International Journal of Research in Engineering and Innovation
(IJREI)
journal home page: http: //www.ijrei.com
ISSN (Online): 2456-6934

ORIGINAL ARTICLE

Thermodynamic performances of three staged cascaded VCR systems using ecofriendly ultra-low GWP refrigerants

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Article Information

Received: 25 July 2024
Revised: 29 Oct 2024
Accepted: 02 Nov 2024
Available online: 17 Nov 2024

Keywords:

Three staged VCR systems
HFO & HCFO Refrigerants
Thermodynamic Evaluation
Global Warming Ozone Depletion

Abstract

It is imperative that refrigerants with less global warming potential be used instead of hydro chlorofluorocarbons and hydrofluorocarbons from an environmental standpoint. employing an energy evaluation, it is possible to determine the viability and potential of employing alternative refrigerants in the current refrigeration system. This will result in an enhancement of the thermal efficiency of the systems for refrigeration. The literature offers a number of substitutes for CFC refrigerants that use HFC and HFC blends and have a higher potential to cause global warming without depleting the ozone layer. This study examined the thermodynamic performances of three-stage cascaded vapour compression refrigeration systems for ultra-low applications. The systems used eco-friendly low global warming potential refrigerants, hydrocarbons in a higher temperature cycle between 55ºC and 30ºC, and low GWP HFO and HC refrigerants in a medium temperature cycle between -10ºC and 90ºC. Additionally, low GWP refrigerants without ozone depletion were used in a low temperature cycle between -160 and -120 ºC degrees Celsius. The system that uses HFOs and HCFO refrigerants has been found to have the best thermodynamic (first and second law) performances. Investigated were the effects of eco-friendly refrigerants in each cycle, the effects of evaporator and HTC temperatures on thermal performances, the ideal temperatures for HTC and MTC, the optimal Cascaded COP, and the energy efficiency of three staged cascaded vapour compression refrigeration systems.

1. Introduction

Recent years have seen a number of issues that environmentalists have raised concern about as threats to the planet's survival. Among many other concerning issues, the two most serious ones are global warming and ozone layer degradation. Several responsible parties are intensifying these issues. As suggested by Adebayo, et.al, [1] the refrigerants used in refrigerators and air conditioners are the most significant. In many home refrigeration systems and food storage applications, conventional refrigeration techniques like the vapour compression method are used. However, these systems can only withstand a maximum temperature of -25°C using HFC and HCFC fluid due to replacing high GWP ecofriendly fluids· It is not thermodynamically feasible to use a single staged vapour compression refrigeration system. This problem requires a different approach in order to achieve the necessary level of cooling impact at very low temperatures (i.e.-90ºC or below). To handle this circumstance, the Cascade Refrigeration System is a useful choice, because at that temperature, the pressure ratio of the simple vapour compression system, increased dramatically employing a

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https://doi.org/10.36037/IJREI.2024.8502

single stage VCRS is not feasible thermodynamically or economically. This problem calls for a different approach to achieve the desired level of cooling effect at very low temperatures. The pressure ratio of the system became very large. It is challenging to handle this enormous pressure ratio employing a single-stage refrigeration system A one-stage refrigeration system, such a find it challenging to handle this enormous pressure ratio [2]. The theoretically analyzed cascade refrigeration system with natural and synthetic working fluid pairs for ultra-low temperature applications, few investigators have reached − 55°C [5,9] There are currently many studies in the literature exploring low GWP and no ODP refrigerants minimizing or eliminating the negative effects on the environment. friendly refrigerants are used to carry out the exergy analysis of a multiple evaporator and multistage VCRS. Results show that systems with individual expansion valves show better thermal performances than with multiple type valves. R1234yf and R1234ze are recommended to use [[12,13],14]. Another case study uses eight refrigerants in multistage VCRS with COP maximization as their objective function. COP improves with an increase in the sub cooling conditions. R717 gives the best results over the other fluids considered [16]. Using a liquid–vapor heat exchanger increases the exergy efficiency by 20% of a VCRS using 13 different refrigerants [2014]. Reducing global warming is a common goal for all mankind. For the first time in history, the Paris Agreement was adopted to reduce worldwide greenhouse gas emissions such as CO_2. Therefore, it is imperative to use low GWP refrigerants to replace the conventional refrigerants in refrigeration and air-conditioning equipment, which are necessary for our modern urban livelihoods. Since hydrofluorocarbons (HFCs) conventionally used as refrigerants have a very high GWP, they can have a high impact on global warming in the event of leakage). For that reason, the new HCFOs and HFO were used for reducing HFCs in conventional refrigeration systems with ultra-low GWP refrigerants and comparison was carried out between R1224yd (Z) and R1233zd(E) and HFO-1243zf, R1234ze(E), R1234yf in high temperature cycle at evaporator temperature of -10ºC, HFO-1225ye(Z) and HFO-1336mzz(Z) in medium temperature cycle at evaporator temperature of -90ºC and HFO-1225ye(Z) and HFO-1336mzz(Z) in low temperature cycle at LTC evaporator temperature of -120ºC to -150ºC. Reducing global warming is a common goal for all mankind. For the first time in history, the Paris Agreement was adopted to reduce worldwide greenhouse gas emissions such as CO_2. In this connection, it is imperative to use low GWP refrigerants to replace the conventional refrigerants in refrigeration and air-conditioning equipment, which are indispensable for our modern urban livelihoods. The refrigerants are used inside a closed housing structure of the equipment. A simplified refrigeration cascade is shown system comprises two interdependent loop cycles: high temperature cycle (HTC) and low-temperature cycle (LTC). They form the global system cycle including an evaporator (4–1), two compressors, LTC (1–2) and HTC (5–6), a condenser (6–7), two expanders LTC (3–4) and HTC (7–8), an evaporator–condenser (2–3) for LTC and (8–5) for HTC. Refrigerant load (QE) is absorbed in the evaporator (LTC), and heat is released to the ambient by the condenser in the HTC loop. LTC and HTC compressors draw the refrigerants at points 1 and 5, respectively. Refrigerants leave the compressors superheated at points 2 and 6 and then condense along paths 2–3 and 6–7, before being expanded at their respective evaporating conditions 4–1 and 8–5. In the evaporator–condenser, thermal exchange occurs between LTC and HTC subsystems where refrigerant in the HTC loop evaporates, condensing in the process the refrigerant in the low-pressure loop. In the present work, R744 is used in the LT loop, while any of R717, R290, R600, R600a and R1270 is used in the HT loop This paper is mainly deals with ultra-low temperature applications and also to find optimal temperature for maximum (optimal efficiency which was not available in existing literature and also compared to the performance data of the HCFO and HFO refrigerants. For finding environmentally appropriate operating fluids and searching for a suitable low GWP refrigerants for replacing high GWP and high ozone depleting refrigerants.

2. Literature Review

Previous research suggests that cascade refrigeration systems are widely used. Because of the ongoing environmental problems around refrigerants, scientists are emphasizing the need to develop environmentally acceptable replacement refrigerants. The various forms of cascading refrigeration systems, researchers have mostly focused on two staged cascade processes. In the literatures discovered, the following two-stage cascade VCR systems using the refrigerants such as R134a, R744-R717, R744, propylene, R717, ethane, various mix refrigerants, R11, trans-critical R744-R290, R152a–R23, R290–R23, R507–R23, R234a–R23, R717–R23, and R404a–R23 [6]. But certain systems need ultra-low temperatures, as low as -120ºC to -160ºC. It is challenging to find an effective system such as cascaded VCR systems for low-temperature applications, particularly one that uses environmentally friendly and ultra-low GWP refrigerants. In industrial processes such as natural gas liquefaction, petroleum gas liquefaction, steel alloy treatment processes, military and national defense equipment, medicine and vaccine preservation for Covid-19 virus (needs around -70ºC, cryogenic process (below 100ºC), and other very low-temperature applications (e.g, freeze-drying, chemical industries) [11, 18]. Normally Temperatures as low as 170ºC or below may be required for the liquefaction of certain natural gas, petroleum, and cryogenic applications, as well as pharmaceutical storage suggested three staged /four staged cascaded refrigeration systems using low GWP HFC, HFO, HCFO, in high temperature cycle (HTC) and HCFO-1233zd(E), HFO-1336mzz(Z) and R1225ye(Z) in medium temperature cycle and HFO-1225ye(Z) & R1336mzz(Z) in low temperature cycle [16]. It is especially hard to do this using a conventional approach without compromising on complexity and economics. The overall pressure ratio increases as the evaporator temperature decreases. Using a single- or dual-stage refrigeration system to regulate this pressure ratio is difficult. Since three-stage cascade refrigeration systems are a relatively new concept in cascade refrigeration systems, there are not many research assessing its performance and uses [20, 21]. A three-stage cascade refrigeration system's quantitative design was demonstrated [7] three-stage cascade refrigeration system especially for cryogenic applications. The device used methane pairs of refrigerants to achieve an evaporator temperature of -158 ◦C in three cycles Sun et al. [27] developed a three-stage cascade refrigerant system by utilizing low global warming potential for different refrigerant pairings. This study recommended ethylene, propylene, R717, R152a, and R161. A cryogenic distillation column was used to extract the collected carbon monoxide and methane. Based on the modelling results, a three-stage cascade refrigerant system employing R41 and R170 for intermediate cycles and low global warming potential for varied high-temperature cycles. R1150 was suggested for the lowest circuit, with evaporator temperatures ranging from -120ºC to -80 ºC] [27]. Similarly, triple cascade refrigeration in the liquefaction of natural gas using nitrogen, propane, and nitrogen monoxide were also analyzed [28]. A comparison was made with a different configuration that made use of a mixture of methane, ethylene, and propane as refrigerant. This technique significantly improved performance by 25% when compared to a single-stage cycle and an upgraded triple cascade system utilizing the second refrigerant combination. It was found that the system's lowest temperature was -150◦C, and its coefficient of performance was 1.68 [29]. The use of three-stage cascade refrigeration in LNG liquefaction and found that the system's enhanced efficiency was caused by the creation of perfect operating conditions through simulation [23]. Thermal modelling of a three-stage cascade refrigeration system for sperm preservation. R134a or R404a was used in the low-temperature circuit, and R1234yf or R1234ze was used in the high-temperature circuit. R134a, R404a, and R1234ze together yielded the best thermal performances [21]. Three-stage cascade refrigeration system at -40ºC to liquefy natural gas have been used [4]. Most of the refrigerants mentioned above have a strong potential to cause ozone depletion and global warming. In a three-stage auto cascade refrigeration system, a zeotropic combination of two permutations of five environmentally benign refrigerants. With an operating temperature of -97◦C, the system produced an energy efficiency that was 22.6% higher than the conventional system and an overall coefficient of performance (COP) of 0.253 [26]. In a three-stage auto cascade system, R1234yf/R23/R14 was resulting in an exergy efficiency of 26.15% and a COP of 0.614 [24]. Due to their low GWP and zero ODP, hydrofluorocarbons and hydrocarbon-based refrigerants have been suggested as replacements in numerous studies. The two, pure hydrocarbon refrigerants seem like a promising choice. A four -staged cascade refrigeration system using hydrocarbon refrigerants have been modelled and found that R600a in high temperature cycle, R41 in medium temperature cycle and Ethylene in low temperature cycle gives better results than using R290 in HT cycle, R170 in medium temperature cycle and R50 in low temperature. The primary drawback of using hydrocarbon refrigerants is their tendency to catch fire [17]. However,, as the use of flammable refrigerants was previously forbidden, this problem can be avoided by utilizing safety. Current regulations permit the use of flammable fluids with additional safety precautions. According to multiple researchers, hydrocarbon-based refrigerants provide a variety of benefits over chlorofluorocarbon-based refrigerants despite the flammability issue. The present study to find out optimal MTC and HTC evaporator temperature for getting maximum energy efficiency ($COP\_{Cascade}$) and cascaded exergetic efficiency. The COP of each cycle and heat rejected by condensers, and effect of mass flow rates of refrigerants have been investigated. The effect of ecofriendly refrigerants and exergy efficiency variations with HTC, MTC & LTC temperature and to find optimal temperature for maximum (optimal efficiency which was not available in existing literature and also compared to the performance data of the HCFO and HFO refrigerants.

