MTC Condenser Heat Rejected	285.8	285.8	290.0	290.0
LTC Condenser Heat Rejected	219.8	219.8	223.1	223.1
HTC Evaporator Load	285.8	285.8	290.0	290.0
MTC Evaporator Load	219.8	219.8	223.1	223.1
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	3.335	3.335	3.335	3.335
COP_LTC	3.903	3.902	3.635	3.635

Table 2(g): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HC refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -22ºC, HTC condenser temperature=40ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants	R600a	R600a	R290	R290
MTCEcofriendly refrigerants	R41	R41	R41	R41
LTCEcofriendly refrigerants	Ethylene	Propylene	Propylene	Ethylene
COP_Cascade_Three Staged	0.8303	0.8538	0.840	0.8175
Exergy Efficiency	0.5216	0.5361	0.5275	0.5133
Exergy of fuel "kW"	210.7	205.0	208.3	214.1
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor Work_HTC "kW"	97.34	95.5	99.24	100.7
Compressor Work_MTC "kW"	65.19	64.22	64.22	65.19
Compressor Work_LTC "kW"	48.14	44.84	44.84	48.14
HTC Mass flow Rate(kg/s)	1.261	1.242	1.175	1.192
MTC Mass flow Rate(kg/s)	0.6319	0.6225	0.6225	0.6319
LTC Mass flow Rate(kg/s)	0.4884	0.4402	0.4402	0.4884
COP_Cascade two_ Staged	1.373	1.373	1.345	1.345
Exergy Efficiency	0.5475	0.5475	0.5357	0.5363
Exergy of fuel "kW"	162.5	160.1	163.5	165.9
Exergy of product "kW"	88.99	87.67	87.67	88.99
COP_ HTC	2.962	2.962	2.862	2.862
Exergy Efficiency	0.5543	0.5357	0.5357	0.5357
Exergy of fuel "kW"	97.34	99.24	99.24	100.7
Exergy of product "kW"	53.96	53.16	53.16	53.96
HTC Condenser Heat Rejected	385.7	380.0	383.3	389.1
MTC Condenser Heat Rejected	288.3	284.1	284.4	288.3
MTC Evaporator Load	223.1	219.8	219.8	223.1
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	3.423	3.423	3.423	3.423
COP_LTC	3.635	3.903	3.902	3.635

3.1 Effect of HCFO-1233zd(E) and HFO-1225ye(Z) in MT and LT cycles

Table 3(a) demonstrated the cascaded VCRS using eco-friendly refrigerants R1225ye(Z) and HFO-1336mzz(Z) in the lower temperature cycle at -90ºC of evaporator temperature in the high temperature cycle, and HCFO-1224yd(Z) & HFO-1225ye(Z) and HFO-1336mzz(Z) in the medium temperature cycle at -60ºC of evaporator temperature in the MT cycle, the three staged cascaded VCRS using eco-friendly refrigerant HCFO-1224yd(Z) in the high temperature cycle (HTC) at -10ºC of evaporator temperature & and HCFO-1233zd(E) in the MT cycle at -60ºC of evaporator temperature and HFO-1225ye(Z) in the lower temperature cycle at -90ºC of evaporator temperature gives higher thermal exergy performances than the cascaded VCRS using HCFO-1224yd(Z) in the high temperature cycle (HTC) at -10ºC of evaporator, HCFO-1233zd(E) in the medium temperature cycle at -60ºC of evaporator temperature in the medium temperature cycle and HFO-1336mzz(Z) in the lower temperature cycle at -90ºC of evaporator temperature. However lowest energy-exergy performance was observed by using HCFO-1224yd(Z) in the high temperature cycle (HTC) at -10ºC of evaporator, HFO-1225ye(Z) in the medium temperature cycle at -60ºC of evaporator temperature in the medium temperature cycle and HFO-1336mzz(Z) in the lower temperature cycle at -90ºC of evaporator temperature in three staged cascaded VCRS.

Table 3(a): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC refrigerants @-10°C of evaporator temperature	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)
MTC refrigerants @-60°C of evaporator temperature	R1233 zd(E)	R1233zd(E)	R1225ye(Z)	R-1336 mzz(Z)
LTC refrigerants @-90°C of evaporator temperature	R1225ye(Z)	R-1336 mzz(Z)	R-1336 mzz(Z)	R1225ye(Z)
$COP\_{Cascade\_Three\ Staged}$	0.7829	0.7780	0.7684	0.7726
Exergy Efficiency	0.4916	0.4885	0.4825	0.4851
Exergy of fuel "kW"	223.5	224.9	227.7	226.5
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor $Work\_{HTC}$ "kW"	101.9	102.3	103.0	102.7
Compressor $Work\_{MTC}$ "kW"	77.47	77.74	79.83	79.68
Compressor $Work\_{LTC}$ "kW"	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.799	2.809	2.828	2.820
MTC Mass flow Rate(kg/s)	1.349	1.354	1.797	1.596
LTC Mass flow Rate(kg/s)	1.109	0.9821	0.9821	1.109
$COP\_{Cascade\ two\_\ Staged}$	1.222	1.222	1.203	1.202
Exergy Efficiency	0.4871	0.4871	0.4797	0.4792
Exergy of fuel "kW"	179.4	180.0	182.8	182.4
Exergy of product "kW"	87.39	87.7	87.7	87.39
$COP\_{\ HTC}$	2.91	2.91	2.91	2.91
Exergy Efficiency	0.3870	0.3870	0.3870	0.3870
Exergy of fuel "kW"	101.9	102.3	103.0	102.7
Exergy of product "kW"	39.46	39.5	39.87	39.74
HTC Condenser Heat Rejected	398.5	399.9	402.7	401.5
MTC Condenser Heat Rejected	296.6	297.7	299.7	298.5
LTC Condenser Heat Rejected	219.1	219.9	219.9	219.1
HTC Evaporator Load	296.6	297.7	299.7	298.5
MTC Evaporator Load	219.1	219.1	219.9	219.1
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_{MTC}	2.829	2.829	2.755	2.750
COP_{LTC}	3.965	3.896	3.896	3.965

Table 3(b) demonstrated the cascaded VCRS using eco-friendly refrigerants R1225ye(Z) and HFO-1336mzz(Z) in the HT cycle at -10°C of evaporator temperature, and HFO-1225ye(Z) and HFO-1336mzz(Z) in the MT cycle at -60°C of evaporator temperature in the MT cycle, giving higher thermal (energy-exergy) performances. Using HCFO -1233zd(E), HFO-1336mzz(Z), and R1225ye(Z) in MTC, these cascaded three tiered VCRS performed better in terms of (energy-exergy) performance. Similar to this, the cascaded VCRS with HFO-1225ye(Z) in the high temperature cycle at -10°C of evaporator temperature & HCFO-1233zd(E) in the MT cycle at -60°C of evaporator temperature in the medium temperature cycle & -90°C of evaporator temperature in the low temperature cycle using HFO-1336mzz(Z) ecofriendly refrigerant were found to have the lowest thermal performances. Three stages cascaded VCRs with HFO-1225ye(Z) in HTC, HCFO-1233zd(E) in MTC, and HFO-1336mzz(Z) in the lower temperature cycle are shown to have the lowest thermal performances.

