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Thermal performance optimization of three staged cascaded VCR systems using blends HFO refrigerant pairs

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Abstract

Several alternatives are available in the literature for using HFC and HCFC refrigerants which for causing higher global warming potential without ozone depletion for replacing CFC refrigerants of high GWP with ozone depletion. In this paper, thermodynamic (energy-exergy) performances of three staged cascaded VCR system for the ultra-low temperature applications using ecofriendly low global warming potential HFO blended refrigerants in higher temperature cycle in the temperature range of 50°C to 0°C and using blends of HFO blended refrigerants in medium temperature cycle of 10°C to -50°C and also using HFO blended refrigerants in low temperature cycle of -50°C to -90°C have been investigated. The numerical computation has been carried out using HFO blended refrigerants used in three staged cascaded VCRS & it was found that three staged cascaded VCR systems using HFO blends gives reasonable thermal performances for replacing HFC-134a & HFC-404a.

1. Introduction

The refrigeration process absorbs heat at low temperatures to provide a temperature lower than the ambient temperature while rejecting heat to the environment at higher degrees. In numerous settings, including major hotels, food storage facilities, and food processing factories, food is kept in a variety of compartments and at a variety of temperatures. A compressor, an expansion valve, a condenser, and an evaporator are the four main parts of a straightforward VCR. Therefore, it is necessary to enhance the thermal performances of VCRS (i.e. vapor compression refrigeration system). according to analytical research by Nikolaidis et al., [1] found the changes in the evaporator and condenser temperatures have a considerable impact on the irreversibility of a two stage R22 VCR system and concluded that the working conditions for the condenser and evaporator should be optimized. The issue of systems using VCR technology consuming a lot of electricity can be handled by enhancing the thermodynamic capacities of the system. Thermal performance of VCR systems based on vapour compression refrigeration technology can be improved. The refrigeration effect to net work input, termed as coefficient of performance (COP) is used to calculate the energy efficiency of the VCR system. The COP of a vapour compression refrigeration system can be higher by either increasing refrigeration effect or decreasing work input in terms of exergy of fuel input. As a result of variations in the evaporator and condenser temperatures. They claimed that the working conditions for the condenser and evaporator should be optimized. Taking into account both having higher and lower evaporator temperatures, the exergy of the product is an output, and the exergy of fuel is determined in terms of minimum electrical energy consumption for operating compressors. The throttling procedure in a VCR system is a known expansion process lot of exergy destruction. Refrigerant flashing to vapour in the evaporator is one of the main sources of exergy

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loss in cycle performance, which not only reduces cooling capacity but also increases the size of the evaporator.

By adopting a multi-stage expansion with a flash chamber, where the flash vapours are eliminated after each step of expansion, the cooling capacity be increased and evaporator size be decreased, this problem can be resolved. By compound or multi-stage compression processes which can be used in place of single-stage compression to reduce work input.

The refrigerant being passed through can also improve the cooling effect argued that the operational circumstances of the condenser and evaporator. The refrigerant being passed through can also improve the cooling effect argued that the working conditions for the condenser and evaporator should be optimized. Since cascade VCR is a method that combined two or more VCR cycles. The refrigerant being passed through can also improve the cooling effect. Environmentalists have expressed concern in recent years about some different problems that threaten the earth planet. The issue is being augmented by a number of factors, including ozone layer depletion (ODP) and global warming (GWP). Several studies have demonstrated the importance of using environmentally friendly operating fluids in current systems [1]. Using a carbon dioxide-propane (R744-R290) optimum cascade evaporating system, Bhattacharyya et al. [2] determined thermal energy performance (COP) by changing evaporation temperature of R744 in low temperature circuits. Bolaji et al.'s [3] experimental comparison of HFC-R32, HFC-152a, and HFC-R134a refrigerants in a vapour compression refrigerator found that R32 had the lowest thermal performance when compared to HFC-134a. Bhattacharyya et al. [3] evaluated the thermal performance of a cascade refrigeration-heat pump system using a model with internal and exterior irreversibility. systems for cooling. Cascading vapour compression refrigeration (v) is a method that mixes two or more vapour compression refrigeration cycles. In the VCR cycle, Yumrutas et al. [4] investigated the effects of condensing and evaporating temperature on the effectiveness of the system, pressure losses, and exergy losses. The energy losses of the compressor and expansion valve are also only little affected by changes in condenser temperature, and first law efficiency and energy efficiency increase as evaporator and condenser temperatures rise. H.M. Getu and Bansal P.K. [5,] regression analysis was used to optimized the design and operating parameters for the carbon dioxide-ammonia (R744-R717) cascade refrigeration system, including condensing temperature, subcooling temperature, evaporating temperature, superheating temperature, and temperature difference in a cascaded heat exchanger. The usage of various refrigerants causes significant environmental degradation, which decreases human living standards, causes ozone depletion, and contributes to global warming. Finding low-GWP, zero ODP, and ecologically friendly refrigerants is therefore essential. Mishra [6–10] evaluated the energy-exergy efficiencies (performances of the first and second laws of thermodynamics) of cascade vapour compression refrigeration systems employing novel HFO environmentally friendly refrigerants. an endeavour to reduce ozone loss and global warming.

The first and second law performances of the cascaded vapour compression refrigeration system with R1234ze(Z) in the higher temperature cycle and R1233zd(E) in the low-temperature cycle give the best thermodynamic performances, according to the various combinations of using six different eco-friendly refrigerants in the high-temperature cycle in the temperature range of from 50°C to 0°C for which other five eco-friendly low GWP refrigerants in the medium temperature range of fro Additionally, R1234yf performed the worst in high or low temperature cycles up to a temperature range of -50°C when compared to other HFO refrigerants. It was found that using HFO-1234yf in a low-temperature cycle led to 3.25% lower first and second law efficiencies than using HFC-134a, and that using R1234ze(Z) in a high-temperature cycle led to a 5% reduction in the exergy destruction ratio. The two fuels were compared in a low-temperature cycle up to a temperature of -50°C.