3. Results and Discussion

Following input values have been taken to validate developed thermal model of three staged cascaded VCR system.

(i) HTC condenser temperature=40ºC.
(ii) HTC evaporator temperature=-22ºC.
(iii) MTC evaporator temperature=-60ºC.
(iv) MTC evaporator temperature=-90ºC.
(v) Cooling load on LTC evaporator=175 “kW”
(vi) MTC temperature overlapping=10.
(vii) LTC temperature overlapping=10

The validation computed results obtained with developed thermal model with conventional system have been shown in Table 1 respectively. It was found that computed values from developed model are in matching the values of conventional three staged conventional system using CFC refrigerants.

Table 1: (a)Validation of thermal model

	System [Model]	System [16]
HTC Refrigerants	R12	R12
MTC Refrigerants	R22	R22
LTC Refrigerants	R13	R13
First law Efficiency_CASCADE_VCRS	0.8750	0.858
Exergy of Fuel_ CASCADE_VCRS “kW”	200.0	204.0
First law Efficiency_LTC_VCRS	3.763	3.74
First law Efficiency_MTC_VCRS	3.681	3.70
LTC Compressor work “kW”	46.5	46.8
MTC Compressor work “kW”	60.17	59.8
HTC Mass flow rate (Kg/sec)	2.728	2.72
MTC Mass flow rate (Kg/sec)	1.152	1.15
LTC Mass flow rate (Kg/sec)	1.501	1.501
system Cooling Load Q_Eva_LTC “kW”	175.0	175.0

3.1 Comparison of energy-exergy performances of three staged cascaded vapour compression refrigeration systems

Thermodynamic performances of ten three staged cascaded vapour compression refrigeration systems have been compared with the conventional refrigeration using CFC refrigerants and it was found that the performance of system-1 to system-3 is superior than conventional three staged cascaded VCR system However, system-4 to system-10 gives slightly less thermal performances as compared with conventional system. It clearly shows that the use of ultra-low GWP ecofriendly HCFO and HFO refrigerants can be used for replacing high GWP refrigerants as shown in Table 1(b) to Table 1(d) respectively.

Table 1(b): Maximum Thermodynamic performances of modified vapour compression refrigeration system usingHFO and HCFO refrigerants

	System-1	System-2	System-3	System-4	Conventional System [Model]
HTC Refrigerants	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)	R12
MTC Refrigerants	R1225ye(Z)	R1336mzz(Z)	R1233zd(E)	R1233zd(E)	R22
LTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)	R13
First law Efficiency_$_{\text{CASCADE\_VCRS}}$	0.9007	0.9048	0.8918	0.8640	0.8750
EDR$_{\text{CASCADE\_VCRS}}$	0.7706	0.7624	0.7881	0.8454	0.8225
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.5648	0.5674	0.5592	0.5418	0.5487
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ “kW”	193.4	193.4	196.2	202.6	200.0
Exergy of product $_{\text{CASCADE\_VCRS}}$ “kW”	109.7	109.7	109.7	109.7	109.7
First law Efficiency_$_{\text{Cascade\_VCRS\_Two\_Staged}}$	1.472	1.468	1.441	1.395	1.443
EDR$_{\text{CASCADE\_VCRS}}$	0.7065	0.7110	0.7434	0.8008	0.7409
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.5860	0.5844	0.5736	0.5553	0.5744
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ “kW”	149.4	149.3	152.1	157.6	153.5
Exergy of product $_{\text{CASCADE\_VCRS}}$ “kW”	87.54	87.23	87.23	87.54	88.18
First law Efficiency_$_{\text{LTC\_VCRS}}$	3.896	3.965	3.965	3.896	3.763
First law Efficiency_$_{\text{MTC\_VCRS}}$	3.689	3.671	3.738	3.738	3.681
LTC Compressor work “kW”	44.91	44.14	44.14	44.91	46.5
MTC Compressor work “kW”	59.61	59.7	58.62	58.83	60.17
First law Efficiency_$_{\text{HTC\_VCRS}}$	3.113	3.113	2.972	2.821	3.018
EDR$_{\text{HTC\_VCRS}}$	0.7219	0.7219	0.8039	0.9005	0.7763
Exergy_Efficiency_ $_{\text{HTC\_VCRS}}$	0.5808	0.5808	0.5543	0.5262	0.5630
Exergy of Fuel_ $_{\text{HTC\_VCRS}}$ “kW”	89.74	89.56	93.47	98.82	93.33
Exergy of product $_{\text{HTC\_VCRS}}$ “kW”	52.14	52.02	51.81	52.0	52.54
HTC Condenser Heat Rejected “kW”	363.9	368.4	371.2	377.6	375.0
MTC Condenser Heat Rejected“kW”	279.5	278.8	277.8	278.7	281.7
LTC Condenser Heat Rejected“kW”	219.9	219.1	219.1	219.9	221.5
Cooling Load on system Q_$_{\text{Eva\_LTC}}$ “kW”	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.004	1.999	2.416	2.894	2.728
MTC Mass flow rate (Kg/sec)	1.623	1.443	1.237	1.241	1.152
LTC Mass flow rate (Kg/sec)	0.9821	1.109	1.109	0.9821	1.501

Table 1(c): Maximum Thermodynamic performances of modified vapour compression refrigeration system usingHFO and HCFO refrigerants

	System-5	System-6	System-7	System-8	System-9	System-10
HTC Refrigerants	R1243zf	R1243zf	R1243zf	R1243zf	R1234ze(E)	R1234ze(E)
MTC Refrigerants	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
LTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency_$_{\text{CASCADE\_VCRS}}$	0.8628	0.8685	0.8623	0.8584	0.8687	0.8744
EDR $_{\text{CASCADE\_VCRS}}$	0.8482	0.8361	0.8494	0.8578	0.8357	0.8237
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.5411	0.5446	0.5407	0.5383	0.5447	0.5483
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ “kW”	202.8	201.5	203.0	203.9	201.5	200.1
Exergy of product $_{\text{CASCADE\_VCRS}}$ “kW”	109.7	109.7	109.7	109.7	109.7	109.7
First law Efficiency_$_{\text{CASCADE\_VCRS}}$	1.393	1.393	1.380	1.383	1.405	1.405
EDR $_{\text{CASCADE\_VCRS}}$	0.8037	0.8037	0.8205	0.8158	0.7882	0.7882
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.5544	0.5544	0.5493	0.5507	0.5592	0.5592
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ “kW”	157.9	157.3	158.8	159.0	156.5	156.0
Exergy of product $_{\text{CASCADE\_VCRS}}$ “kW”	87.54	87.23	87.23	87.54	87.54	87.23
First law Efficiency_$_{\text{LTC\_VCRS}}$	3.896	3.965	3.965	3.896	3.896	3.965
First law Efficiency_$_{\text{MTC\_VCRS}}$	3.738	3.738	3.671	3.689	3.738	3.738

LTC Compressor work “kW”	44.91	44.14	44.14	44.91	44.91	44.14
MTC Compressor work “kW”	58.83	58.62	59.7	59.7	58.83	58.62
First law Efficiency_$_{HTC\_VCRS}$	2.813	2.813	2.813	2.813	2.853	2.853
EDR $_{HTC\_VCRS}$	0.9055	0.9055	0.9055	0.9055	0.8793	0.8793
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.5248	0.5248	0.5248	0.5248	0.5321	0.5321
Exergy of Fuel_ $_{HTC\_VCRS}$ “kW”	99.08	98.73	99.11	99.36	97.71	97.37
Exergy of product $_{HTC\_VCRS}$ “kW”	52.0	51.81	52.02	52.14	52.0	51.81
HTC Condenser Heat Rejected “kW”	377.8	376.5	378.0	378.9	376.5	375.1
MTC Condenser Heat Rejected“kW”	278.7	277.8	278.8	279.5	278.7	277.8
LTC Condenser Heat Rejected“kW”	219.9	219.1	219.1	219.9	219.9	219.1
Cooling Load on system Q_$_{Eva\_LTC}$ “kW”	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.179	2.172	2.18	2.185	2.467	2.458
MTC Mass flow rate (Kg/sec)	1.623	1.237	1.443	1.623	1.241	1.237
LTC Mass flow rate (Kg/sec)	0.9821	1.109	1.109	0.9821	0.9821	1.109

Table 1(d): Maximum Thermodynamic performances of modified vapour compression refrigeration system usingHFO and HCFO refrigerants