Table 3(b): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC refrigerants @-10°C of evaporator temperature	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R-1336mzz(Z)
MTC refrigerants @-60°C of evaporator temperature	R-1336 mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
LTC refrigerants @-90°C of evaporator temperature	R1225ye(Z)	R-1336mzz(Z)	R-1336mzz(Z)	R1225ye(Z)
$COP\_{Cascade\_Three\ Staged}$	0.7836	0.7793	0.7361	0.7744
Exergy Efficiency	0.4920	0.4893	0.4622	0.4863
Exergy of fuel "kW"	223.2	224.6	226.0	240.8
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor $Work\_{HTC}$ "kW"	99.52	99.82	115.1	104.4
Compressor $Work\_{MTC}$ "kW"	79.68	79.83	77.74	77.47
Compressor $Work\_{LTC}$ "kW"	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.317	2.324	3.564	2.828
MTC Mass flow Rate(kg/s)	1.596	1.797	1.354	1.349
LTC Mass flow Rate(kg/s)	1.109	0.9821	0.9821	1.109

COP_Cascade two_ Staged	1.223	1.224	1.141	1.205
Exergy Efficiency	0.4877	0.4882	0.4548	0.4806
Exergy of fuel "kW"	179.2	179.7	192.8	181.8
Exergy of product "kW"	87.39	87.7	87.7	87.39
COP_ HTC	3.003	3.003	2.587	2.842
Exergy Efficiency	0.3994	0.3994	0.344	0.378
Exergy of fuel "kW"	99.52	99.82	115.1	104.4
Exergy of product "kW"	39.74	39.87	39.59	39.45
HTC Condenser Heat Rejected	398.3	399.6	412.7	401.0
MTC Condenser Heat Rejected	298.8	299.7	299.7	296.6
LTC Condenser Heat Rejected	219.1	219.9	219.1	219.9
HTC Evaporator Load	298.8	299.7	299.7	296.6
MTC Evaporator Load	219.1	219.9	219.1	219.9
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	2.750	2.755	2.829	2.829
COP_LTC	3.965	3.896	3.829	3.965

Effect of various HFO and HCFO refrigerants on the thermal performance of a cascaded three-staged VCRS at - 22°C for the HTC and for the MTC evaporator temperature -60°C, and -90°C for the LTC evaporator temperature have been calculated and shown in table 3(c), respectively. It was discovered that the system (using HFO-1234ze(E) in HTC, HFO-1225ye(Z) in MTC and HFO-1336mzz(Z) gives lowest thermal (energy-exergy) performances. However, HFO-1234Ze(E) in HTC, HCFO-1233zd(E) in MTC and HFO-1225ye(Z) in LTC gives higher thermal (energy-exergy) performances. Similarly, three-stage cascaded VCR system employing HFO-1234Ze(E) in HTC, and HFO-1336mzz(Z) in MTC& HFO-1225ye(Z) in LTC has slightly similar thermal performances. It demonstrates clearly that the typical three-stage cascaded VCR system may be substituted by using HCFOs in HTC, HCFO and HFO in MTC, and HFO in LTC for replacing high GWP refrigerants.

Table 3(c): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW.

HTC Ecofriendly refrigerants-10ºC	R1234Ze(E)	R1234Ze(E)	R1234Ze(E)	R1234Ze(E)
MTC Eco-friendly refrigerants @-60ºC	R1233zd(E)	R1233 zd(E)	R1225ye(Z)	R-1336mzz(Z)
LTC Ecofriendly refrigerants at-90ºC	R1225ye(Z)	R-1336 zz(Z)	R-1336mzz(Z)	R1225ye(Z)
COP_Cascade_Three Staged	0.7482	0.7346	0.6971	0.7346
Exergy Efficiency	0.4698	0.4613	0.4669	0.4637
Exergy of fuel "kW"	233.9	238.2	235.3	237.0
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor Work_HTC "kW"	112.3	113.5	112.7	113.1
Compressor Work_MTC "kW"	77.47	79.83	77.74	79.68
Compressor Work_LTC "kW"	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.991	3.023	3.002	3.014
MTC Mass flow Rate(kg/s)	1.349	1.797	1.354	1.596
LTC Mass flow Rate(kg/s)	1.109	0.9821	0.9821	1.109
COP_Cascade two_ Staged	1.155	1.138	1.155	1.137
Exergy Efficiency	0.4605	0.4537	0.4605	0.4532
Exergy of fuel "kW"	189.8	193.3	190.4	192.8
Exergy of product "kW"	87.39	87.7	87.7	87.39
COP_ HTC	2.642	2.642	2.642	2.642
Exergy Efficiency	0.3513	0.3513	0.3513	0.3513
Exergy of fuel "kW"	112.3	113.5	112.7	113.1
Exergy of product "kW"	39.45	39.87	39.55	39.74
HTC Condenser Heat Rejected "kW"	408.9	413.2	410.3	412.0
MTC Condenser Heat Rejected "kW"	296.6	299.7	297.7	298.8
LTC Condenser Heat Rejected "kW"	219.1	219.9	219.9	219.1
HTC Evaporator Load "kW"	296.6	299.7	297.7	298.8
MTC Evaporator Load "kW"	219.1	219.9	219.1	219.1
LTC Evaporator Load "kW"	175.0	175.0	175.0	175.0
COP_MTC	2.829	2.825	2.75	2.755
COP_LTC	3.965	3.896	3.896	3.965