Mishra [10] performed an exergy analysis on four-stage cascade refrigeration systems that use environmentally friendly refrigerants for low-temperature applications [11,12]. and optimized the effects of performance parameters on the system's total COP & exergy efficiency, exergy destruction ratio (EDR), The system performances are affected by temperature overlapping (approaches), condenser temperature, and evaporator temperature changes, among other performance characteristics. The thermodynamic performances of refrigeration systems are assessed by using 3E (i.e., energy, exergy, and environmental) analysis, but and HFC-152a display roughly the greater thermal performances. cryogenics operates at low temperatures between -80°C and -100°C and has been employed in the chemical, petroleum, and pharmaceutical industries. Additionally, the importance of three-stage cascaded VCR systems is highlighted by the daily increase in the need for refrigeration in applications requiring extremely low evaporation temperatures. Cascading VCRS, high temperature circuits employ R1234yf and R1234ze, whilst medium temperature circuits mostly use ethane and thirteen other environmentally benign refrigerants [12].

In low temperature applications (between -80°C and -88°C), it was found. R1234ze-R134a-R410a-ethane was shown to be the best combination because it offers better thermal performance than R1234yf-R134a-R410a-ethane [13].

Many studies have suggested a few hydrofluorocarbons and hydrocarbon-based refrigerants as alternatives due to their low GWP and lack of ODP. Pure hydrocarbon refrigerants offer an intriguing alternative to the other two. The primary disadvantage of hydrocarbon refrigerants is their propensity to ignite. However, present protocols permit the use of flammable refrigerants with additional safety measures, therefore this issue can be avoided by utilizing safety measures in basic and cascaded VCRS. Earlier, the use of flammable refrigerants was prohibited. Despite the flammability concern, hydrocarbon-based refrigerants have a number of advantages over chlorofluorocarbon-based refrigerants. The main disadvantage of engaging hydrocarbon refrigerants is their tendency to catch fire, according to an analysis of eight cascaded vapour compression refrigeration systems using HFO+HFC blends in

HTC and LTC cycles used by author [12-13]. R.S. Mishra's [14-16], found in two staged cascade VCR systems, ecofriendly R454B in high temperature cycles and R513A in lower temperature cycles offer the best thermal performances and required the minimum amount of electricity to operate two compressors in the systems, while R454B in high temperature cycles and R454C in lower temperature cycles offer the lowest thermodynamic performances with large amount of electricity consumption. Sun [17] performed a thermodynamic (energy and exergy) analysis using hydrocarbon refrigerants to determine COP, total compressor work, exergy efficiency, total exergy destruction, mass flow rate and discharge temperatures of compressors, and component exergy destruction and recommended different hydrocarbon refrigerant types at various evaporator temperatures in the three staged cascade VCRS. Alptunganbaba et al. [18] conducted an exergy analysis of a two-evaporator, VCR system employing R1234yf, R1234ze, and R134a as refrigerants. A computer program was created using the software to calculate the effects of evaporator and condenser temperatures on the exergy destruction and exergy efficiency of the system using HFO1234yf and HFO1234ze, are two good substitutes for replacing R134a in terms of their environmentally friendly qualities This was done in addition to calculating the energy- exergy efficiency of the cascaded VCR cycle. Use of hydrocarbon refrigerant types is advised for replacing R134a. Alberto Dopazo and Jose Fernandez-Seara [19] developed a prototype of a cascade refrigeration system using NH3 and CO2 and conducted several experimental tests by cascading more than two VCR stages evaporating temperatures in order to supply a horizontal plate freezer with a 9 kW refrigeration capacity at an evaporating temperature of 50°C and discovered the impact of the operating parameters on the cascade system's performance. An alternate refrigerant that works well is a blend of carbon dioxide and methane, which can achieve a minimum temperature of -80° C. Simulation studies conducted by Nasruddin et al. [20], carbon dioxide and propane to replace R410a and R134a in cascaded VCRS

The feasibility of substituting R1224yd(Z), R1233zd(E), and R1336mzz(Z) for R245fa were discussed by Florian Kaufmann et. al, [21] & Mishra [22] conducted an energy-exergy analysis of three-stage cascaded vapour compression refrigeration systems using HFC-152a, HFC-245fa, and HFC-32 to replace R404a and R134a, which have a negative environmental impact due to their extremely high GWP.

The literature indicates that researchers have carefully examined the first law performance in terms of coefficient of performance and the second law performance in terms of exergy efficiency for the following systems:

(i) simple VCR system with single evaporator;
(ii) Simple VCR with liquid vapour heat exchanger, flash intercooler, flash chamber, water intercooler, liquid sub-cooler, and stages in compression (double stage, triple stage, and so on). (iii) Vapour compression refrigeration systems with numerous multi-stage expansion and compound compression evaporator systems. The use of nano mixed refrigerants in primary and secondary circuits for single-stage and multiple-stage vapour compression refrigeration systems.

The thermodynamic performances in terms of COP and exergetic efficiency when HFO blends are used in three-stage cascaded vapour compression refrigeration systems have not been thoroughly researched by many investigators. In this paper, the impact of HFO blended refrigerants on energy-exergy performances has been examined.

2. Results and Discussion

The following three staged cascaded refrigeration systems have been used

System-1: Cascaded VCR system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly, R515A low GWP refrigerant in medium temperature cycle and R513A low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=40°C, T_ambient=25°C, T_Eva_HTC=-25°C, T_Eva_MTC=- 60°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-2: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly and R513A medium temperature cycle and low GWP of R515A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=40°C, T_ambient=25°C, T_Eva_HTC=-25°C, T_Eva_MTC=- 60°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

Table-1(a) compare the ideal thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), by changing HFO blends in HT cycles at 273K evaporator temperatures, and using different HFO blends in medium temperature cycles at 223K evaporator temperatures, and using different HFO blends in LT cycles at the lowest evaporator temperatures (of 213K) and found that system-1 (uses R450A in HT cycle, R513A in MT cycles and R515A in MT cycles) gives highest COP (energy efficiency) and exergy efficiency with lower electrical energy consumption for running three compressors in whole cascade system.