	System-11	System-12	System-13	System-14	System-15	System-16
HTC Refrigerants	R1234 ze(E)	R1234 ze(E)	R1234yf	R1234yf	R1234yf	R1234yf
MTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerants	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)
First law Efficiency_$_{CASCADE\_VCRS}$	0.8681	0.8642	0.8394	0.8449	0.83339	0.8352
EDR$_{CASCADE\_VCRS}$	0.8370	0.8454	0.8996	0.8874	0.9009	0.9094
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.5444	0.5419	0.5264	0.5298	0.5261	0.5237
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	201.6	202.5	208.5	207.1	208.6	209.5
Exergy of product $_{CASCADE\_VCRS}$ “kW”	109.7	109.7	109.7	109.7	109.7	109.7
First law Efficiency_$_{CASCADE\_VCRS}$	1.392	1.395	1.345	1.345	1.332	1.336
EDR $_{CASCADE\_VCRS}$	0.8049	0.8002	0.8683	0.8683	0.8853	0.8805
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.5541	0.5555	0.5353	0.5353	0.5304	0.5318
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	157.4	157.6	163.6	163.0	164.5	164.6
Exergy of product $_{CASCADE\_VCRS}$ “kW”	87.23	87.54	87.54	87.23	87.23	87.54
First law Efficiency_$_{LTC\_VCRS}$	3.965	3.896	3.896	3.965	3.965	3.896
First law Efficiency_$_{MTC\_VCRS}$	3.671	3.738	3.738	3.738	3.671	3.689
LTC Compressor work “kW”	44.14	44.91	44.91	44.14	44.14	44.91
MTC Compressor work “kW”	59.7	59.61	58.83	58.62	59.7	59.61
First law Efficiency_$_{HTC\_VCRS}$	2.853	2.853	2.662	2.662	2.662	2.662
EDR $_{HTC\_VCRS}$	0.8793	0.8793	1.014	1.014	1.014	1.014
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.5321	0.5321	0.4965	0.4965	0.4965	0.4965
Exergy of Fuel_ $_{HTC\_VCRS}$ “kW”	97.75	97.99	104.7	104.4	104.8	105.0
Exergy of product $_{HTC\_VCRS}$ “kW”	52.02	52.14	52.0	51.81	52.02	52.14
HTC Condenser Heat Rejected “kW”	376.6	377.5	383.5	382.1	383.6	384.5
MTC Condenser Heat Rejected“kW”	278.8	279.5	278.7	277.8	278.8	279.5
LTC Condenser Heat Rejected“kW”	219.1	219.9	219.9	219.1	219.1	219.9
Cooling Load on system Q_$_{Eva\_LTC}$ “kW”	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.468	2.474	2.971	2.960	2.972	2.979
MTC Mass flow rate (Kg/sec)	1.443	1.623	1.241	1.237	1.443	1.623
LTC Mass flow rate (Kg/sec)	1.109	0.9821	0.9821	1.109	1.109	0.9821

3.2 Effect of HFO and HCFO refrigerants in ultra-low temperature applications

Maximum thermodynamic performances of eight, three staged cascaded vapour compression refrigeration systems have been compared using HFO and HCFO refrigerants and it was found that the performance of system-4 is superior than other three staged cascaded VCR system However, system-8 gives slightly less thermal performances as compared with system-4. However,, system-5 gives lowest thermal performances. It clearly shows that ultra-low GWP ecofriendly HFO-1225ye(Z) in LTC circuit and HFO-1336mzz(Z) in MTC circuit gives better thermal energy-exergy performances than using HFO-1336mzz(Z) in LTC circuit and HFO-1225ye(Z) in MTC for ultra-low temperature applications as shown in Table 2(a) to Table 2(b) respectively

Table 2(a): Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ *=50ºC,* $T_{\_Eva\_LTC}$ *=-150ºC,* $T_{\_Eva\_MTC}$ *=-90ºC,* $T_{\_Eva\_HTC}$ *=-30ºC,MTC temperature overlapping(Approach*$_{\_MTC}$ *) =10, ITC temperature overlapping (Approach*$_{\_LTC}$ *) =10,*$Q_{\_Eva\_LTC}$*=175 "kW"*

	System-1	System-2	System-3	System-4
HTC Refrigerants	R1234yf	R1243zf	R1234ze(E)	R1233zd(E)
MTC Refrigerants	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)
LTC Refrigerants	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
First law Efficiency$_{\_CASCADE\_VCRS}$	0.2772	0.2921	0.2922	0.3112
EDR $_{CASCADE\_VCRS}$	1.540	1.411	1.411	1.263
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3936	0.4147	0.4149	0.4419
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	631.2	599.10	598.9	562.3
Exergy of product $_{CASCADE\_VCRS}$ "kW"	248.5	248.5	248.5	248.5
First law Efficiency$_{\_CASCADE\ \_MTC\_Two\_staged}$	0.6852	0.7345	0.7349	0.8005
EDR $_{CASCADE\_VCRS}$	1.327	1.171	1.170	0.9920
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4297	0.4606	0.4609	0.5020
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	498.4	446.3	446.0	409.5
Exergy of product $_{CASCADE\_VCRS}$ "kW"	205.6	205.6	205.6	205.6
First law Efficiency$_{\_LTC\_VCRS}$	1.619	1.145	1.145	1.145
First law Efficiency$_{\_MTC\_VCRS}$	1.738	1.921	1.921	1.921
LTC Compressor work "kW"	152.8	152.8	152.8	152.8
MTC Compressor work "kW"	170.6	170.6	170.6	170.6
First law Efficiency$_{\_HTC\_VCRS}$	1.619	1.808	1.810	2.086
EDR $_{HTC\_VCRS}$	1.738	1.452	1.450	1.125
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3653	0.4078	0.4082	0.4707
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	307.8	275.7	275.4	238.9
Exergy of product $_{HTC\_VCRS}$ "kW"	112.4	112.4	112.4	112.4
HTC Condenser Heat Rejected "kW"	806.2	774.1	773.9	737.3
MTC Condenser Heat Rejected"kW"	498.4	498.4	498.4	498.4
LTC Condenser Heat Rejected "kW"	327.8	327.8	327.8	327.8
LTC evaporator Cooling Load "kW"	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	6.783	4.668	5.386	4.117
MTC Mass flow rate (Kg/sec)	2.311	2.311	2.311	2.311
LTC Mass flow rate (Kg/sec)	1.102	1.102	1.102	1.102

Table 2(b): Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ *=50ºC,* $T_{\_Eva\_LTC}$ *=-150ºC,* $T_{\_Eva\_MTC}$ *=-90ºC,* $T_{\_Eva\_HTC}$ *=-30ºC, MTC temperature overlapping(Approach*$_{\_MTC}$ *) =10, ITC temperature overlapping (Approach*$_{\_LTC}$ *) =10,*$Q_{\_Eva\_LTC}$*=175 "kW"*

	System-5	System-6	System-7	System-8
HTC Refrigerants	R1234yf	R1243zf	R1234ze(E)	R1233zd(E)
MTC Refrigerants	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
LTC Refrigerants	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)
First law Efficiency$_{\_CASCADE\_VCRS}$	0.2706	0.2850	0.2852	0.3036
EDR $_{CASCADE\_VCRS}$	1.603	1.471	1.470	1.320
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3842	0.4047	0.4049	0.4310
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	646.7	613.9	613.7	576.4
Exergy of product $_{CASCADE\_VCRS}$ "kW"	248.5	248.5	248.5	248.5
First law Efficiency$_{\_CASCADE\ \_MTC\_Two\_staged}$	0.6947	0.7450	0.7454	0.8123
EDR $_{CASCADE\_VCRS}$	1.296	1.141	1.139	0.9631
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4356	0.4671	0.4674	0.5094
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	484.9	452.10	451.9	414.6
Exergy of product $_{CASCADE\_VCRS}$ "kW"	211.2	211.2	211.2	211.2
First law Efficiency$_{\_LTC\_VCRS}$	1.081	1.081	1.081	1.081
First law Efficiency$_{\_MTC\_VCRS}$	1.968	1.968	1.968	1.968
LTC Compressor work "kW"	161.8	161.8	161.8	161.8
MTC Compressor work "kW"	171.2	171.2	171.2	171.2

First law Efficiency_$_{\text{HTC\_VCRS}}$	1.619	1.808	1.810	2.086
EDR $_{\text{HTC\_VCRS}}$	1.738	1.452	1.450	1.125
Exergy_Efficiency_ $_{\text{HTC\_VCRS}}$	0.3653	0.4078	0.4082	0.4707
Exergy of Fuel_ $_{\text{HTC\_VCRS}}$ "kW"	313.7	281.0	280.7	243.5
Exergy of product $_{\text{HTC\_VCRS}}$ "kW"	114.6	114.6	114.6	114.6
HTC Condenser Heat Rejected "kW"	821.7	788.9	788.7	751.4
MTC Condenser Heat Rejected"kW"	508.0	508.0	508.0	508.0
LTC Condenser Heat Rejected "kW"	336.8	336.8	336.8	336.8
LTC evaporator Cooling Load "kW"	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	6.913	4.757	5.489	4.195
MTC Mass flow rate (Kg/sec)	2.631	2.631	2.631	2.631
LTC Mass flow rate (Kg/sec)	0.9680	0.9680	0.9680	0.9680

3.3 Effect of Hydrocarbons

Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration systems at three different LTC evaporator temperatures (-160°C, -155°C & -150°C, have been compared using hydrocarbon refrigerants and it was found that the performance of system is increasing as LTC evaporator temperature is increasing as shown in Table 3(a) to Table 3(c) respectively. Similarly, the first law (energy) performance of three hydrocarbons in HTC circuit have been compared and it was found that HC-600a used in HTC circuit gives highest thermodynamic performances than using HC-1270(propylene) and HC-290 used in HTC circuit. However,, R-290 in HTC cycle gives lowest thermodynamic (energy-exergy) performances. Similarly, Maximum thermodynamic performances of three staged cascaded VCR system using R-170 (ethane) in MTC cycle at -100°C of MTC evaporator temperature have been compared with R41 used in MTC circuit and it was found that the R41 in MTC circuit gives better thermal energy-exergy performances than using R170 (ethane) in MTC for ultra-low temperature applications as shown in Table 3(a) to Table 3(c)respectively

Table 3(a): Maximum thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications (T_$_{\text{Cond\_HTC}}$ =50°C, T_$_{\text{Eva\_LTC}}$ =-160°C, T_$_{\text{Eva\_MTC}}$ =-100°C, T_$_{\text{Eva\_HTC}}$ =-30°C,MTC temperature overlapping(Approach_$_{\text{MTC}}$) =10, ITC temperature overlapping (Approach_$_{\text{LTC}}$) =10,Q_$_{\text{Eva\_LTC}}$=175 "kW"