Effect of different HFO-1243zf refrigerant on the thermal performances of cascaded three staged VCRS at - 22ºC of HTC evaporator temperature, -60ºC of MTC evaporator temperature using and HCFO-1233zd(E) and HFO-1225ye(Z) & HFO-1336mzz(Z) in MTC, & -90ºC of LTC evaporator temperature using HFO-1225ye(Z) & HFO-1336mzz(Z) have been computed & shown in table-3(d) respectively and it was found that system using HFO-1243zf in HTC, HFO-1336mzz(Z) in MTC & HFO-1225ye(Z) in LTC gives best thermal performances than the system (using HFO-1243zf in HTC, HFO-1225ye(Z) in MTC & HFO-1336mzz(Z) in LTC) The three staged cascaded VCR system using HFO-1243zf in HTC, HFO-1225ye(Z) in MTC, HFO-1336mzz(Z) in LTC gives lowest thermal (energy-exergy) performances. It clearly shows that HCFOs in HTC and HCFO and HFO in MTC and HFOs in LTC can replaced conventional three staged cascaded VCR system

Table 3(d): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW.

HTC Ecofriendly refrigerants-10ºC	R1243zf	R1243zf	R1243zf	R1243zf
MTC Eco-friendly refrigerants@ -60ºC	R1233zd(E)	R1233 zd(E)	R1225ye(Z)	R-1336mzz(Z)
LTC Ecofriendly refrigerants @ -90ºC	R1225ye(Z)	R-1336 mzz(Z)	R-1336 mzz(Z)	R1225ye(Z)
$COP\__{Cascade\_Three\ Staged}$	0.7452	0.7406	0.7317	0.7356
Exergy Efficiency	0.4679	0.4650	0.4594	0.4619
Exergy of fuel “kW”	234.8	236.3	239.2	237.9
Exergy of product “kW”	109.9	109.9	109.9	109.9
Compressor $Work\__{HTC}$ “kW”	113.2	113.6	114.4	114.1
Compressor $Work\__{MTC}$ “kW”	77.47	77.74	79.83	79.68
Compressor $Work\__{LTC}$ “kW”	44.14	44.91	44.91	44.14
HTC Mass flow Rate(kg/s)	2.647	2.656	2.765	2.666
MTC Mass flow Rate(kg/s)	1.349	1.354	1.797	1.596
LTC Mass flow Rate(kg/s)	1.109	0.9821	0.9821	1.109
$COP\__{Cascade\ two\_\ Staged}$	1.149	1.149	1.132	1.131
Exergy Efficiency	0.4582	0.4582	0.4514	0.451
Exergy of fuel “kW”	190.7	191.4	194.3	193.8
Exergy of product “kW”	87.39	87.7	87.7	87.39
$COP\__{HTC}$	2.619	2.619	2.619	2.619
Exergy Efficiency	0.3484	0.3484	0.3484	0.3484
Exergy of fuel “kW”	113.2	113.6	114.4	114.1
Exergy of product “kW”	39.45	39.55	39.87	39.74
HTC Condenser Heat Rejected “kW”	409.8	411.3	414.6	412.9
MTC Condenser Heat Rejected “kW”	296.6	297.7	299.7	298.8
LTC Condenser Heat Rejected “kW”	219.1	219.9	219.9	219.1
HTC Evaporator Load “kW”	296.6	297.7	299.7	298.8
MTC Evaporator Load “kW”	219.1	219.9	219.9	219.1
LTC Evaporator Load “kW”	175.0	175.0	175.0	175.0
$COP\__{MTC}$	2.829	2.829	2.755	2.75
$COP\__{LTC}$	3.965	3.986	3.896	3.965

The effects of various HFO and HCFO refrigerants on the thermal performances of a cascaded three-staged VCRS at -22°C for the HTC evaporator temperature, for the MTC evaporator temperature of -60°C, and -90°C for the LTC evaporator temperature have been calculated and shown in table 3(e), respectively. It was discovered that the system using HFO-1234yf in HTC, HCFO-1233zd(E) in the MTC and HFO-1225ye(Z) gives highest thermal (energy-exergy) performances. However, three-stage cascaded VCR system employing HFO-1234yf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z) in LTC are provided lowest thermal(energy-exergy) performances. Similarly, HFO-1234yf in HTC, HFO-1336mzz(Z) in MTC, and HFO-1225ye(Z) in LTC gives slightly lower performances than using HFO-1234yf in HTC, HCFO-1233zd(E) in MTC, and HFO-1225ye(Z) in LTC of three staged cascaded VCRS. It demonstrates clearly that the three-stage Cascaded VCR system by using HCFOs in HTC, MTC, and LTCare substitutes for HFC-134a& R404a.

Table 3(e): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants. at LTC evaporator temperature -90ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTCEcofriendly refrigerants @ -10ºC	R1234yf	R1234 yf	R1234 yf	R1234 yf
MTCEcofriendly refrigerants @ -60ºC	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
LTCEcofriendly refrigerants @ -90ºC	R1225ye(Z)	R-1336 mzz(Z)	R1225ye(Z)	R-1336 mzz(Z)
$COP\_{Cascade\_Three\ Staged}$	0.711	0.7069	0.7022	0.6985
Exergy Efficiency	0.4461	0.4439	0.4409	0.4386
Exergy of fuel "kW"	246.1	247.6	249.2	250.5
Exergy of product "kW"	109.9	109.9	109.9	109.9
Compressor $Work\_{HTC}$ "kW"	124.5	124.9	125.4	125.8
Compressor $Work\_{MTC}$ "kW"	77.47	77.74	79.68	79.83
Compressor $Work\_{LTC}$ "kW"	44.14	44.91	44.14	44.91
HTC Mass flow Rate(kg/s)	3.752	3.766	3.78	3.792
MTC Mass flow Rate(kg/s)	1.349	1.354	1.596	1.797
LTC Mass flow Rate(kg/s)	1.109	0.9821	1.109	0.9821
$COP\_{Cascade\ two\_\ Staged}$	1.085	1.085	1.069	1.07
Exergy Efficiency	0.4327	0.4321	0.4261	0.4265
Exergy of fuel "kW"	201.9	202.7	205.1	205.6
Exergy of product "kW"	87.39	87.70	87.39	87.7
COP_{HTC}	2.383	2.383	2.383	2.383
Exergy Efficiency	0.3169	0.3169	0.3169	0.3169
Exergy of fuel "kW"	124.5	124.9	125.4	105.8
Exergy of product "kW"	39.45	39.59	39.14	39.87
HTC Condenser Heat Rejected "kW"	421.1	422.6	424.2	425.5
MTC Condenser Heat Rejected "kW"	296.6	297.7	298.8	301.7
LTC Condenser Heat Rejected "kW"	219.1	219.9	219.1	299.7
HTC Evaporator Load "kW"	296.6	297.7	298.8	301.7
MTC Evaporator Load "kW"	219.1	219.9	219.1	219.9
LTC Evaporator Load "kW"	175.0	175.0	175.0	175.0
COP_{MTC}	2.829	2.829	2.75	2.755
COP_{LTC}	3.965	3.986	3.965	3.896

3.2 Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95ºC.