Table-1(b) compare the actual thermal performances (COP) of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), by changing HFO blends in HT cycle at 273K evaporator temperatures, and using different HFO blends in MT cycle at 223K evaporator temperatures, and using different HFO blends in low temperature cycles at the lowest evaporator temperatures (of 213K) and found that system-2 (uses R450A in HT cycle, R515A in MT cycles and R513A in lower temperature cycles) gives highest COP (energy efficiency) and exergy efficiency with lower electrical energy consumption for running three compressors in whole cascade system.

Table-1(a) *Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on ideal thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=313K, T_HTC_eva=248K, T_MIT_eva=213K, T_LIT_eva=183K, Temperature_Overlapping_MTC =10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100%, compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW"),*

Performance Parameters of three staged Cascade systems	System--I	System-II
HTC Refrigerant	R450A	R450A
MTC Refrigerant	R513A	R515A
LTC Refrigerant	R515A	R513A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.8443	0.8403
Exergetic_Efficiency Cascaded_3 stage	0.5302	0.528
Power required to run whole system (Exergy of Fuel_Total "kW"	207.3	208.1
Exergy of product_Total "kW"	109.91	109.877
HTC Condenser Heat Rejected "kW"	382.3	383.1
HTC Evaporator cooling Load "kW"	275.0	275.6
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.348	1.348
Exergetic_Efficiency Cascaded_Two_Staged	0.5315	0.5376
Power required to run two staged Cascade system "kW"	162.8	163.2
Exergy of product of two staged Cascade system "kW"	86.5282	87.7363
MTC Condenser Heat Rejected"kW"	275.0	275.6
Evaporator cooling Load_MTC "kW"	219.5	220.0
HTC First law Efficiency (COP_HTC)	2.564	2.564
HTC Exergetic Efficiency	0.5166	0.5166
HTC compressor Work (Exergy of Fuel_HTC)	107.3	107.3
Exergy of product_HTC "kW"	55.431	55.431
LTC Condenser Heat Rejected "kW"	219.5	220.0
HTC Evaporator Heat cooling Load "kW"	175.0	175.0
MTC First law Efficiency (COP_MTC)	3.951	3.951
LTC First law Efficiency (COP_LTC)	3.937	3.893
Mass flow rate in high temperature cycle(Kg/sec)	2.42	2.425
Mass flow rate in intermediate (Medium) temperature cycle(Kg/sec)	1.425	1.403
Mass flow rate in low temperature cycle(Kg/sec)	0.9686	1.003
HTC compressor work "kW"	107.3	107.3
MTC compressor work "kW"	55.55	55.67
LTC compressor work "kW"	44.45	44.95

Table-2(a) compare the ideal thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), by changing HFO blends in HT cycles at 273K evaporator temperatures, and using different HFO blends in MT cycle at 223K evaporator temperatures, and using different HFO blends in LT cycles at the lowest evaporator temperatures (of 213K) and found that system-2 (uses R450A in HT cycle, R513A in MT cycles and R515A in lower temperature cycles) gives highest COP (energy efficiency) and exergy efficiency with lower electrical energy consumption for running three compressors in whole cascade system.

Table-1(b) *Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on ideal thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=313K, T_HTC_eva=248K, T_MIT_eva=213K, T_LIT_eva=183K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW"),*

Performance parameters of Cascade systems	System-I	System--II
HTC Refrigerant	R450A	R450A
MTC Refrigerant	R513A	R515A
LTC Refrigerant	R515A	R513A
Cascaded 3 staged First law Efficiency	0.6302	0.6329
Exergetic_Efficiency_Cascaded_3 Stage	0.3957	0.3974
Power required to run whole system (Exergy of Fuel_Total "kW"	277.7	276.5
Exergy of product_Total "kW"	109.90	109.90
Condenser Heat Rejected_HTC "kW"	452.7	451.5
HTC Evaporator cooling Load "kW"	304.3	303.5
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.044	1.044
Exergetic_Efficiency_Cascaded_2_Stage	0.4132	0.4162
Power required to run two staged Cascade system (Exergy of Fuel_Cascade_MTC_VCRS) "kW"	221.5	220.9
Exergy of product of two staged Cascade system (Exergy of product_Cascade_ MTC_VCRS "kW"	92.19	91.94
Condenser Heat Rejected_ MTC "kW"	304.3	303.5
Evaporator cooling Load_ MTC "kW"	231.2	230.6
HTC First law Efficiency (COP_HTC)	2.051	2.051
HTC Exergetic Efficiency	0.4133	0.4133
HTC compressor Work	148.4	148.0
Exergy of product_HTC "kW"	61.32	61.16
LTC Condenser Heat Rejected "kW"	231.2	230.6
HTC Evaporator Heat cooling Load	175.0	175.0
MTC First law Efficiency (COP_MTC)	3.161	3.160
LTC First law Efficiency (COP_LTC)	3.114	3.149
Mass flow rate in high temperature cycle(Kg/sec)	2.678	2.671
Mass flow rate in intermediate (Medium) temperature cycle(Kg/sec)	1.425	1.497

Mass flow rate in low temperature cycle	1.003	0.9686
HTC compressor work "kW"	148.4	148.4
MTC compressor work "kW"	73.14	72.95
LTC compressor work "kW"	56.19	55.57

Table2(a): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on actual thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW").