	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerants	R600a	R600a	R290	R290	R1270	R1270
MTC Refrigerants	R170	R41	R170	R41	R170	R41
LTC Refrigerants	R1150	R1150	R1150	R1150	R1150	R1150
First law Efficiency_$_{\text{CASCADE\_VCRS}}$	0.2214	0.2205	0.2172	0.2163	0.2186	0.2177
EDR $_{\text{CASCADE\_VCRS}}$	1.765	1.776	1.818	1.829	1.80	1.811
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.3616	0.3602	0.3548	0.3534	0.3571	0.3557
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ "kW"	790.5	790.3	805.7	808.9	800.5	803.7
Exergy of product $_{\text{CASCADE\_VCRS}}$ "kW"	285.9	285.9	285.9	285.9	285.9	285.9
First law Efficiency_$_{\text{CASCADE\_VCRS}}$	0.6196	0.6164	0.6042	0.6011	0.6094	0.6063
EDR $_{\text{CASCADE\_VCRS}}$	1.238	1.250	1.295	1.307	1.276	1.288
Exergy_Efficiency_ $_{\text{CASCADE\_VCRS}}$	0.4468	0.4444	0.4357	0.4334	0.4394	0.4371
Exergy of Fuel_ $_{\text{CASCADE\_VCRS}}$ "kW"	596.2	599.3	611.3	614.5	606.1	609.3
Exergy of product $_{\text{CASCADE\_VCRS}}$ "kW"	266.3	266.3	266.3	266.3	266.3	266.3
First law Efficiency_$_{\text{LTC\_VCRS}}$	0.9003	0.9003	0.9003	0.9003	0.9003	0.9003
First law Efficiency_$_{\text{MTC\_VCRS}}$	1.387	1.376	1.387	1.376	1.387	1.376
LTC Compressor work "kW"	194.4	194.4	194.4	194.4	194.4	194.4
MTC Compressor work "kW"	266.4	268.5	266.4	268.5	266.4	268.5
First law Efficiency_$_{\text{HTC\_VCRS}}$	1.928	1.928	1.843	1.843	1.872	1.872
EDR $_{\text{HTC\_VCRS}}$	1.299	1.299	1.405	1.405	1.369	1.369
Exergy_Efficiency_ $_{\text{HTC\_VCRS}}$	0.4349	0.4349	0.4158	0.4158	0.4222	0.4222
Exergy of Fuel_ $_{\text{HTC\_VCRS}}$ "kW"	329.7	330.8	344.9	346.0	329.7	340.8
Exergy of product $_{\text{HTC\_VCRS}}$ "kW"	143.4	143.4	143.4	143.4	143.4	143.4
HTC Condenser Heat Rejected "kW"	965.5	968.7	980.7	983.7	975.5	978.7
MTC Condenser Heat Rejected"kW"	635.8	637.9	635.8	637.9	635.8	637.9
LTC Condenser Heat Rejected"kW"	369.4	369.4	369.4	369.4	369.4	369.4
Cooling Load on system Q_$_{\text{Eva\_LTC}}$ "kW"	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	3.307	3.318	3.138	3.148	2.972	2.981
MTC Mass flow rate (Kg/sec)	1.263	1.072	1.263	1.072	1.263	1.072
LTC Mass flow rate (Kg/sec)	0.4527	0.4527	0.4527	0.4527	0.4527	0.4527

Table 3(b): Maximum thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ =50ºC, $T_{\_Eva\_LTC}$ =-155ºC, $T_{\_Eva\_MTC}$ =-100ºC, $T_{\_Eva\_HTC}$ =-30ºC,MTC temperature overlapping(Approach$_{\_MTC}$) =10, ITC temperature overlapping (Approach$_{\_LTC}$) =10,$Q_{\_Eva\_LTC}$=175 "kW"

	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerants	R1270	R1270	R600a	R600a	R290	R290
MTC Refrigerants	R170	R41	R170	R41	R170	R41
LTC Refrigerants	R1150	R1150	R1150	R1150	R1150	R1150
First law Efficiency_$_{CASCADE\_VCRS}$	0.2452	0.2442	0.2483	0.2473	0.2436	0.2426
EDR $_{CASCADE\_VCRS}$	1.679	1.690	1.645	1.656	1.697	1.708
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3732	0.3717	0.3780	0.3765	0.3707	0.3692
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	713.8	716.7	704.7	707.6	718.5	721.5
Exergy of product $_{CASCADE\_VCRS}$ "kW"	266.4	266.4	266.4	266.4	266.4	266.4
First law Efficiency_$_{CASCADE\_VCRS}$	0.6094	0.6164	0.6196	0.6164	0.6042	0.6011
EDR $_{CASCADE\_VCRS}$	1.276	1.288	1.238	1.250	1.295	1.307
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4394	0.4371	0.4461	0.4444	0.4357	0.4334
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	552.2	555.1	543.2	546.0	557.0	581.2
Exergy of product $_{CASCADE\_VCRS}$ "kW"	242.7	242.7	242.7	242.7	242.7	242.7
First law Efficiency_$_{LTC\_VCRS}$	1.083	1.083	1.083	1.083	1.083	1.083
First law Efficiency_$_{MTC\_VCRS}$	1.387	1.376	1.387	1.376	1.387	1.376
LTC Compressor work "kW"	161.5	161.5	161.5	161.5	161.5	161.5
MTC Compressor work "kW"	242.7	244.6	242.7	244.6	242.7	244.6
First law Efficiency_$_{HTC\_VCRS}$	1.872	1.872	1.928	1.928	1.843	1.872
EDR $_{HTC\_VCRS}$	1.369	1.369	1.299	1.299	1.299	1.299
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.4222	0.4222	0.4349	0.4349	0.4349	0.4349
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	309.5	310.5	300.4	301.4	314.3	315.3
Exergy of product $_{HTC\_VCRS}$ "kW"	130.7	131.1	130.7	131.7	130.7	131.7
HTC Condenser Heat Rejected "kW"	888.8	891.7	879.7	882.6	893.5	896.5
MTC Condenser Heat Rejected"kW"	579.3	581.2	579.3	581.2	579.3	581.2
LTC Condenser Heat Rejected"kW"	336.5	336.5	336.5	336.5	336.5	336.5
Cooling Load on system $Q_{\_Eva\_LTC}$ "kW"	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.707	2.716	3.013	3.023	2.859	2.868
MTC Mass flow rate (Kg/sec)	1.263	0.9771	1.151	0.9771	1.151	0.9771
LTC Mass flow rate (Kg/sec)	0.4460	0.4460	0.4460	0.4460	0.4460	0.4460

Table 3(c): Maximum thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ =50ºC, $T_{\_Eva\_LTC}$ =-150ºC, $T_{\_Eva\_MTC}$ =-90ºC, $T_{\_Eva\_HTC}$ =-30ºC,MTC temperature overlapping(Approach$_{\_MTC}$) =10, ITC temperature overlapping (Approach$_{\_LTC}$) =10,$Q_{\_Eva\_LTC}$=175 "kW"

	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerants	R1270	R1270	R600a	R600a	R290	R290
MTC Refrigerants	R170	R41	R170	R41	R170	R41
LTC Refrigerants	R1150	R1150	R1150	R1150	R1150	R1150
First law Efficiency_$_{CASCADE\_VCRS}$	0.2722	0.2724	0.2759	0.2759	0.2705	0.2705
EDR $_{CASCADE\_VCRS}$	1.587	1.586	1.552	1.554	1.604	1.604
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3865	0.3867	0.3918	0.3916	0.3841	0.3839
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	642.9	642.5	634.2	634.6	646.9	647.3
Exergy of product $_{CASCADE\_VCRS}$ "kW"	248.5	248.5	248.5	248.5	248.5	248.5
First law Efficiency_$_{CASCADE\_VCRS}$	0.7175	0.7180	0.7308	0.7308	0.7115	0.7109
EDR $_{CASCADE\_VCRS}$	1.223	1.221	1.182	1.184	1241	1.243
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4499	0.4502	0.4583	0.4579	0.4461	0.4458
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	476.2	475.9	467.5	467.9	480.2	480.6
Exergy of product $_{CASCADE\_VCRS}$ "kW"	214.3	214.3	214.3	214.3	214.3	214.3
First law Efficiency_$_{LTC\_VCRS}$	1.05	1.05	1.05	1.05	1.05	1.05
First law Efficiency_$_{MTC\_VCRS}$	1.785	1.787	1.785	1.787	1.785	1.787
LTC Compressor work "kW"	166.7	166.7	166.7	166.7	166.7	166.7
MTC Compressor work "kW"	191.4	191.2	191.4	191.2	191.4	191.2
First law Efficiency_$_{HTC\_VCRS}$	1.872	1.872	1.928	1.928	1.843	1.872
EDR $_{HTC\_VCRS}$	1.387	1.369	1.299	1.299	1.405	1.405
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.4222	0.4222	0.4349	0.4349	0.4461	0.4158

Exergy of Fuel_ $_{HTC\_VCRS}$ “kW”	284.8	284.7	276.4	276.5	289.10	289.2
Exergy of product $_{HTC\_VCRS}$ “kW”	120.3	120.2	120.2	120.3	120.2	120.3
HTC Condenser Heat Rejected “kW”	817.9	817.6	809.2	809.6	821.9	822.3
MTC Condenser Heat Rejected“kW”	533.1	532.9	532.9	533.10	532.9	533.10
LTC Condenser Heat Rejected“kW”	341.7	341.7	341.7	341.7	341.7	341.7
Cooling Load on system Q_$_{Eva\_LTC}$ “kW”	175.0	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.492	2.492	2.772	2.773	2.630	2.630
MTC Mass flow rate (Kg/sec)	1.124	0.9698	0.9698	1.124	0.9698	1.124
LTC Mass flow rate (Kg/sec)	0.4685	0.4685	0.4685	0.4685	0.4685	0.4685

3.4 Effect of HTC hydrocarbon refrigerants on actual thermodynamic performances of three staged cascaded vapour compression refrigeration system for ultra-low temperature applications

Actual thermodynamic performances of three staged cascaded vapour compression refrigeration systems at LTC evaporator temperatures (-130°C) have been compared using hydrocarbon refrigerants and it was found that the performance of system is increasing as LTC evaporator temperature is increasing as shown in Table 4(a) to Table 4(c) respectively. Similarly, the first law (energy) performance of three hydrocarbons in HTC circuit have been compared and it was found that HC-600a used in HTC circuit gives highest thermodynamic performances than using HC-1270(propylene) and HC-290 used in HTC circuit. However, R-290 in HTC cycle gives lowest thermodynamic (energy-exergy) performances. Similarly, actual thermodynamic performances of three staged cascaded VCR system using R-170 (ethane) in MTC cycle at -80°C of MTC evaporator temperature have been compared with R41 used in MTC circuit and it was found that the R41 in MTC circuit gives better thermal energy-exergy performances than using R170 (ethane) in MTC for ultra-low temperature applications as shown in Table 4(a) & Table 4(b)respectively