Thermal performances of three staged cascaded vapor compression refrigeration systems were calculated and displayed in table 4(a), respectively. It was discovered that the system using HCFO-1224yd(Z) in HCFO1233zd(E) in MTC, HFO-1336mzz(Z) in LTC gives the best thermal performance, and the system using HCFO-1224yd(Z) in HCFO-1233zd(E) in MTC, HFO- The lowest thermal performances are provided by systems using HCFO-1224yd(Z) in HFO- 1225ye(Z) in MTC, and HFO- 1336 mzz(Z) in LTC.

Table 4(a): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Eco-friendly refrigerants@-10ºC	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)
MTC Eco-friendly refrigerants @-60ºC	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
LTC Eco-friendly refrigerants@-95ºC	R-1336 mzz(Z)	R1225ye(Z)	R1225ye(Z)	R-1336 mzz(Z)
$COP\_{Cascade\_Three\ Staged}$	0.7345	0.7284	0.7197	0.7251
Exergy Efficiency	0.4948	0.4907	0.4848	0.4884
Exergy of fuel "kW"	238.2	240.2	243.2	241.3
Exergy of product "kW"	117.9	117.9	117.9	117.9
Compressor $Work\_{HTC}$ "kW"	105.2	106.2	106.9	106.5
Compressor $Work\_{MTC}$ "kW"	80.33	80.71	82.88	82.62
Compressor $Work\_{LTC}$ "kW"	52.23	53.33	53.33	52.23
HTC Mass flow Rate(kg/s)	2.902	2.916	2.936	2.924
MTC Mass flow Rate(kg/s)	1.399	1.405	1.866	1.655
LTC Mass flow Rate(kg/s)	1.127	0.9996	0.9996	1.127
$COP\_{Cascade\ two\_\ Staged}$	1.222	1.222	1.203	1.202
Exergy Efficiency	0.4871	0.4871	0.4797	0.4792

Exergy of fuel "kW"	186.0	186.9	189.8	189.1
Exergy of product "kW"	90.61	91.05	91.05	90.61
COP_ HTC	2.91	2.91	2.91	2.91
Exergy Efficiency	0.3870	0.3870	0.3870	0.3870
Exergy of fuel "kW"	105.7	106.2	106.9	106.5
Exergy of product "kW"	40.91	41.10	41.21	41.39
HTC Condenser Heat Rejected	413.2	415.2	418.2	416.3
MTC Condenser Heat Rejected	307.6	309.0	311.2	309.9
LTC Condenser Heat Rejected	227.2	228.3	228.3	227.2
HTC Evaporator Load	307.6	309.0	311.2	309.9
MTC Evaporator Load	227.2	228.3	228.3	227.2
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	2.829	2.829	2.755	2.750
COP_LTC	3.351	3.282	3.282	3.351

Table-4(b) The three-stage cascaded VCR system with HCFO-R1233zd(E), HFO-1225ye(Z), and HFO-1336mzz(Z) delivers the best thermal (energy-exergy) performances. However, compared to a cascaded system using HFO-1336mzz(Z) in HTC, HCFO-R1233zd(E) in MTC, and HFO-1225ye(Z), HFO-1233zd(E) in HTC, MTC, and LTC, the thermal performance of these devices is marginally greater. However, utilizing HFO-1225ye(Z) in HTC, HCFO-R1233zd(E) in MTC, and HFO-1336mzz(Z) results in the lowest thermal (energy-exergy) performance. It is evident that the standard three-stage cascaded VCR system using R12 in the high temperature cycle, R22 in the medium temperature cycle, and R13 in the low temperature cycle can be substituted by HCFOs in HTC, HCFO and HFO in MTC, and HCFO and HFO in LTC.

Table 4(b): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Eco-friendly refrigerants @-10ºC	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
MTC Eco-friendly refrigerants @-60ºC	R-1336 mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233 zd(E)
LTC Eco-friendly refrigerants @-95ºC	R1225ye(Z)	R-1336 mzz(Z)	R1225ye(Z)	R-1336 mzz(Z)
COP_Cascade_Three Staged	0.7296	0.7352	0.7268	0.6903
Exergy Efficiency	0.4915	0.4952	0.4896	0.4650
Exergy of fuel "kW"	239.8	238.0	240.8	253.5
Exergy of product "kW"	117.9	117.9	117.9	117.9
Compressor Work_HTC "kW"	103.6	103.2	108.2	119.5
Compressor Work_MTC "kW"	82.88	82.62	80.33	80.71
Compressor Work_LTC "kW"	53.33	52.23	52.23	53.33
HTC Mass flow Rate(kg/s)	2.413	2.403	2.932	3.701
MTC Mass flow Rate(kg/s)	1.866	1.655	1.399	1.405
LTC Mass flow Rate(kg/s)	0.9996	1.127	1.127	0.9996
COP_Cascade two_ Staged	1.224	1.223	1.205	1.141
Exergy Efficiency	0.4882	0.4877	0.4806	0.4548
Exergy of fuel "kW"	186.5	185.8	188.5	200.2
Exergy of product "kW"	91.05	91.61	91.61	91.05
COP_ HTC	3.303	3.303	2.842	2.587
Exergy Efficiency	0.3994	0.3994	0.378	0.344
Exergy of fuel "kW"	103.6	103.2	108.2	119.5
Exergy of product "kW"	41.39	41.21	40.91	41.10
HTC Condenser Heat Rejected	414.8	413.0	415.8	428.5
MTC Condenser Heat Rejected	311.2	309.9	307.6	309.0
LTC Condenser Heat Rejected	228.3	227.2	227.2	228.3
HTC Evaporator Load	311.2	309.9	307.6	309.0
MTC Evaporator Load	228.3	227.2	227.2	228.3
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	2.755	2.75	2.829	2.899
COP_LTC	3.282	3.351	3.351	3.282

The effects of various HFO and HCFO refrigerants on the thermal performances of a cascaded three-staged VCRS at -22°C for the HTC evaporator temperature, -60°C for the MTC evaporator temperature, and -90°C for the LTC evaporator temperature have been calculated and are shown in table 4(c), respectively. It was discovered that the system using HFO-

1234ze(E) in HTC, HFO-1336m The use of HFO-1234ze(E) in HTC, HCFO-1233zd(E) in MTC, and HFO-1225ye(Z) in LTC were shown to have the lowest thermal (energy-exergy) performances, with higher electrical energy consumption when all (three) compressors were operating.