Performance Parameters of Cascade systems	System1 HFO Blends	System-2 HFO Blends
HTC Refrigerant	R450A	R450A
MTC Refrigerant	R515A	R513A
LTC Refrigerant	R513A	R515A
Cascaded Three staged First law Efficiency	0.675	0.6794
Exergetic_Efficiency_Cascaded_3_Stage	0.4547	0.4576
Power required to run whole system (Exergy of Fuel_Total "kW"	259.2	257.6
Exergy of product_Total "kW"	117.9	117.9
HTC Condenser Heat Rejected "kW"	434.2	432.6
HTC Evaporator cooling Load "kW"	312.6	311.4
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.109	1.111
Exergetic_Efficiency_Cascaded_2 Stage	0.4421	0.4431
Power required to run two staged Cascade system "kW"	205.9	204.9
Exergy of product of two staged Cascade system	91.05	90.79
MTC Condenser Heat Rejected "kW"	312.6	311.4
MTC Evaporator cooling Load "kW"	228.3	227.7
HTC First law Efficiency (COP_HTC)	2.570	2.570
HTC Exergetic Efficiency	0.3418	0.3418
HTC compressor Work	121.6	121.2
Exergy of product_HTC "kW"	41.58	41.42
LTC Condenser Heat Rejected"kW"	228.3	227.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.709	2.719
LTC First law Efficiency (COP_LTC)	3.282	3.322
Mass flow rate in high temperature cycle	3.079	3.067
Mass flow rate in intermediate (Medium) temperature cycle (Kg/sec)	1.662	1.683
Mass flow rate in low temperature cycle	1.024	0.9853
HTC compressor work "kW"	121.6	121.2
MTC compressor work "kW"	84.28	83.73
LTC compressor work "kW"	53.31	52.68

Table-2(b) compare the actual thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), by changing HFO blends in HT cycles at 273K evaporator temperatures, and using different HFO blends in MT cycles at 223K evaporator temperatures, and using different HFO blends in LT cycles at the lowest evaporator temperatures (of 213K) and found that system-2 (uses R450A in HT cycle, R513A in MT cycles and R515A in lower temperature cycles) gives highest COP (energy efficiency) and exergy efficiency with lower electrical energy consumption for running three compressors in whole cascade system.

Table2(b): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on actual thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC =10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC=80%, compressors isentropic efficiency_LTC= 80%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System1 HFO Blends	System-2 HFO Blends
HTC Refrigerant	R450A	R450A
MTC Refrigerant	R515A	R513A
LTC Refrigerant	R513A	R515A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.5001	0.5035
Exergetic_Efficiency_Cascaded_3_Stage	0.3369	0.3392
Power required to run whole system (Exergy of Fuel_Total "kW"	349.9	347.6
Exergy of product_Total "kW"	117.9	117.9
HTC Condenser Heat Rejected"kW"	524.9	522.6
HTC Evaporator cooling Load "kW"	353.1	351.6
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	0.8530	0.8549
Exergetic_Efficiency_Cascaded_2 Stage	0.3402	0.3409
Power required to run two staged Cascade system "kW"	283.3	281.7
Exergy of product of two staged Cascade system	96.36	96.04
MTC Condenser Heat Rejected"kW"	524.9	522.6
MTC Evaporator cooling Load "kW"	353.1	351.6
HTC First law Efficiency (COP_HTC)	2.056	2.056
HTC Exergetic Efficiency		
HTC compressor Work	171.8	171.0
Exergy of product_HTC "kW"	46.97	46.76
LTC Condenser Heat Rejected"kW"	353.1	351.6
LTC Evaporator Heat cooling Load "kW"	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.167	2.175
LTC First law Efficiency (COP_LTC)	2.626	2.658
Mass flow rate in high temperature cycle (Kg/sec)	3.478	3.463
Mass flow rate in intermediate (Medium) temperature cycle (Kg/sec)	1.759	1.781
Mass flow rate in low temperature cycle(Kg/sec)	1.024	0.9853
HTC compressor work "kW"	171.8	171.0
MTC compressor work "kW"	111.5	110.7
LTC compressor work "kW"	66.64	65.84

2.1 Detailed Thermal performance of cascaded VCRS

Following three staged cascaded VCR systems have been considered for evaluating thermal energy-exergy performances.

System-1: Cascaded VCR system using ecofriendly low GWP R454B refrigerant in higher temperature cycle, ecofriendly, R513A low GWP refrigerant in medium temperature cycle and low GWP refrigerant R515A in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC=0°C, T_Eva_MTC=- 50°C, T_Eva_LTC= -90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-2: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R454B refrigerants in higher temperature cycle using ecofriendly and R515A medium temperature cycle and low GWP of R513A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC=- 50°C T_Eva_LTC=-90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-3: Cascaded VCR system using ecofriendly low GWP R513A refrigerant in higher temperature cycle, ecofriendly, low GWP R454B refrigerant in medium temperature cycle and low GWP refrigerant R515A in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC=0°C, T_Eva_MTC=- 50°C T_Eva_LTC= -90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-4: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R515A refrigerants in higher temperature cycle using ecofriendly and R454B medium temperature cycle and low GWP of R513A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=-90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-5: Cascaded VCR system using ecofriendly low GWP R454B refrigerant in higher temperature cycle, ecofriendly, low GWP refrigerant R454B in medium temperature cycle and low GWP refrigerant R515A in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC=0°C, T_Eva_MTC=- 50°C T_Eva_LTC= -90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-6: Cascaded VCR system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly and R454B medium temperature cycle and low GWP of R515A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC=- 50°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-7: Cascaded VCR system using ecofriendly low GWP 450A refrigerant in higher temperature cycle, ecofriendly, low GWP R513A refrigerant in medium temperature cycle and low GWP refrigerant R454B in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC=0°C, T_Eva_MTC=- 50°C T_Eva_LTC= -90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-8: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R450A refrigerants in higher temperature cycle, ecofriendly R-515A and medium temperature cycle and low GWP of R454B in refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-9: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R515A refrigerants in higher temperature cycle using ecofriendly and R513A medium temperature cycle and low GWP of R454B in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=-90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-10: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R513A refrigerants in higher temperature cycle using ecofriendly and R515A medium temperature cycle and low GWP of R454B in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=-

90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-11: Cascaded thermodynamic performances of VCR using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly and R515A medium temperature cycle and low GWP of R513A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

System-12: Cascaded thermodynamic performances of VCR system using ecofriendly low GWP R450A refrigerants in higher temperature cycle using ecofriendly and R513A medium temperature cycle and low GWP of R515A in low GWP refrigerant in low temperature cycle (Q_Eva_LTC=175kW, T_cond=55°C, T_ambient=25°C, T_Eva_HTC= 0°C, T_Eva_MTC= -50°C T_Eva_LTC=- 90°C, MTC Temperature overlapping=10, LTC Temperature overlapping=10, Compressor efficiency_HTC=100%. Compressor efficiency_MTC=100%. Compressor efficiency_LTC=100%.