Table 4(a): Actual thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ =50°C, $T_{\_Eva\_LTC}$ =-130°C, $T_{\_Eva\_MTC}$ =-80°C, $T_{\_Eva\_HTC}$ =-22°C, MTC temperature overlapping (Approach$_{\_MTC}$) =10, ITC temperature overlapping (Approach$_{\_LTC}$) =10, HTC compressor Efficiency=0.80, MTC compressor Efficiency=0.80, LTC compressor Efficiency=0.80, Q_Eva_LTC=175 “kW”

HTC Refrigerants	R1270	R600a	R290
MTC Refrigerants	R41	R41	R41
LTC Refrigerants	R1150	R1150	R1150
First law Efficiency$_{\_CASCADE\_VCRS}$	0.2867	0.2915	0.2853
EDR $_{CASCADE\_VCRS}$	2.224	2.171	2.240
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3101	0.3154	0.3086
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	610.4	600.3	613.4
Exergy of product $_{CASCADE\_VCRS}$ “kW”	189.3	189.3	189.3
First law Efficiency$_{\_CASCADE\_VCRS}$	0.6469	0.6609	0.6428
EDR $_{CASCADE\_VCRS}$	1.848	1.787	1.866
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3512	0.3588	0.3490
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	476.9	466.8	479.9
Exergy of product $_{CASCADE\_VCRS}$ “kW”	167.5	167.5	167.5
First law Efficiency$_{\_LTC\_VCRS}$	1.311	1.311	1.311
First law Efficiency$_{\_MTC\_VCRS}$	1.571	1.571	1.571
LTC Compressor work “kW”	133.5	133.5	133.5
MTC Compressor work “kW”	196.4	196.4	196.4
First law Efficiency$_{\_HTC\_VCRS}$	1.80	1.867	1.781
EDR $_{HTC\_VCRS}$	1.978	1.871	2.01
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3358	0.3483	0.3490
Exergy of Fuel_ $_{HTC\_VCRS}$ “kW”	280.5	270.4	283.5
Exergy of product $_{HTC\_VCRS}$ “kW”	94.18	94.18	94.18
HTC Condenser Heat Rejected “kW”	785.4	775.3	788.4
MTC Condenser Heat Rejected“kW”	504.9	504.9	504.9
LTC Condenser Heat Rejected“kW”	308.5	308.5	308.5
Cooling Load on system Q_$_{Eva\_LTC}$ “kW”	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.272	2.49	2.381
MTC Mass flow rate (Kg/sec)	0.9058	0.9058	0.9058
LTC Mass flow rate (Kg/sec)	0.4716	0.4716	0.4716

Table 4(b): Actual thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications ($T_{\_Cond\_HTC}$ =50°C, $T_{\_Eva\_LTC}$ =-130°C, $T_{\_Eva\_MTC}$ =-80°C, $T_{\_Eva\_HTC}$ =-22°C,MTC temperature overlapping(Approach_$_{MTC}$) =10, ITC temperature overlapping (Approach_$_{LTC}$) =10, HTC compressor Efficiency=0.80, MTC compressor Efficiency=0.80, LTC compressor Efficiency=0.80, Q_Eva_LTC=175 "kW"

HTC Refrigerants	R1270	R600a	R290
MTC Refrigerants	R170	R170	R170
LTC Refrigerants	R1150	R1150	R1150
First law Efficiency_$_{CASCADE\_VCRS}$	0.2834	0.2882	0.2820
EDR $_{CASCADE\_VCRS}$	2.2620	2.208	2.278
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3066	0.3117	0.3051
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	617.5	607.3	620.5
Exergy of product $_{CASCADE\_VCRS}$ "kW"	189.3	189.3	189.3
First law Efficiency_$_{CASCADE\_VCRS}$	0.6374	0.6511	0.6334
EDR $_{CASCADE\_VCRS}$	1.890	1.823	1.908
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3460	0.3535	0.3439
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	484.0	473.8	487.0
Exergy of product $_{CASCADE\_VCRS}$ "kW"	167.5	167.5	167.5
First law Efficiency_$_{LTC\_VCRS}$	1.311	1.311	1.311
First law Efficiency_$_{MTC\_VCRS}$	1.571	1.571	1.571
LTC Compressor work "kW"	133.5	133.5	133.5
MTC Compressor work "kW"	201.0	201.0	201.0
First law Efficiency_$_{HTC\_VCRS}$	1.80	1.867	1.781
EDR $_{HTC\_VCRS}$	1.978	1.871	2.01
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3358	0.3483	0.3490
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	283.0	272.8	286.1
Exergy of product $_{HTC\_VCRS}$ "kW"	95.03	95.03	95.03
HTC Condenser Heat Rejected "kW"	792.5	782.3	795.5
MTC Condenser Heat Rejected"kW"	504.9	504.9	504.9
LTC Condenser Heat Rejected"kW"	308.5	308.5	308.5
Cooling Load on system Q_$_{Eva\_LTC}$ "kW"	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.293	2.513	2.403
MTC Mass flow rate (Kg/sec)	1.062	1.062	1.062
LTC Mass flow rate (Kg/sec)	0.4716	0.4716	0.4716

3.5 Effect of HTC ultra-low GWP refrigerants (HFOs &HCFOs) on actual thermodynamic performances of three staged cascaded vapour compression refrigeration system for ultra-low temperature applications

The thermodynamic performance of three-stage cascaded vapor compression refrigeration systems was evaluated at different low-temperature cycle (LTC) evaporator temperatures using environmentally friendly HFO and HCFO refrigerants. The analysis was conducted at an LTC evaporator temperature of -120°C, with a condenser temperature of 40°C, a high-temperature cycle (HTC) evaporator temperature of -22°C, and a medium-temperature cycle (MTC) evaporator temperature of -60°C. The results revealed that the system using HCFO-1233zd(E) in the HTC cycle, HFO-1336mzz(Z) in the MTC cycle, and R1225ye(Z) in the LTC cycle demonstrated the highest thermodynamic performance. This combination proved superior to configurations involving HCFO-1233zd(E) in the HTC cycle, HFO-1225ye(Z) in the MTC circuit, and HFO-1336mzz(Z) in the LTC cycle. Further analysis was conducted to compare system performance at an LTC evaporator temperature of 130°C using the same refrigerants across the HTC, MTC, and LTC cycles. Results showed that system performance improved as the LTC evaporator temperature increased. These performance trends are outlined in Tables 4(d) to 4(e), confirming that higher LTC evaporator temperatures positively impact the overall thermodynamic efficiency.

The first law performance of HCFO and HFO refrigerants in the HTC circuit was examined. It was determined that the combination of HCFO-1233zd(E) in the HTC circuit and HFO-1336mzz(Z) in the MTC cycle provided the highest thermodynamic efficiency. This combination significantly outperformed the system using HCFO-1233zd(E) in the HTC cycle with HFO-1225ye(Z) in the MTC circuit. Conversely, the system incorporating HFO-1234yf in the HTC cycle, R1225ye(Z) in the MTC cycle, and HFO-1336mzz(Z) in the LTC cycle exhibited the lowest thermodynamic performance in terms of both energy and exergy. This indicates that the selection of refrigerants plays a crucial role in achieving optimal system efficiency and performance. These findings emphasize the importance of selecting appropriate refrigerant combinations to improve thermal efficiency, reduce energy consumption, and enhance system reliability.

Table 4(c): Actual thermodynamic performances of modified vapour compression refrigeration system using (T_cond=40^{o}C, T_subcooling=30^{o}C, T_Eva_HTC= -22^{o}C, T_Eva_HTC=-60^{o}C, T_Eva_LTC= -120^{o}C, Approach_$_{MTC}$ =10, Approach_$_{LTC}$ =10.

HTC Refrigerants	R1233zd(E)	R1233zd(E)	R1225ye(Z)	R1336mzz(Z)
MTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
LTC Refrigerants	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency_$_{CASCADE\_VCRS}$	0.4278	0.417	0.4020	0.4223
EDR $_{CASCADE\_VCRS}$	1.472	1.536	1.630	1.504
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4046	0.3944	0.3802	0.3994
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	409.1	419.7	435.3	414.3
Exergy of product $_{CASCADE\_VCRS}$ “kW”	165.5	165.5	165.5	165.5
First law Efficiency_$_{CASCADE\_VCRS}$	1.138	1.141	1.080	1.117
EDR $_{CASCADE\_VCRS}$	1.207	1.201	1.325	1.250
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.4530	0.4542	0.430	0.4445
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	273.2	277.80	293.4	278.5
Exergy of product $_{CASCADE\_VCRS}$ “kW”	123.8	126.20	126.20	123.8
First law Efficiency_$_{LTC\_VCRS}$	1.288	1.233	1.233	1.288
First law Efficiency_$_{MTC\_VCRS}$	2.937	2.952	2.991	2.991
LTC Compressor work “kW”	135.9	141.90	141.90	135.9
MTC Compressor work “kW”	105.9	107.4	106.0	104.0
First law Efficiency_$_{HTC\_VCRS}$	2.491	2.491	2.491	2.491
EDR $_{HTC\_VCRS}$	1.152	1.152	1.152	1.152
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.4646	0.4646	0.4646	0.4646
Exergy of Fuel_ $_{HTC\_VCRS}$ “kW”	167.30	170.40	187.4	174.50
Exergy of product $_{HTC\_VCRS}$ “kW”	77.75	79.16	78.89	77.39
HTC Condenser Heat Rejected “kW”	584.10	594.70	610.3	589.40
MTC Condenser Heat Rejected“kW”	416.80	424.30	422.90	414.90
LTC Condenser Heat Rejected“kW”	310.6	316.9	316.9	310.9
Cooling Load on system Q_$_{Eva\_LTC}$ “kW”	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	2.989	3.043	4.390	3.608
MTC Mass flow rate (Kg/sec)	2.047	2.339	1.789	1.755
LTC Mass flow rate (Kg/sec)	1.218	1.092	1.092	1.218

Table 4(d): Actual thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{Eva\_LTC}$ =-130^{o}C, T_$_{Eva\_MTC}$ =-80^{o}C, T_$_{Eva\_HTC}$ =-22^{o}C,MTC temperature overlapping(Approach_$_{MTC}$) =10, ITC temperature overlapping (Approach_$_{LTC}$) =10,Q_Eva_LTC=175 “kW”