Table 4(c): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants@-10°C	R1234Ze(E)	R1234Ze(E)	R1234Ze(E)	R1234Ze(E)
MTC Eco-friendly refrigerants @-60°C	R1233zd(E)	R1233zd(E)	R-1336mzz(Z)	R1225ye(Z)
LTC Ecofriendly refrigerants@-95°C	R-1336 mzz(Z)	R1225ye(Z)	R1225ye(Z)	R-1336mzz(Z)
$COP_{\_Cascade\_Three\ Staged}$	0.7028	0.6971	0.7447	0.7385
Exergy Efficiency	0.4734	0.4696	0.5017	0.4975
Exergy of fuel "kW"	249.0	251.0	235.0	237.0
Exergy of product "kW"	117.9	117.9	117.9	117.9
Compressor Work$_{HTC}$ "kW"	116.4	117.0	102.4	102.9
Compressor Work$_{MTC}$ "kW"	80.33	80.71	80.33	80.71
Compressor Work$_{LTC}$ "kW"	52.23	53.37	52.23	53.33
HTC Mass flow Rate(kg/s)	3.102	3.117	2.385	2.397
MTC Mass flow Rate(kg/s)	1.399	1.405	1.399	1.405
LTC Mass flow Rate(kg/s)	1.127	0.9996	1.127	0.9996
$COP_{\_Cascade\ two\_\ Staged}$	1.155	1.155	1.243	1.243
Exergy Efficiency	0.4605	0.4695	0.4958	0.4958
Exergy of fuel "kW"	196.8	197.7	182.7	183.6
Exergy of product "kW"	90.61	90.05	90.61	91.05
$COP_{\_\ HTC}$	2.642	2.642	3.003	3.003
Exergy Efficiency	0.3513	0.3513	0.3994	0.3994
Exergy of fuel "kW"	116.4	117.0	102.4	102.9
Exergy of product "kW"	40.91	41.1	40.91	41.10
HTC Condenser Heat Rejected"kW"	424.0	426.0	410.0	412.0
MTC Condenser Heat Rejected"kW"	307.6	309.0	307.61	309.0
LTC Condenser Heat Rejected"kW"	227.2	228.3	227.2	228.3
HTC Evaporator Load"kW"	307.6	309.0	307.61	309.0
MTC Evaporator Load"kW"	227.2	228.3	227.2	228.3
LTC Evaporator Load"kW"	175.0	175.0	175.0	175.0
$COP_{\_MTC}$	2.829	2.829	2.829	2.829
$COP_{\_LTC}$	3.351	3.282	3.351	3.282

Effect of HFO-1243zf refrigerant in HTC on the thermal (energy-exergy) performances of cascaded three staged VCRS at - 22°C of HTC evaporator temperature, -60°C of MTC evaporator temperature using HCFO-1233zd(E) and other HFO refrigerants, & -90°C of LTC evaporator temperature using HFO-1336mzz(Z) is shown in table-4(d) respectively. The lowest thermal (energy-exergy) performances are provided by the cascaded three-staged VCR system employing HFO-1234zf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z). Cascaded three-stage VCRS using HFO-1243zf has somewhat lower thermal (energy-exergy) performance than traditional three-stage VCRS using R12 in HTC, R22 in MTC, and R13 in LTC. It adequately proves that traditional three-stage cascaded VCR systems using CFC refrigerants can be replaced by HFO-1243zf in HTC and HCFO-1233zd(E) or HFO-1225ye(Z) and HFO-1336mzz(Z) in MTC at -60°C and HFO-1225ye(Z) and HFO-1336mzz(Z) in LTC at -90°C.

Table (4d): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants@-10°C	R1243zf	R1243zf	R1243zf	R1243zf
MTC Eco-friendly refrigerants @-60°C	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
LTC Ecofriendly refrigerants@-95°C	R-1336 mzz(Z)	R1225ye(Z)	R1225ye(Z)	R-1336mzz(Z)
$COP_{\_Cascade\_Three\ Staged}$	0.6944	0.7001	0.6913	0.6862
Exergy Efficiency	0.4677	0.4716	0.4656	0.4622
Exergy of fuel "kW"	252.0	250.0	253.2	253.2
Exergy of product "kW"	117.9	117.9	117.9	117.9
Compressor Work$_{HTC}$ "kW"	118.0	117.4	118.3	118.8
Compressor Work$_{MTC}$ "kW"	80.71	80.33	82.62	82.68

Compressor Work_LTC "kW"	53.33	52.23	52.23	53.33
HTC Mass flow Rate(kg/s)	2.757	2.744	2.765	2.777
MTC Mass flow Rate(kg/s)	1.405	1.399	1.655	1.866
LTC Mass flow Rate(kg/s)	0.9996	1.127	1.127	0.9996
COP_Cascade two_ Staged	1.149	1.149	1.131	1.132
Exergy Efficiency	0.4582	0.4582	0.451	0.4514
Exergy of fuel "kW"	198.7	197.7	200.9	201.7
Exergy of product "kW"	91.05	90.61	90.61	91.05
COP_ HTC	2.619	2.619	2.619	2.619
Exergy Efficiency	0.3484	0.3484	0.3484	0.3484
Exergy of fuel "kW"	118.2	117.4	118.3	118.8
Exergy of product "kW"	41.1	40.91	41.21	41.39
HTC Condenser Heat Rejected"kW"	427.0	425.0	428.2	430.0
MTC Condenser Heat Rejected"kW"	309.0	307.6	309.9	311.2
LTC Condenser Heat Rejected"kW"	228.3	228.3	227.2	228.3
HTC Evaporator Load"kW"	309.0	307.6	309.9	311.2
MTC Evaporator Load"kW"	228.3	228.3	227.2	228.3
LTC Evaporator Load"kW"	175.0	175.0	175.0	175.0
COP_MTC	2.829	2.829	2.75	2.755
COP_LTC	3.282	3.351	3.351	3.282