Tables 3(a) compare the ideal thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), using R450A in HT cycle at 273K evaporator temperatures, different HFO blends in MT cycle at 223K evaporator temperatures, and using different HFO blends in LT cycle at the lowest evaporator temperatures (of 213K)and found that system-2 (using R450A in HT cycle, R454B in MT cycle, and R513A in LT cycle) gives highest energy-exergy performances, while System-1 (using R-450A in HT cycle, R-454B in MT cycle, and R513A in LT cycle) was found to have the slightly lower thermal performance than using system-2. The lowest energy-exergy performances were observed in system-3 using R450A in HT cycle, R513A in MT cycle, and R454B in LT cycle

Table-3(b) compare the ideal thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR ystems at various condenser temperatures (of 328 K), using different in HT cycles at 273K of evaporator temperatures, different HFO blends in MT cycles at 213K evaporator temperatures, and using different HFO blends in LT cycles at the lower evaporator temperatures (of 213K) and found higher that system-7 (uses R450A in HT cycle, R515A in HT cycle and R513A in HT cycle) while slightly lower thermal performances have been observed in system-8 (uses R450A in HT cycle, R513A in HT cycle and R515A in LT cycle) than system-7 respectively.

Table-3(c) compared the ideal thermal performances of eco-friendly HFO refrigerant blends in three-stage VCR systems at various condenser temperatures (of 328 K), by changing HFO blends in HT cycle at 273K evaporator temperatures, and using different HFO blends in MT cycles at 223K evaporator temperatures, and using different HFO blends in LT cycles at the lowest evaporator temperatures (of 213K) and found that system-12 (uses R515A in HT cycle, R454B in HT cycles and R513A in HT cycles) gives highest COP (energy efficiency) and exergy efficiency with lower electrical energy consumption for running three compressors in whole cascade system.

Table3(a): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on ideal thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=273K, T_MIT_eva=223K, T_LIT_eva=183K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-1	System-2	System-3	System-4
HTC Refrigerant	R450A	R450A	R450A	R450A
MTC Refrigerant	R-454B	R-454B	R-513A	R515A
LTC Refrigerant	R515A	R-513A	R-454B	R-454B
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.7324	0.7357	0.7137	0.7168
Exergetic_Efficiency_Cascaded_Three_Staged	0.4599	0.4620	0.4481	0.4501
Power required to run whole system (Exergy of Fuel_Total "kW"	238.9	237.9	245.2	244.1
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	413.9	412.9	420.2	419.10
HTC Evaporator cooling Load "kW"	319.2	318.3	324.0	323.2
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.297	1.297	1.312	1.320
Exergetic_Efficiency_Cascaded_Two_Staged	0.4359	0.4359	0.4410	0.4435
Exergy of Fuel_Cascade_MTC_VCRS "kW"	180.2	179.7	181.7	180.7
Exergy of product_Cascade_ MTC_VCRS "kW"	78.56	78.35	80.14	80.14
MTC Condenser Heat Rejected"kW"	319.2	318.3	324.0	323.2
MTC Evaporator cooling Load "kW"	233.7	233.1	238.4	238.4
HTC First law Efficiency (COP_HTC)	3.368	3.368	3.368	3.368
HTC Exergetic Efficiency	0.3083	0.3083	0.3083	0.3083
HTC compressor Work (Exergy of Fuel_HTC)	94.76	94.52	96.2	95.95
Exergy of product_HTC "kW"	29.21	29.14	29.65	29.58

LTC Condenser Heat Rejected"kW"	233.7	233.1	238.4	238.4
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.736	2.736	2.787	2.814
LTC First law Efficiency (COP_LTC)	2.979	3.011	2.758	2.758
Mass flow rate in high temperature cycle(Kg/sec)	2.948	2.940	2.933	2.985
Mass flow rate in medium temperature cycle(Kg/sec)	1.043	1.040	1.828	1.837
Mass flow rate in low temperature cycle(Kg/sec)	1.077	1.037	0.6314	0.6314
HTC compressor work "kW"	94.76	94.52	96.2	95.95
MTC compressor work "kW"	85.44	85.22	85.55	84.73
LTC compressor work "kW"	58.73	58.13	63.45	63.45
Power required to run three staged Cascade system "kW"	238.9	237.9	245.2	244.1
Power required to run two staged Cascade system "kW"	180.2	179.7	181.7	180.7

Table3(b): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on ideal thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=273K, T_MIT_eva=223K, T_LIT_eva=183K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-5	System-6	System-7	System-8
HTC Refrigerant	R-515A	R513A	R450A	R450A
MTC Refrigerant	R513A	R-515A	R-515A	R513A
LTC Refrigerant	R-454B	R-454B	R513A	R-515A
Cascaded Three staged (COP_Cascade_System)	0.7226	0.7117	0.7454	0.7387
Exergetic_Efficiency_Cascaded_Three_Staged	0.4537	0.4469	0.4680	0.4639
Exergy of Fuel_Total "kW"	242.2	245.9	234.8	236.9
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	417.2	420.9	409.8	411.9
HTC Evaporator cooling Load "kW"	324.0	324.0	316.0	317.6
Cascaded Two Staged (COP_Cascade_MTC)	1.334	1.307	1.32	1.312
Exergetic_Efficiency_Cascaded_Two_Staged	0.4484	0.4393	0.4435	0.4410
Exergy of Fuel_Cascade_MTC_VCRS "kW"	178.7	182.4	176.7	178.2
Exergy of product of two staged Cascade system "kW"	80.14	84.73	78.35	78.56
MTC Condenser Heat Rejected"kW"	324.0	324.0	316.0	317.6
MTC Evaporator cooling Load "kW"	238.4	238.4	233.1	233.7
HTC First law Efficiency (COP_HTC)	3.477	3.308	3.368	3.368
HTC Exergetic Efficiency	0.3182	0.3029	0.3083	0.3083
HTC compressor Work (Exergy of Fuel_HTC)	93.19	97.7	93.81	94.29
Exergy of product_HTC "kW"	29.65	29.65	28.92	29.07
LTC Condenser Heat Rejected"kW"	238.4	238.4	233.1	233.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.814	2.814	2.787
LTC First law Efficiency (COP_LTC)	2.758	2.758	3.011	2.979
Mass flow rate in high temperature cycle(Kg/sec)	3.099	3.320	2.919	2.934
Mass flow rate in (Medium) temperature cycle(Kg/sec)	1.828	1.837	1.796	1.791
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.6314	1.037	1.077
HTC compressor work "kW"	93.19	97.7	93.81	94.29
MTC compressor work "kW"	85.55	84.73	82.84	83.86
LTC compressor work "kW"	63.45	63.45	58.13	58.73
Power required to run three staged Cascade system "kW"	242.2	245.9	234.8	236.9
Power required to run two staged Cascade system "kW"	178.7	182.4	176.7	178.2