HTC Refrigerants	R1233zd(E)	R1233zd(E)	R-1243zf	R-1243zf
MTC Refrigerants	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency_$_{CASCADE\_VCRS}$	0.3221	0.3269	0.3032	0.3067
EDR $_{CASCADE\_VCRS}$	1.870	1.828	2.049	2.005
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3485	0.3536	0.3280	0.3327
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	543.20	535.5	577.2	568.9
Exergy of product $_{CASCADE\_VCRS}$ “kW”	189.3	189.3	189.3	189.3
First law Efficiency_$_{CASCADE\_VCRS}$	0.7296	0.7222	0.6745	0.6678
EDR $_{CASCADE\_VCRS}$	1.525	1.551	1.731	1.758
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3960	0.3920	0.3661	0.3625
Exergy of Fuel_ $_{CASCADE\_VCRS}$ “kW”	413.5	412.5	449.2	446.0
Exergy of product $_{CASCADE\_VCRS}$ “kW”	164.5	161.7	164.5	161.7
First law Efficiency_$_{LTC\_VCRS}$	1.368	1.424	1.368	1.424
First law Efficiency_$_{MTC\_VCRS}$	1.718	1.690	1.718	1.690
LTC Compressor work “kW”	128.0	122.8	128.0	122.8
MTC Compressor work “kW”	176.4	176.2	176.4	176.2

First law Efficiency_$_{HTC\_VCRS}$	2.007	2.007	1.757	1.757
EDR $_{HTC\_VCRS}$	1.672	1.672	2.051	2.051
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3743	0.3743	0.3278	0.3278
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	238.9	236.3	272.8	269.8
Exergy of product $_{HTC\_VCRS}$ "kW"	89.42	88.44	89.42	88.44
HTC Condenser Heat Rejected "kW"	718.2	710.4	752.2	743.9
MTC Condenser Heat Rejected"kW"	479.4	474.1	479.4	474.1
LTC Condenser Heat Rejected"kW"	303.0	297.9	303.0	297.9
Cooling Load on system Q_$_{Eva\_LTC}$ "kW"	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	3.781	3.74	4.274	4.227
MTC Mass flow rate (Kg/sec)	2.43	2.15	2.430	2.15
LTC Mass flow rate (Kg/sec)	0.9774	1.110	0.9774	1.110

Table 4(e): Actual thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications (T_$_{Cond\_HTC}$ =50°C, T_$_{Eva\_LTC}$ =-150°C, T_$_{Eva\_MTC}$ =-90°C, T_$_{Eva\_HTC}$ =-30°C,MTC temperature overlapping(Approach_$_{MTC}$) =10, ITC temperature overlapping (Approach_$_{LTC}$) =10,Q_Eva_LTC=175 "kW"

HTC Refrigerants	R-1234ze(E)	R-1234ze(E)	R-1234yf	R-1234yf
MTC Refrigerants	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
LTC Refrigerants	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
First law Efficiency_$_{CASCADE\_VCRS}$	0.3041	0.3085	0.2897	0.2939
EDR $_{CASCADE\_VCRS}$	2.040	1.997	2.191	2.145
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3289	0.3337	0.3134	0.3179
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	575.5	567.3	604.0	595.5
Exergy of product $_{CASCADE\_VCRS}$ "kW"	189.3	189.3	189.3	189.3
First law Efficiency_$_{CASCADE\_VCRS}$	0.6770	0.6703	0.6365	0.6303
EDR $_{CASCADE\_VCRS}$	1.721	1.748	1.894	1.922
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3675	0.3639	0.3455	0.3422
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	447.5	444.4	476.0	472.6
Exergy of product $_{CASCADE\_VCRS}$ "kW"	164.5	167.7	164.5	161.7
First law Efficiency_$_{LTC\_VCRS}$	1.368	1.424	1.368	1.424
First law Efficiency_$_{MTC\_VCRS}$	1.718	1.69	1.718	1.69
LTC Compressor work "kW"	128.0	122.9	128.0	122.9
MTC Compressor work "kW"	176.4	176.2	176.4	176.2
First law Efficiency_$_{HTC\_VCRS}$	1.768	1.768	1.60	1.60
EDR $_{HTC\_VCRS}$	2.032	2.032	2.351	2.351
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3298	0.3298	0.2984	0.2984
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	271.2	268.2	299.6	296.4
Exergy of product $_{HTC\_VCRS}$ "kW"	89.42	88.44	89.42	88.44
HTC Condenser Heat Rejected "kW"	750.5	742.3	779.0	750.5
MTC Condenser Heat Rejected"kW"	479.4	474.1	479.4	474.1
LTC Condenser Heat Rejected"kW"	303.0	297.9	303.0	297.9
Cooling Load on system Q_$_{Eva\_LTC}$ "kW"	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	4.880	4.826	6.08	6.013
MTC Mass flow rate (Kg/sec)	2.43	2.15	2.43	2.15
LTC Mass flow rate (Kg/sec)	0.9774	1.110	0.9774	1.110

3.6 Effect of LTC evaporator temperature on actual thermodynamic performances on three staged cascaded vapour compression refrigeration system for ultra-low temperature applications

Table 5 illustrates the impact of LTC evaporator temperature on the thermodynamic performance of three-stage cascaded vapor compression refrigeration systems using hydrocarbon refrigerants. The results indicate that as the LTC evaporator temperature increases, the system's energy performance decreases, suggesting reduced overall efficiency at higher temperatures. In contrast, the exergy performance improves with increasing LTC evaporator temperature, reflecting better thermodynamic effectiveness. This inverse relationship between energy and exergy performance underscores the importance of balancing operating conditions to maximize overall system efficiency. Understanding this trade-off allows for better optimization of refrigeration systems, enhancing their performance and sustainability in low-temperature applications.

Table 5: Effect of LTC evaporator temperature on actual thermodynamic performances of modified vapour compression refrigeration system for ultra-low temperature applications (T_{Cond_HTC} =50°C, T_{Eva_MTC} =-90°C, T_{Eva_HTC} =-30°C,MTC temperature overlapping(Approach$_{MTC}$) =10, ITC temperature overlapping (Approach$_{LTC}$) =10,Q_{Eva_LTC}=175 "kW", HTC compressor Efficiency=0.80, MTC compressor Efficiency=0.80, LTC compressor Efficiency=0.80,

T_{Eva_LTC} (°C)	-155	-150	-145	-150	-150
HTC Refrigerants	R1270	R1270	R1270	R600a	R290
MTC Refrigerants	R170	R170	R170	R170	R170
LTC Refrigerants	R1150	R1150	R1150	R1150	R1150
First law Efficiency$_{CASCADE_VCRS}$	0.1715	0.1917	0.2125	0.1944	0.1903
EDR $_{CASCADE\_VCRS}$	2.831	2.675	2.511	2.624	2.702
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.2611	0.2721	0.2816	0.2760	0.2701
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	1020.0	913.1	823.7	900.3	919.8
Exergy of product $_{CASCADE\_VCRS}$ "kW"	266.4	248.5	231.9	248.5	248.5
First law Efficiency$_{CASCADE_VCRS}$	0.4604	0.4604	0.4605	0.4685	0.4564
EDR $_{CASCADE\_VCRS}$	2.012	2.012	2.012	1.96	2.039
Exergy_Efficiency_ $_{CASCADE\_VCRS}$	0.3321	0.3321	0.3321	0.3378	0.3291
Exergy of Fuel_ $_{CASCADE\_VCRS}$ "kW"	818.5	745.0	683.8	732.2	751.7
Exergy of product $_{CASCADE\_VCRS}$ "kW"	271.8	247.4	227.1	247.4	247.4
First law Efficiency$_{LTC_VCRS}$	0.8666	1.041	1.251	1.041	1.041
First law Efficiency$_{MTC_VCRS}$	1.109	1.109	1.109	1.109	1.109
LTC Compressor work "kW"	201.9	168.1	139.9	168.1	168.1
MTC Compressor work "kW"	338.8	309.3	283.9	309.3	309.3
First law Efficiency$_{HTC_VCRS}$	1.497	1.497	1.497	1.543	1.475
EDR $_{HTC\_VCRS}$	1.961	1.961	1.961	1.874	2.006
Exergy_Efficiency_ $_{HTC\_VCRS}$	0.3378	0.3378	0.3378	0.3480	0.3327
Exergy of Fuel_ $_{HTC\_VCRS}$ "kW"	478.7	435.7	399.9	422.9	442.4
Exergy of product $_{HTC\_VCRS}$ "kW"	161.7	147.2	135.1	147.2	147.2
HTC Condenser Heat Rejected "kW"	1195.0	1088.0	998.7	1075.0	1095.0
MTC Condenser Heat Rejected"kW"	716.8	652.4	598.8	652.4	652.4
LTC Condenser Heat Rejected"kW"	376.9	343.1	314.9	431.1	431.1
Cooling Load on system Q_{Eva_LTC} "kW"	175.0	175.0	175.0	175.0	175.0
HTC Mass flow rate (Kg/sec)	3.350	3.049	2.799	3.394	3.220
MTC Mass flow rate (Kg/sec)	1.289	1.173	1.077	1.173	1.173
LTC Mass flow rate (Kg/sec)	0.4460	0.4394	0.4331	0.4394	0.4394

3.7 *Effect of Hydrocarbons*

3.7.1 *Performance of two staged cascaded VCR systems using low GWP ecofriendly refrigerants*

The effect of low GWP ecofriendly refrigerants used in three staged cascaded VCR systems on thermal (energy) performances of three staged cascaded systems have been shown in Table 3(a) and Table 3(h) respectively It was found that system using R-41 in MTC cycle gives better thermodynamic performances than using ethane (R-170) in the medium temperature cycle. Similarly, three staged cascaded VCR system using R600a in HTC cycle gives best thermal performances than using R-290 and propylene in the HT cycle.