Effect of different HFO refrigerants on the thermal performances of cascaded three staged VCRS at - 22°C of HTC evaporator temperature, -60°C of MTC evaporator temperature, & -90°C of LTC evaporator temperature, respectively, have been computed & shown in table-4(e) respectively. It was found that the cascaded three staged system using HFO-1234yf in HTC, HFO-1225ye(Z) in MTC, and HFO-1336mzz(Z) has lowest thermal (energy-exergy) performance., However, cascaded three staged system using HFO-1234yf in HTC, HCFO-1233zd(E) in MTC, and HFO-1225ye(Z) in LTC provides highest thermal (energy-exergy) performances.

Table 4(e): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants	R1234yf	R1234 yf	R1234 yf	R1234 yf
MTCEcofriendly refrigerants	R1233zd(E)	R1233 zd(E)	R-1336 mzz(Z)	R1225ye(Z)
LTCEcofriendly refrigerants	R1225ye(Z)	R-1336 mzz(Z)	R1225ye(Z)	R-1336 mzz(Z)
COP_Cascade_Three Staged	0.6689	0.6636	0.6607	0.6559
Exergy Efficiency	0.4506	0.447	0.4450	0.4418
Exergy of fuel "kW"	261.6	263.70	264.9	266.8
Exergy of product "kW"	117.9	117.9	117.9	117.9
Compressor Work_HTC "kW"	129.1	129.7	130.0	130.6
Compressor Work_MTC "kW"	80.33	80.71	82.62	82.88
Compressor Work_LTC "kW"	52.33	53.33	52.23	53.33
HTC Mass flow Rate(kg/s)	3.891	3.91	3.92	3.937
MTC Mass flow Rate(kg/s)	1.399	1.405	1.655	1.866
LTC Mass flow Rate(kg/s)	1.127	0.9996	1.127	0.9996
COP_Cascade two_ Staged	1.085	1.085	1.069	1.07
Exergy Efficiency	0.4327	0.4327	0.4261	0.4265
Exergy of fuel "kW"	209.4	210.4	212.7	213.5
Exergy of product "kW"	90.61	91.05	90.61	91.05
COP_ HTC	2.389	2.389	2.383	2.383
Exergy Efficiency	0.3169	0.3169	0.3169	0.3169
Exergy of product "kW"	40.91	41.10	41.21	41.39
MTC Condenser Heat Rejected	307.6	309.0	309.9	311.2
LTC Condenser Heat Rejected	227.2	228.3	229.2	228.2
HTC Evaporator Load	307.6	309.0	309.9	311.2
MTC Evaporator Load	227.2	228.3	229.2	228.2
LTC Evaporator Load	175.0	175.0	175.0	175.0
COP_MTC	2.829	2.829	2.75	2.755
COP_LTC	3.351	3.282	3.351	3.282
Exergy of product "kW"	40.91	41.10	41.21	41.39

At - 22°C for the HTC evaporator temperature, -60°C for the MTC evaporator temperature, and -90°C for the LTC evaporator temperature, respectively, the effects of various HFO blended refrigerants on the thermal (energy-exergy) performances of cascaded three stages VCRS have been investigated and shown in table-4(g) respectively and the system utilizing R450A in the HTC, R515A in the MTC, and R513 was found to be best due to its higher thermal performances. however, the three-stage cascaded VCR system with R-450A in HTC, R-515a in MTC, and R-454b in LTC has the lowest thermal (energy-exergy) performances and the highest electrical energy consumption. Evidently, the traditional three-stage cascaded VCR system using R12 in HTC, R22 in MTC, and R13 in LTC has been replaced by HFO mixes in HTC, MTC, and LTC.

Table 4(g): Thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO and HFO refrigerants at LTC evaporator temperature -95°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants	R450A	R450A	R450A	R450A
MTC Ecofriendly refrigerants	R513A	R515A	R513A	R515A
LTC Ecofriendly refrigerants	R515A	R513A	R454B	R454B
$COP_{\_Cascade\_Three\ Staged}$	0.6750	0.6794	0.6601	0.6447
Exergy Efficiency	0.4447	0.4576	0.4446	0.4343
Exergy of fuel “kW”	259.2	257.6	265.10	271.4
Exergy of product “kW”	117.9	117.9	117.9	117.9
Compressor $Work_{\_HTC}$ “kW”	121.6	121.2	120.6	127.3
Compressor $Work_{\_MTC}$ “kW”	84.28	83.73	86.14	85.82
Compressor $Work_{\_LTC}$ “kW”	53.31	52.68	58.35	58.35
HTC Mass flow Rate(kg/s)	3.079	3.067	3.271	3.503
MTC Mass flow Rate(kg/s)	1.662	1.683	1.699	1.725
LTC Mass flow Rate(kg/s)	1.024	0.9853	0.608	0.608
$COP_{\_Cascade\ two\_\ Staged}$	1.109	1.111	1.07	1.095
Exergy Efficiency	0.4421	0.4431	0.4265	0.4367
Exergy of fuel “kW”	205.9	204.9	213.5	213.1
Exergy of product “kW”	91.05	90.79	93.06	93.06
$COP_{\_\ HTC}$	2.57	2.57	2.649	2.508
Exergy Efficiency	0.3418	0.3418	0.3523	0.3336
Exergy of fuel “kW”	121.6	121.2	120.6	127.3
Exergy of product “kW”	41.58	41.42	42.49	42.45
HTC Condenser Heat Rejected	434.2	432.6	440.1	446.4
MTC Condenser Heat Rejected	312.6	311.4	319.5	319.2
LTC Condenser Heat Rejected	228.3	227.7	233.4	233.4
HTC Evaporator Load	312.6	311.4	319.5	319.2
MTC Evaporator Load	228.3	227.7	233.4	233.4
LTC Evaporator Load	175.0	175.0	175.0	175.0
$COP_{\_MTC}$	2.709	2.570	2.709	2.719
$COP_{\_LTC}$	3.282	3.322	2.999	2.999

3.3 Optimum thermal performances of best cascaded VCR systems using HFOs, HCFOs Blends of HFO refrigerants

Comparing the best cascaded VCR systems' energy-exergy performances utilizing HFOs and HCFOs & hydrocarbons Table-5(a) shows the optimum thermal performances at LTC evaporator temperature of -90°C. It was discovered that cascaded three staged VCR systems using R1233zd(E) in HTC, R-1336mzz(Z) in MTC, and R1225ye(Z) in LTC give the best thermal (energy-exergy) performances with the least amount of electrical energy consumption.