Table3(c): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-9	System-10	System-11	System-12
HTC Refrigerant	R454B	R454B	R-513A	R515A
MTC Refrigerant	R-513A	R515A	R454B	R454B
LTC Refrigerant	R515A	R-513A	R-515A	R513A

Cascaded Three staged (COP_Cascade_System)	0.7219	0.7283	0.7272	0.7450
Exergetic_Efficiency_Cascaded_Three_Staged	0.4533	0.4573	0.4566	0.4678
Power required to run whole system (Exergy_Fuel_Total) "kW"	242.4	240.3	240.7	238.9
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	417.4	417.4	417.4	417.4
HTC Evaporator cooling Load "kW"	317.6	316.0	319.2	318.3
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.273	1.280	1.285	1.319
Exergetic_Efficiency_Cascaded_Two_Staged	0.4277	0.4302	0.4318	0.4432
Exergy of Fuel_Cascade_MTC_VCRS "kW"	183.7	182.2	181.9	176.8
Exergy of product_Cascade_ MTC_VCRS "kW"	78.56	78.35	78.56	78.35
MTC Condenser Heat Rejected"kW"	317.6	316.0	319.2	318.3
MTC Evaporator cooling Load "kW"	233.7	233.1	233.7	233.1
HTC First law Efficiency (COP_HTC)	3.182	3.182	3.308	3.477
HTC Exergetic Efficiency	0.2912	0.2912	0.3028	0.3182
HTC compressor Work (Exergy of Fuel_HTC)	99.82	99.31	96.49	91.56
Exergy of product_HTC "kW"	29.07	28.92	29.21	29.14
LTC Condenser Heat Rejected"kW"	233.7	233.1	233.7	233.1
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.814	2.736	2.736
LTC First law Efficiency (COP_LTC)	2.979	3.011	2.979	3.011
Mass flow rate in high temperature cycle(Kg/sec)	1.975	1.965	3.279	3.045
Mass flow rate in medium temperature cycle(Kg/sec)	1.791	1.796	1.043	1.040
Mass flow rate in low temperature cycle(Kg/sec)	1.077	1.037	1.077	1.037
HTC compressor work "kW"	99.82	99.31	96.49	91.56
MTC compressor work "kW"	83.86	82.84	85.44	85.22
LTC compressor work "kW"	58.73	58.13	58.73	58.13
Power required for three staged Cascade system "kW"	242.4	240.3	240.7	238.9
Power required for two staged Cascade system"kW"	183.7	182.2	181.9	176.8

2.2 Effect of HFO Blends in HT Cycle on thermal performances of Three staged VCRS

Tables 4(a) through 4(d) compare the ideal thermal performances of eco-friendly HFO refrigerant blends in three-staged VCR systems at various condenser temperatures (of 328 K), using R454B in HT cycles at 273K evaporator temperatures, HFO blends in MT cycles at 213K evaporator temperatures, and using HFO blends in MT cycles at the lowest evaporator temperatures (of 183K) and it was found that system-16 (using R452A in HT cycle and R513A in MT cycle and R454B in LT cycle) performed lowest thermal energy performance (COP) and exergy performance (Exergy efficiency with higher electrical energy consumption in running of whole system using three compressors) and system-15, which uses R450A, for HT cycles, R515A for MT cycles, and R513A for LT cycles, has the highest energy-exergy performances.

Table-4(a) shows, the effect of different high temperature eco-friendly HFO blended refrigerants at evaporator temperature of 273 K on the ideal thermal performances of three staged VCR systems at condenser (of 328 K) in HT and evaporator temperature (of) 273 K and HFO blends R-515A are used in the MT cycle at evaporator temperature (of 223K) and HFO blends R-513A are used in the LT cycle at evaporator temperature (of 223K) is shown in Table 4(a). and found that system-1, which operates at HT cycle with R450A, MT cycle at evaporator temperature with R-515A, and LT cycle at R-513A using HFO blends gives highest thermal energy-exergy performance and the lowest thermal energy-exergy performance was found by System-4, which uses R452A in the HT cycle, HFO blends R-515A in the MT cycle at evaporator temperature, and HFO blends R-513A in the LT cycle.

The effects of high-temperature environmentally friendly HFO blended refrigerants at an evaporator temperature of 263 K on the ideal thermal performances of three staged VCR systems at various condenser temperatures (of 328 K), using R450A in HT cycle at an evaporator temperature of 273 K, and using HFO blends R-513A in MT cycle and R515A in LT cycle lowest evaporator temperatures (of 178 K), are shown in Table-4(b). It was observed that system-7 (operates at HT cycle with R450A, MT cycle at evaporator temperature with R-513A, and low temperatures at R-515A using HFO blends) gives highest thermal energy-exergy performances. Similarly, the lowest energy-exergy performances are attained in system-12 when R449A is used in HT cycles, R513A in MT cycles, and 515A in LT cycle. Table 4(c) illustrates the impact of various high temperature environmentally friendly HFO blended refrigerants on the ideal thermal performances of three staged VCR systems at the condenser (of 328 K) and evaporator temperature of 273K and using R-515A in MT cycle at evaporator temperature of 223K and using HFO blends R454B in LT cycle lowest evaporator temperature (of 223 K). It was found that System-16 using R452A in HT cycle and