Table 3(a): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_{eva_HTC}=40°C, T_{eva_HTC}=-22°C, T_{eva_MTC}=-60°C, T_{eva_LTC}=-90, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_{eva_LTC}=175 "kW")

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP$_{Cascade_Ethane_Two_Staged}$	1.140	1.167	1.132	1.218	1.202	1.148	1.240
COP$_{Cascade_41_Two_Staged}$	1.154	1.182	1.146	1.234	1.218	1.163	1.256

Table 3(b): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_{eva_HTC}=40°C, T_{eva_HTC}=-22°C, T_{eva_MTC}=-60°C, T_{eva_LTC}=-100°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10)

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP$_{Cascade_Ethane_Two_Staged}$	1.140	1.167	1.132	1.218	1.202	1.148	1.240
COP$_{Cascade_41_Two_Staged}$	1.154	1.182	1.146	1.234	1.218	1.163	1.256

Table 3(c): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_$_{eva\_HTC}$=40ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-60ºC, T_$_{eva\_LTC}$=-110ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”)

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	1.140	1.167	1.132	1.218	1.202	1.148	1.10
COP_$_{Cascade\_41\_Two\_Staged}$	1.154	1.182	1.146	1.234	1.218	1.163	1.102

Table 3(d): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (for T_$_{eva\_HTC}$=50ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-60ºC, T_$_{eva\_LTC}$=-120ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	1.140	1.167	1.132	1.218	1.202	1.148	1.240
COP_$_{Cascade\_41\_Two\_Staged}$	1.154	1.182	1.146	1.234	1.218	1.163	1.256

Table 3(e): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (for T_$_{eva\_HTC}$=50ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-90ºC, T_$_{eva\_LTC}$=-120ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	0.7083	0.7220	0.7043	0.7464	0.7391	0.7123	0.757
COP_$_{Cascade\_41\_Two\_Staged}$	0.7175	0.7315	0.7135	0.7564	0.7489	0.7217	0.7672

Table 3(f): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_$_{eva\_HTC}$=50ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-90ºC, T_$_{eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”)

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	0.7083	0.7220	0.7043	0.7464	0.7391	0.7123	0.7570
COP_$_{Cascade\_41\_Two\_Staged}$	0.7175	0.7315	0.7135	0.7564	0.7489	0.7217	0.7672

Table 3(g): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_$_{eva\_HTC}$=50ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-90ºC, T_$_{eva\_LTC}$=-140ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”)

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	0.7123	0.7220	0.7043	0.7464	0.7391	0.7123	0.7570
COP_$_{Cascade\_41\_Two\_Staged}$	0.7175	0.7315	0.7135	0.7564	0.7489	0.7217	0.7672

Table 3(h): Effect of hydrocarbons on thermal performances of three staged cascaded VCR systems for ultra-low temperature applications (T_$_{eva\_HTC}$=50ºC, T_$_{eva\_HTC}$=-22ºC, T_$_{eva\_MTC}$=-90ºC, T_$_{eva\_LTC}$=-150, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 “kW”)

Refrigerant	R1270	R600a	R290	R152a	R245fa	R32	R717
COP_$_{Cascade\_Ethane\_Two\_Staged}$	0.7083	0.7220	0.7043	0.7064	0.7391	0.7123	0.757
COP_$_{Cascade\_41\_Two\_Staged}$	0.7175	0.7315	0.7135	0.7564	0.7489	0.7217	0.7672

3.7.2 *Effect of optimum HTC temperature on optimal first law performance of three staged cascaded VCR systems using HCFO-1233zd(E) in HTC, and HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits*

The effect of HTC evaporator temperature on the thermal (energy) performance of sixteen three-stage cascaded vapor compression refrigeration (VCR) systems is presented in Tables 4(a) and 4(b). The analysis shows that increasing the HTC evaporator temperature enhances both energy and exergy performance, reaching an optimal value at a specific HTC temperature before performance starts to decline. This indicates that there is an ideal HTC evaporator temperature at which the system operates at maximum efficiency. The optimal HTC evaporator temperatures for different three-stage cascaded VCR systems are detailed in Tables 4(a) and 4(b), highlighting the temperature points where energy efficiency peaks. The exergy performance of the sixteen cascaded systems is shown in Tables 4(c) and 4(d). The exergy efficiency follows the same trend, increasing with the rise in HTC evaporator temperature until it reaches an optimal point, after which it starts to drop. This suggests that an optimal HTC evaporator temperature exists not only for energy performance but also for exergy efficiency. The results underscore the importance of maintaining the HTC evaporator temperature within an optimal range to achieve maximum system performance. A carefully balanced HTC evaporator temperature can enhance both energy and exergy efficiency, reducing overall system energy consumption and improving operational reliability. Identifying and maintaining this balance is crucial for improving the overall thermodynamic performance of cascaded VCR systems, making them more efficient and sustainable for low-temperature applications.

Table 4(a): Effect of optimum HTC temperature on optimal second law (exergy) thermal performances of three staged cascaded VCR systems using HCFO-1233zd(E) in HTC, and HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for $T_{\_eva\_HTC}$=50°C, $T_{\_eva\_HTC}$=-10°C, $T_{\_eva\_MTC}$=-70°C, $T_{\_eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, $Q_{\_eva\_LTC}$=175 "kW"

Tree staged Cascaded VCR systems	System-1	System-2	System-3	System-4
Optimum temperature	-16°C to -17°C	-16°C to -17°C	-23°C	-17°C to -18°C
HTC Refrigerant	R1233zd(E)	R1233zd(E)	Propylene	Propylene
MTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	Ethane	R41
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.4427	0.4540	0.3910	0.3955

Table 4(b): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for $T_{\_eva\_HTC}$=50°C, $T_{\_eva\_HTC}$=-10°C, $T_{\_eva\_MTC}$=-70°C, $T_{\_eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, $Q_{\_eva\_LTC}$=175 "kW"

	System-5	System-6	System-7	System-8
Optimum MTC temperature	-22°C	-16°C to -17°C	22°C & -23°C	-17°C
HTC Refrigerant	R290	R290	R600a	R600a
MTC Refrigerant	Ethane	R41	Ethane	R41
LTC Refrigerant	ethylene	ethylene	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.3892	0.3943	0.3971	0.4019

Table 4(c): Optimum thermal performances of three staged cascaded VCR systems using HCFO-1224yd(Z) in HTC, HCFO-1233zd(E) and HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for $T_{\_eva\_HTC}$=50°C, $T_{\_eva\_HTC}$=-10°C, $T_{\_eva\_MTC}$=-70°C, $T_{\_eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, $Q_{\_eva\_LTC}$=175 "kW"

	System-1	System-2	System-3		System-4
Optimum temperature	-16°C to -17°C	-16°C to -17°C	-21°C to -24°C		-17°C to -19°C
HTC Refrigerant	R1233zd(E)	R1233zd(E)	Propylene		Propylene
MTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	Ethane		R41
LTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	ethylene		ethylene
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4789	0.4911	0.4229		0.4278

Table 4(d): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for $T_{\_eva\_HTC}$=50°C, $T_{\_eva\_HTC}$=-10°C, $T_{\_eva\_MTC}$=-70°C, $T_{\_eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, $Q_{\_eva\_LTC}$=175 "kW"

	System-5	System-6	System-7	System-8
Optimum temperature	-21°C & -22°C	-16°C to -17°C	22°C & -23°C	-17°C to -18°C
HTC Refrigerant	R290	R290	R600a	R600
MTC Refrigerant	Ethane	R41	Ethane	R41
LTC Refrigerant	ethylene	ethylene	ethylene	ethylene
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4210	0.4265	0.4295	0.4347

3.7.3 Effect of MTC evaporator temperature on optimum exergy performance of three staged cascaded VCR systems using low GWP ecofriendly HFO and HCFO refrigerants

The optimal performance of three-stage cascaded vapor compression refrigeration (VCR) systems using HCFO-1224yd(Z) in the high-temperature cycle (HTC), HCFO-1233zd(E), and HFO refrigerants (R1225ye(Z) and R1336mzz(Z)) in the medium-temperature cycle (MTC), and HFO refrigerants (R1225ye(Z) and R1336mzz(Z)) in the low-temperature cycle (LTC) for ultra-low temperature applications was evaluated. The effect of MTC evaporator temperature on the thermal performance (COP) of sixteen three-stage cascaded systems is presented in Tables 5(a) to 5(e). The analysis revealed that increasing the MTC evaporator temperature enhances the energy performance of the cascaded system, reaching an optimal value at a specific MTC evaporator temperature before declining. This indicates that there is an ideal MTC evaporator temperature at which the system achieves maximum energy efficiency. Once this threshold is exceeded, the performance begins to drop due to the thermodynamic limitations of the system.

Similarly, the optimal MTC evaporator temperature for maximum exergy efficiency is detailed in Tables 6(a) to 6(f) for the different cascaded VCR systems. The results show that both energy and exergy performance follow a similar trend, where performance increases with rising MTC evaporator temperature until it reaches an optimum point, after which it starts to decrease.

Table 5(a): Optimum thermal performances of three staged cascaded VCR systems using HCFO-1224yd(Z) in HTC, HCFO-1233zd(E) and HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-68^{o}C and -70^{o}C	-73^{o}C and -74^{o}C	-65^{o}C and-66^{o}C	-72^{o}C and -73^{o}C
HTC Refrigerant	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP$_{\_Cascade\_three\ staged}$	0.4554	0.4428	0.4492	0.4373

Table 5(b): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum MTC temperature	-68^{o}C and -69^{o}C	-72^{o}C to-75^{o}C	-65^{o}C to -67^{o}C	-72^{o}C and-73^{o}C
HTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP$_{\_Cascade\_three\ staged}$	0.4522	0.4279	0.4531	0.4411

Table 5(c): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum MTC temperature	-68^{o}C and -69^{o}C	-73^{o}C to-75^{o}C	-65^{o}C to -67^{o}C	-72^{o}C and-73^{o}C
HTC Refrigerant	R1243zf	R1243zf	R1243zf	R1243zf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP$_{\_Cascade\_three\ staged}$	0.4410	0.4288	0.4352	0.4236

Table 5(d): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum MTC temperature	-67^{o}C to -69^{o}C	-69^{o}C	-65^{o}C to -67^{o}C	-72^{o}C and-73^{o}C
HTC Refrigerant	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP$_{\_Cascade\_three\ staged}$	0.4428	0.430	0.4368	0.4253

Table 5(e): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum MTC temperature	-68^{o}C & -69^{o}C	-73^{o}C and-74^{o}C	-64^{o}C to -67^{o}C	-72^{o}C and-73^{o}C
HTC Refrigerant	R1234yf	R1234yf	R1234yf	R1234yf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP$_{\_Cascade\_three\ staged}$	0.4292	0.4175	0.4234	0.4124

Table 6(a): Optimum thermal performances of three staged cascaded VCR systems using HCFO-1224yd(Z) in HTC, HCFO-1233zd(E) and HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50^{o}C, T$_{\_eva\_HTC}$=-10^{o}C, T$_{\_eva\_MTC}$=-70^{o}C, T$_{\_eva\_LTC}$=-130^{o}C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-68^{o}C to -69^{o}C	-72^{o}C to -75^{o}C	-65^{o}C and -66^{o}C	-71^{o}C to-73^{o}C
HTC Refrigerant	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{Cascade\_\ three\ staged}$	0.4927	0.4789	0.4859	0.4730

Table 6(b): Optimum first law (energy) performance(cascaded COP) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T_$_{eva\_HTC}$=50°C, T_$_{eva\_HTC}$=-10°C, T_$_{eva\_MTC}$=-70°C, T_$_{eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 "kW"