Table 5 (a): Optimum thermal (energy-exergy) performances of three staged cascaded VCR systems using HC refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -22°C, HTC condenser temperature=40°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW

HTC Ecofriendly refrigerants	R-1233zd(E)	R1234ze(E)	R-1243zf	R1234yf	R600a	R600a	R12(model)
MTCEcofriendly refrigerants	R-1336 mzz(Z)	R1233zd(E)	R1233zd(E)	R1233zd(E)	Ethane	R41	R22
LTCEcofriendly refrigerants	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	Propylene	Propylene	R13
$COP_{\_Cascade\_Three\ Staged}$	0.9048	0.8744	0.8685	0.8449	0.8445	0.8538	0.875
Exergy Efficiency	0.5682	0.5491	0.5454	0.5305	0.5303	0.5361	0.5494
Exergy of fuel “kW”	193.4	200.1	201.5	207.1	207.2	205.0	200.0
Exergy of product “kW”	109.9	109.9	109.9	109.9	109.9	109.9	109.9

Compressor Work_HTC "kW"	89.56	97.37	98.73	104.4	96.47	95.5	93.33
Compressor Work_MTC "kW"	59.70	58.62	58.62	58.62	65.91	64.22	60.17
Compressor Work_LTC "kW"	44.14	44.14	44.14	44.14	44.84	44.84	46.5
HTC Mass flow Rate(kg/s)	1.999	2.458	2.894	2.960	1.249	1.242	2.728
MTC Mass flow Rate(kg/s)	1.443	1.237	1.241	1.237	0.7076	0.6225	1.152
LTC Mass flow Rate(kg/s)	1.109	1.109	1.109	1.109	0.4402	0.4402	1.501
COP_Cascade two_ Staged	1.468	1.405	1.395	1.345	1.354	1.373	1.443
Exergy Efficiency	0.5855	0.5602	0.5563	0.5362	0.5399	0.5475	0.5754
Exergy of fuel "kW"	149.3	156.0	157.6	163.0	162.2	160.1	153.5
Exergy of product "kW"	87.39	87.37	87.39	87.39	87.67	87.67	88.33
COP_ HTC	3.113	2.853	2.821	2.662	2.962	2.962	3.018
Exergy Efficiency	0.5826	0.5338	0.5265	0.4981	0.5543	0.5357	0.5648
Exergy of product "kW"	52.18	51.98	51.98	51.98	53.48	53.16	52.71
HTC Condenser Heat Rejected	368.4	375.1	376.5	382.1	382.2	380.0	375.0
MTC Condenser Heat Rejected	278.8	278.7	277.8	277.8	285.8	284.1	281.7
LTC Condenser Heat Rejected	219.1	219.1	219.1	219.1	219.8	219.8	221.5
HTC Evaporator Load	278.8	278.7	277.8	277.8	285.8	284.1	281.7
LTC Evaporator Load	175.0	175.0	175.0	175.0	175.0	175.0	175.0
COP_MTC	3.671	3.738	3.738	3.738	3.335	3.423	3.681
COP_LTC	3.965	3.965	3.965	3.965	3.903	3.903	3.763

Comparing the best cascaded vapor compression refrigeration systems' energy-exergy performances utilizing HFOs and HCFOs. Table-5(a) shows the optimum thermal performances at LTC evaporator temperature of -95°C at LTC evaporator temperature and it was discovered that cascaded three staged VCR systems using R1233zd(E) in HTC, R-1336mzz(Z) in MTC, and R1225ye(Z) in LTC give the best thermal (energy-exergy) performances with the least amount of electrical energy consumption

Table 5(b): Optimum thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO & HFO refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -90°C, MTC evaporator temperature -60°C, HTC evaporator temperature -10°C, HTC condenser temperature=55°C, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW.

HTC refrigerants @ -10°C	R1224yd(Z)	R1233zd(E)	R1234Ze(E)	R1243zf	R1234yf	R152a
MTC refrigerants @ -60°C	R1233 zd(E)	R-1336 mzz(Z)	R1233zd(E)	R1233zd(E)	R1233zd(E)	R245fa
LTC refrigerants @ -95°C	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R32
COP_Cascade_Three Staged	0.7829	0.7836	0.7482	0.7452	0.711	0.7644
Exergy Efficiency	0.4916	0.4920	0.4698	0.4679	0.4461	0.480
Exergy of fuel "kW"	223.5	223.2	233.9	234.8	246.1	228.9
Exergy of product "kW"	109.9	109.9	109.9	109.9	109.9	109.9
Compressor Work_HTC "kW"	101.9	99.52	112.3	113.2	124.5	102.2
Compressor Work_MTC "kW"	77.47	79.68	77.47	77.47	77.47	79.06
Compressor Work_LTC "kW"	44.14	44.14	44.14	44.14	44.14	47.65
HTC Mass flow Rate(kg/s)	2.799	2.317	2.991	2.647	3.752	1.519
MTC Mass flow Rate(kg/s)	1.349	1.596	1.349	1.349	1.349	1.376
LTC Mass flow Rate(kg/s)	1.109	1.109	1.109	1.109	1.109	0.4897
COP_Cascade two_ Staged	1.222	1.223	1.155	1.149	1.085	1.228
Exergy Efficiency	0.4871	0.4877	0.4605	0.4582	0.4327	0.4898
Exergy of fuel "kW"	179.4	179.2	189.8	190.7	201.9	181.3
Exergy of product "kW"	87.39	87.39	87.39	87.39	87.39	88.79
COP_ HTC	2.91	3.003	2.642	2.619	2.383	2.952
Exergy Efficiency	0.3870	0.3994	0.3513	0.3484	0.3169	0.3926
Exergy of fuel "kW"	101.9	99.52	112.3	113.2	124.5	102.2
Exergy of product "kW"	39.46	39.74	39.45	39.45	39.45	40.13
HTC Condenser Heat Rejected "kW"	398.5	398.3	408.9	409.8	421.1	403.9
MTC Condenser Heat Rejected "kW"	296.6	298.8	296.6	296.6	296.6	301.7
LTC Condenser Heat Rejected "kW"	219.1	219.1	219.1	219.1	219.1	222.6
HTC Evaporator Load "kW"	296.6	298.8	296.6	296.6	296.6	301.7
MTC Evaporator Load "kW"	219.1	219.1	219.1	219.1	219.1	222.6
LTC Evaporator Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
COP_MTC	2.829	2.750	2.829	2.829	2.829	2.816
COP_LTC	3.965	3.965	3.965	3.965	3.965	3.673