R513A in MT cycle and R454B in LT cycle performed lowest thermal energy-exergy performances. However, system-14 (using R450A in HT cycle and R515A in MT cycle and R454B in LT cycle) performed highest thermal energy-exergy performances. Table 4(d) illustrates the impact of various high temperature environmentally friendly HFO blended refrigerants on the ideal thermal performances of three staged VCR systems at the condenser (of 328 K) and evaporator temperature of 273K and using R-513A in MT cycle at evaporator temperature of 223K and using HFO blends R454B in LT cycle at lowest evaporator temperature (of 223 K). It was found that System-16 using R452A in HT cycle and R513A in MT cycle and R454B in LT cycle performed lowest thermal energy-exergy performances. However, system-14 (using R515A in HT cycle and R513A in MT cycle and R454B in LT cycle performed highest thermal energy-exergy performances

Table4(a): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerant	R450A	R-454B	R-454C	R452A	R-448A	R-448A
MTC Refrigerant	R515A	R515A	R515A	R515A	R515A	R515A
LTC Refrigerant	R513A	R513A	R513A	R513A	R513A	R513A
Cascaded Three staged COP_Cascade_System	0.7454	0.7178	0.7058	0.6743	0.6902	0.7283
Exergetic_Efficiency_Cascaded_Three_Staged	0.4680	0.4507	0.4432	0.4234	0.4334	0.4573
Exergy of Fuel_Total "kW"	234.8	243.8	247.2	259.5	253.6	240.3
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	409.8	418.8	422.9	434.5	428.6	415.3
HTC Evaporator cooling Load "kW"	316.0	316.0	316.0	316.0	316.0	316.0
Cascaded Two Staged COP_Cascade_MTC	1.320	1.256	1.228	1.157	1.193	1.28
Exergetic_Efficiency_Cascaded_Two_Staged	0.4435	0.4220	0.4128	0.3890	0.4009	0.4302
Exergy of Fuel_Cascade_MTC_VCRS "kW"	176.7	185.7	189.8	201.4	195.4	182.2
Exergy of product_Cascade_ MTC_VCRS "kW"	78.35	78.35	78.35	78.35	78.35	78.35
MTC Condenser Heat Rejected"kW"	316.0	316.0	316.0	316.0	316.0	316.0
MTC Evaporator cooling Load "kW"	233.1	233.1	233.1	233.1	233.1	233.1
HTC First law Efficiency (COP_HTC)	3.368	3.073	2.954	2.665	2.807	3.182
HTC Exergetic Efficiency	0.3083	0.2812	0.2704	0.2439	0.2569	0.2912
HTC compressor Work (Exergy of Fuel_HTC)	93.81	102.8	107.0	118.6	112.6	99.31
Exergy of product_HTC "kW"	78.35	78.35	78.35	78.35	78.35	78.35
LTC Condenser Heat Rejected"kW"	233.1	233.1	233.1	233.1	233.1	233.1
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.814	2.814	2.814	2.814	2.814	2.814
LTC First law Efficiency (COP_LTC)	3.011	3.011	3.011	3.011	3.011	3.011
Mass flow rate in high temperature cycle(Kg/sec)	2.919	2.614	2.798	4.074	2.790	1.965
Mass flow rate in medium temperature cycle(Kg/sec)	1.796	1.796	1.796	1.796	1.796	1.796
Mass flow rate in low temperature cycle(Kg/sec)	1.037	1.037	1.037	1.037	1.037	1.037
HTC compressor work "kW"	93.81	102.8	107.0	118.6	112.6	99.31
MTC compressor work "kW"	82.84	82.84	82.84	82.84	82.84	82.84
LTC compressor work "kW"	58.13	58.13	58.13	58.13	58.13	58.13
Power required for three staged Cascade system "kW"	234.8	243.8	247.2	259.5	253.6	240.3
Power required to run two staged Cascade system"kW"	176.7	185.7	189.8	201.4	195.4	182.2

Table4(b): Effect of eco-friendly HFO blends refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressor's isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-7	System-8	System-9	System-10	System-11	System-12
HTC Refrigerant	R450A	R-454B	R-454C	R452A	R-448A	R-449A
MTC Refrigerant	R513A	R513A	R513A	R513A	R513A	R513A
LTC Refrigerant	R515A	R515A	R515A	R515A	R515A	R515A
Cascaded First law Efficiency (COP_Cascade_System)	0.7387	0.7219	0.6842	0.7115	0.6997	0.6685
Exergetic_Efficiency_Cascaded_Three_Staged	0.4639	0.4533	0.4296	0.4467	0.4396	0.4198
(Exergy of Fuel_Total "kW"	236.9	242.4	255.8	259.5	253.6	240.3
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	411.9	417.4	430.8	421.0	425.1	436.8