Optimum MTC temperature	-68°C and -69°C	-72°C to-75°C	-65°C to -67°C	-72°C and-73°C
HTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4891	0.4629	0.4902	0.4721

Table 6(c): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T_$_{eva\_HTC}$=50°C, T_$_{eva\_HTC}$=-10°C, T_$_{eva\_MTC}$=-70°C, T_$_{eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 "kW"

Optimum temperature	-67°C to -70°C	-72°C to -74°C	-65°C and -66°C	-71°C to-73°C
HTC Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R1233zd(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4891	0.4629	0.4902	0.4721

Table 6(d): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T_$_{eva\_HTC}$=50°C, T_$_{eva\_HTC}$=-10°C, T_$_{eva\_MTC}$=-70°C, T_$_{eva\_LTC}$=-130°C, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_$_{eva\_LTC}$=175 "kW"

Optimum temperature	-67°C to -69°C	-73°C to -74°C	-65°C and -67°C	-72°C to-73°C
HTC Refrigerant	R1243zf	R1243zf	R1243zf	R1243zf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4770	0.4636	0.4706	0.4582

Table 6(e): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T_$_{eva\_HTC}$=50°C, T_$_{eva\_HTC}$=-10°C, T_$_{eva\_MTC}$=-70°C, T_$_{eva\_LTC}$=-130°C, Temperature Overlapping$_{\_MTC}$= Temperature Overlapping_ =10, Q_$_{eva\_LTC}$=175 "kW"

Optimum temperature	-67°C and -68°C	-68°C	-65°C	-71°C
HTC Refrigerant	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.50	0.50	0.4905	0.4909

Table 6(f): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using HCFO-1233zd(E), HFOs (R1225ye(Z) & HFO1336mzz(Z)) in HTC, HFOs (R1225ye(Z) & R1336mzz(Z)) in MTC circuits and HFOs(R1225ye(Z) & R1336mzz(Z)) in LTC circuits for ultra-low temperature applications (for T_$_{eva\_HTC}$=50°C, T_$_{eva\_HTC}$=-10°C, T_$_{eva\_MTC}$=-70°C, T_$_{eva\_LTC}$=-130°C, Temperature Overlapping$_{\_MTC}$= Temperature Overlapping_ =10, Q_$_{eva\_LTC}$=175 "kW"

Optimum temperature	-68°C and -69°C	-73°C and-74°C	-64°C to -67°C	-72°C and-73°C
HTC Refrigerant	R1234yf	R1234yf	R1234yf	R1234yf
MTC Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4643	0.4516	0.4580	0.4461

3.7.4 *Effect of MTC evaporator temperature on optimum exergy performance of three staged cascaded VCR systems using low GWP ecofriendly HFO and HCFO refrigerants.*

The effect of MTC evaporator on thermal (energy and exergy performances) of sixteen three staged cascaded systems have been shown in Table 7(a) to Table 7(d) respectively. It was found that by increasing MTC evaporator temperature the energy performance of three staged cascaded system is increasing and reaching to a optimum value at a given optimum. MTC temperature and then decreasing. The optimum value of MTC evaporator temperature is shown in Table 8(a) to table -8(d) respectively for given different three staged cascaded VCR systems

Table 7(a): Optimum first law (energy performance in terms of COP$_{\_Cascade}$) second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, Ethane (R170) in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

	System-1	System-2	System-3
Optimum temperature	-71ºC to -72ºC	-71ºC to -73ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	Ethane	Ethane	Ethane
LTC Refrigerant	ethylene	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.3825	0.3885	0.3817

Table 7(b): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, R41 in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-74ºC to -75ºC	-74ºC to -75ºC	-65ºC and -66ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	R41	R41	R41
LTC Refrigerant	ethylene	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.3943	0.4006	0.3937

Table 7(c): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, Ethane (R170) in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-71ºC to -72ºC	-71ºC to -73ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	Ethane	Ethane	Ethane
LTC Refrigerant	ethylene	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.3825	0.3885	0.3817

Table 7(d): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, R41 in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-74ºC to -75ºC	-74ºC to -75ºC	-65ºC and -66ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	R41	R41	R41
LTC Refrigerant	ethylene	ethylene	ethylene
COP_$_{\text{Cascade\_three staged}}$	0.3943	0.4006	0.3937

Table 8(a): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, Ethane (R170) in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-67ºC to -70ºC	-72ºC to -73ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	Ethane	Ethane	Ethane
LTC Refrigerant	Ethylene	ethylene	ethylene
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4131	0.4203	0.4131

Table 8(b): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, R41 in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T$_{\_eva\_HTC}$=50ºC, T$_{\_eva\_HTC}$=-10ºC, T$_{\_eva\_MTC}$=-70ºC, T$_{\_eva\_LTC}$=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q$_{\_eva\_LTC}$=175 "kW"

Optimum temperature	-74ºC to -75ºC	-74ºC to -75ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	R41	R41	R41
LTC Refrigerant	ethylene	ethylene	ethylene
ExergyEfficiency$_{\text{Cascade\_ three staged}}$	0.4265	0.4333	0.4259

Table 8(c): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, Ethane (R170) in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T_{eva_HTC}=50ºC, T_{eva_HTC}=-10ºC, T_{eva_MTC}=-70ºC, T_{eva_LTC}=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_{eva_LTC}=175 "kW"

Optimum temperature	-67ºC to -70ºC	-72ºC to -73ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	Ethane	Ethane	Ethane
LTC Refrigerant	Ethylene	ethylene	ethylene
$\text{ExergyEfficiency}_{\text{Cascade\_ three staged}}$	0.4131	0.4203	0.4131

Table 8(d): Optimum second law (exergy) performance (exergetic efficiency) of three staged cascaded VCR systems using hydro-carbons (Propylene (R1270), R 600a, R290) in HTC, R41 in MTC circuits and ethylene in LTC circuits for ultra-low temperature applications (for T_{eva_HTC}=50ºC, T_{eva_HTC}=-10ºC, T_{eva_MTC}=-70ºC, T_{eva_LTC}=-130ºC, Temperature Overlapping_MTC= Temperature Overlapping_LTC=10, Q_{eva_LTC}=175 "kW"

Optimum temperature	-74ºC to -75ºC	-74ºC to -75ºC	-71ºC to-73ºC
HTC Refrigerant	Propylene	R600a	R 290
MTC Refrigerant	R41	R41	R41
LTC Refrigerant	ethylene	ethylene	ethylene
$\text{Exergy Efficiency}_{\text{Cascade\_ three staged}}$	0.4265	0.4333	0.4259

4. Conclusions

Following conclusions were drawn from present paper.

- The validation computed results obtained from developed thermal model with conventional three staged cascaded VCR system are in matching well with the values of conventional three staged conventional system using CFC refrigerants.
- Maximum thermodynamic performances of ten three staged cascaded vapour compression refrigeration systems have been compared with the conventional refrigeration using CFC refrigerants and it was found that the performance of system-1 using HCFO-1233zd(E) in high temperature cycle, HFO-1336mzz(Z), HFO-1225ye(Z) in medium temperature cycle and HFO-1336mzz(Z), HFO-1225ye(Z) in low temperature cycle is superior than conventional three staged cascaded VCR system using CFC refrigerants.
- Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration systems using HFO-1243zf, HFO-1234ze(E) and HFO-1234yf in high temperature (HT) (MT)cycle HFO-1336mzz(Z), HFO-1225ye(Z) in medium temperature cycle and HFO-1336mzz(Z), HFO-1225ye(Z) in low temperature (LT) cycle HFO-1336mzz(Z), HFO-1225ye(Z) in medium temperature cycle and HFO-1336mzz(Z), HFO-1225ye(Z) in low temperature cycle have given slightly less thermal performances with the conventional refrigeration using CFC refrigerants. It clearly shows that The use of ultra-low GWP ecofriendly HCFO and HFO refrigerants can suitably be used for replacing high GWP and High ODP CFC refrigerants.
- Maximum thermal (energy-exergy) performance sof three staged cascaded VCR using HCFO-1233zd(E) in HT cycle, HFO-1225ye(Z), HFO-1336mzz(Z) in MT cycle and HFO-1225ye(Z), HFO-1336mzz(Z) in LT cycle gives higher thermal (energy-exergy) performances than other three staged cascaded VCR system However, system-8 gives slightly less thermal performances as compared with system-4. However, system-5 gives lowest thermal performances. It clearly shows that ultra-low GWP ecofriendly HFO-1225ye(Z) in LTC circuit and HFO-1336mzz(Z) in MTC circuit gives better thermal energy-exergy performances than using HFO-1336mzz(Z) in LTC circuit and HFO-1225ye(Z) in MTC for ultra-low temperature applications.
- Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration systems using hydrocarbons at three different LTC evaporator temperatures (-160ºC, -155ºC & -150ºC, have been compared using hydrocarbon refrigerants and it was found that the performance of three staged cascaded VCR system is increasing as LTC evaporator temperature is increasing.
- Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration systems using hydrocarbon (HC-600a) used in HTC circuit gives highest thermodynamic performances than using HC-1270(propylene) and HC-290 used in HTC circuit. However, R-290 in HTC cycle gives lowest thermodynamic (energy-exergy) performances. Similarly, actual thermodynamic performances of three staged cascaded VCR system using R-170 (ethane) in MTC cycle at -80ºC of MTC evaporator temperature have been compared with R41 used in MTC circuit and it was found that the R41 in MTC circuit gives better thermal energy-exergy performances than using R170 (ethane) in MTC for ultra-low temperature applications
- By increasing HTC evaporator temperature, the energy and exergy performance of three staged cascaded system

is increasing and reaching to a optimum value at a given optimum. HTC temperature and then decreasing. The optimum value of HTC evaporator temperature. The same trends were observed for finding optimum HTC temperature for optimal exergy efficiency of cascaded VCR systems

- Actual thermodynamic performances of three staged cascaded vapour compression refrigeration systems at LTC evaporator temperatures (-130ºC) have been compared using hydrocarbon refrigerants and it was found that the performance of system is increasing as LTC evaporator temperature is increasing.
- By increasing MTC evaporator temperature the energy performance of three staged cascaded system is increasing and reaching to a optimum value at a given optimum. MTC temperature and then decreasing. The optimum value of MTC evaporator temperature.

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***Cite this article as*:** Radhey Shyam Mishra, thermodynamic performances of three staged cascaded VCR systems using ecofriendly ultra-low GWP refrigerants, International Journal of Research in Engineering and Innovation Vol-8, Issue-5 (2024), 171-191. *https://doi.org/10.36037/IJREI.2024.8502*