Comparing the best cascaded VCR systems' energy-exergy performances utilizing HFOs and HCFOs blends of HFO refrigerants were found to provide the best thermal (energy-exergy) performance with the least amount of electrical energy consumption in cascaded three-staged VCR systems using R1234Ze(E) in HTC, R-1336mzz(Z) in MTC, and R1225ye(Z) in LTC as shown in table-5(C) respectively.

Table 5(c): Optimum thermal (energy-exergy) performances of three staged cascaded VCR systems using HCFO & HFO refrigerants with conventional cascaded three staged VCR systems at LTC evaporator temperature -95ºC, MTC evaporator temperature -60ºC, HTC evaporator temperature -10ºC, HTC condenser temperature=55ºC, MTC approach=10, LTC approach=10, Q_eva_LTC=175 kW.

HTC refrigerants	R1224yd(Z)	R1233 zd(E)	R1234Ze(E)	R1243zf	R1234yf	R450A	R-152a
MTC refrigerants	R1233zd(E)	R1225ye(Z)	R-1336mzz(Z)	R1233zd(E)	R1233zd(E)	R515A	R245fa
LTC refrigerants	R-1336mzz(Z)	R-1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R513A	R32
$COP\__{Cascade\_Three\ Staged}$	0.7345	0.7352	0.7447	0.7001	0.6689	0.6794	0.7110
Exergy Efficiency	0.4948	0.4952	0.5017	0.4716	0.4506	0.4576	0.4789
Exergy of fuel "kW"	238.2	238.0	235.0	250.0	261.6	257.6	246.10
Exergy of product "kW"	117.9	117.9	117.9	117.9	117.9	117.9	117.9
Compressor $Work\__{HTC}$ "kW"	105.2	103.2	102.4	117.4	129.1	121.2	106.6
Compressor $Work\__{MTC}$ "kW"	80.33	82.62	80.33	80.33	80.33	83.73	82.43
Compressor $Work\__{LTC}$ "kW"	52.23	52.23	52.23	52.23	52.33	52.68	57.14
HTC Mass flow Rate(kg/s)	2.902	2.403	2.385	2.744	3.891	3.067	1.583
MTC Mass flow Rate(kg/s)	1.399	1.655	1.399	1.399	1.399	1.683	1.435
LTC Mass flow Rate(kg/s)	1.127	1.127	1.127	1.127	1.127	0.9853	0.4940
$COP\__{Cascade\ two\_\ Staged}$	1.222	1.223	1.243	1.149	1.085	1.111	1.228
Exergy Efficiency	0.4871	0.4877	0.4958	0.4582	0.4327	0.4431	0.4898
Exergy of fuel "kW"	186.0	185.8	182.7	197.7	209.4	204.9	189.0
Exergy of product "kW"	90.61	91.61	90.61	90.61	90.61	90.79	92.57
$COP\__{HTC}$	2.91	3.303	3.003	2.619	2.389	2.57	2.952
Exergy Efficiency	0.3870	0.3994	0.3994	0.3484	0.3169	0.3418	0.3926
Exergy of fuel "kW"	105.7	103.2	102.4	117.4	40.91	121.2	106.6
Exergy of product "kW"	40.91	41.21	40.91	40.91	436.6	41.42	41.84
HTC Condenser Heat Rejected	413.2	413.0	410.0	425.0	307.6	432.6	421.1
MTC Condenser Heat Rejected	307.6	309.9	307.61	307.6	227.2	311.4	314.6
LTC Condenser Heat Rejected	227.2	227.2	227.2	228.3	307.6	227.7	232.1
HTC Evaporator Load	307.6	309.9	307.61	307.6	227.2	311.4	314.6
MTC Evaporator Load	227.2	227.2	227.2	228.3	175.0	227.7	232.1
LTC Evaporator Load	175.0	175.0	175.0	175.0	2.829	175.0	175.0
$COP\__{MTC}$	2.829	2.75	2.829	2.829	3.351	2.570	2.816
$COP\__{LTC}$	3.351	3.351	3.351	3.351	40.91	3.322	3.063

4. Conclusion s

Thermal performances of three-stage cascaded VCR systems led to the following conclusions:

- In the three-stage cascaded VCR systems, HFO-1225ye(Z) & HFO-1336mzz(Z) are suitable for replacing HFC-134a & HFC-404a in the ultra-low temperature cycle (LTC) of -90ºC.
- HFC-245fa & HFC-152, HCFO-1224yd(Z), HCFO-1233zd(E), HFO-1234ze(E) & HFO-1243zf, R1225ye(Z) are suited for replacing CFC-12 & R134a in high temperature cycle (HTC) up to - 22ºC in the three-stage cascaded VCR systems.
- HCFO-1233zd(E), HFO-1225ye(Z) and HFO-1336mzz(Z) are suited for replacing R134a, HFC-404a, HFC-410a, HFC-407c, HFC-236fa, HFC-227ea CFC-22 in the medium temperature cycle (MTC) cycle at -60ºC in the three-stage cascaded VCR systems.
- The three staged cascaded VCRS operates in the medium temperature cycle at -60ºC of evaporator temperature utilizing the fuels HC-290, R600a in High temperature cycle, R41, in MTC and Ethylene and propylene in LTC can replace conventional three staged cascaded VCR systems using CFC refrigerants.
- However, HCFO-1233zd(E), R1336mzz(Z), and HFO-1225ye(Z). can be used in higher and medium temperature cycle up to -75ºC and below HFO-1225ye(Z) and R1336mzz(Z) are used in the ultra-low temperature cycle, which has an evaporator temperature of -90ºC.

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