HTC Evaporator cooling Load "kW"	317.6	317.6	317.6	317.6	317.6	317.6
Cascaded Two Staged (COP_Cascade_MTC)	1.320	1.273	1.186	1.248	1.221	1.151
Exergetic_Efficiency_Cascaded_Two_Staged	0.4410	0.4277	0.3987	0.4196	0.4105	0.3869
Exergy of Fuel_Cascade_MTC_VCRS "kW"	178.2	183.7	197.0	187.2	191.4	203.0
Exergy of product of two staged Cascade system	78.56	78.56	78.56	78.56	78.56	78.56
MTC Condenser Heat Rejected"kW"	317.6	317.6	317.6	317.6	317.6	317.6
MTC Evaporator cooling Load "kW"	233.7	317.6	317.6	317.6	317.6	317.6
HTC First law Efficiency (COP_HTC)	3.368	3.187	2.807	3.073	2.954	2.665
HTC Exergetic Efficiency	0.3083	0.2912	0.2569	0.2812	0.2704	0.2439
HTC compressor Work (Exergy of Fuel_HTC)	94.29	99.82	113.2	103.4	107.5	119.2
Exergy of product_HTC "kW"	29.07	29.07	29.07	29.07	29.07	29.07
LTC Condenser Heat Rejected"kW"	233.7	233.7	233.7	233.7	233.7	233.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.787	2.787	2.787	2.787	2.787
LTC First law Efficiency (COP_LTC)	2.979	2.979	2.979	2.979	2.979	2.979
Mass flow rate in high temperature cycle(Kg/sec)	2.934	1.975	2.986	2.627	2.813	4.095
Mass flow rate in (Medium) temperature cycle(Kg/sec)	1.791	1.791	1.791	1.791	1.791	1.791
Mass flow rate in low temperature cycle(Kg/sec)	1.077	1.077	1.077	1.077	1.077	1.077
HTC compressor work "kW"	94.29	99.82	113.2	103.4	107.5	119.2
MTC compressor work "kW"	82.86	82.86	82.86	82.86	82.86	82.86
LTC compressor work "kW"	58.73	58.73	58.73	58.73	58.73	58.73
Power required to run whole system"kW"	236.9	242.4	255.8	259.5	253.6	240.3
Power required to run two staged Cascade system "kW"	178.2	183.7	197.0	187.2	191.4	203.0

Table 4(c) : Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-13	System-14	System-15	System-16	System-17	System-18
HTC Refrigerant	R450A	R513A	R-454C	R452A	R-448A	R-449A
MTC Refrigerant	R515A	R515A	R515A	R515A	R515A	R515A
LTC Refrigerant	R454B	R454B	R454B	R454B	R454B	R454B
Cascaded Three staged First law Efficiency	0.7168	0.7117	0.6646	0.6495	0.6907	0.6794
Exergetic_Efficiency_Cascaded_Three_Staged	0.4501	0.4469	0.4173	0.4078	0.4337	0.4266
Exergy of Fuel_Total "kW"	244.1	245.9	263.3	269.5	253.4	257.6
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	420.8	420.9	438.3	444.5	428.4	432.6
HTC Evaporator cooling Load "kW"	323.2	323.2	323.2	323.2	323.2	323.2
Cascaded Two Staged COP_Cascade_MTC	1.32	1.307	1.193	1.157	1.256	1.228
Exergetic_Efficiency_Cascaded_Two_Staged	0.4435	0.4393	0.4009	0.3890	0.422	0.4128
Exergy of Fuel_Cascade_MTC_VCRS "kW"	180.7	182.4	199.9	206.0	189.9	194.1
Exergy of product of two staged Cascade system "kW"	78.56	78.56	78.56	78.56	78.56	78.56
MTC Condenser Heat Rejected"kW"	323.2	323.2	323.2	323.2	323.2	323.2
MTC Evaporator cooling Load "kW"	238.4	238.4	238.4	238.4	238.4	238.4
HTC First law Efficiency (COP_HTC)	3.368	3.308	3.308	3.308	3.308	3.308
HTC Exergetic Efficiency	0.3083	0.3028	0.2569	0.2439	0.2812	0.2704
HTC compressor Work (Exergy of Fuel_HTC)	95.95	97.7	115.2	121.3	105.2	109.4
Exergy of product_HTC "kW"	29.58	29.58	29.58	29.58	29.58	29.58
LTC Condenser Heat Rejected"kW"	238.4	238.4	238.4	238.4	238.4	238.4
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.814	2.814	2.814	2.814	2.814	2.814
LTC First law Efficiency (COP_LTC)	2.758	2.758	2.758	2.758	2.758	2.758
Mass flow rate in high temperature cycle(Kg/sec)	2.985	3.32	3.038	4.167	2.673	2.862
Mass flow rate in medium temperature cycle(Kg/sec)	1.837	1.837	1.837	1.837	1.837	1.837
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.6314	0.6314	0.6314	0.6314	0.6314
HTC compressor work "kW"	95.95	97.7	115.2	121.3	105.2	109.4
MTC compressor work "kW"	84.74	84.74	84.74	84.74	84.74	84.74
LTC compressor work "kW"	63.45	63.45	63.45	63.45	63.45	63.45

Power required for three staged cascade system "kW"	244.1	245.9	263.3	269.5	253.4	257.6
Power required for two staged cascade system "kW"	180.7	182.4	199.9	206.0	189.9	194.1

Table4(d): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-13	System-14	System-15	System-16	System-17	System-18
HTC Refrigerant	R450A	R515A	R-454C	R452A	R-448A	R-448A
MTC Refrigerant	R513A	R513A	R513A	R513A	R513A	R513A
LTC Refrigerant	R-454B	R-454B	R-454B	R-454B	R-454B	R-454B
Cascaded Three staged (COP_Cascade_System)	0.7137	0.7226	0.6618	0.6468	0.6878	0.6765
Exergetic_Efficiency_Cascaded_Three_Staged	0.4481	0.4537	0.4155	0.4061	0.4318	0.4248
Exergy of Fuel_Total "kW"	245.26	243.23	264.50	270.623	254.516	258.71
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	420.2	417.2	439.4	445.6	425.4	433.7
HTC Evaporator cooling Load "kW"	324.0	324.0	324.0	324.0	324.0	324.0
Cascaded Two Staged COP_Cascade_MTC	1.3120	1.334	1.186	1.151	1.248	1.221
Exergetic_Efficiency_Cascaded_Two_Staged	0.4410	0.4484	0.3987	0.3869	0.4196	0.4105
Exergy of Fuel_Cascade_MTC_VCRS "kW"	181.723	178.72	201.0	207.134	190.99	195.225
Exergy of product_Cascade_ MTC_VCRS "kW"	80.14	80.14	80.14	80.14	80.14	80.14
MTC Condenser Heat Rejected"kW"	324.0	324.0	324.0	324.0	324.0	324.0
MTC Evaporator cooling Load "kW"	238.4	238.4	238.4	238.4	238.4	238.4
HTC First law Efficiency (COP_HTC)	3.368	3.477	2.807	2.665	3.073	2.954
HTC Exergetic Efficiency	0.3083	0.3182	0.2569	0.2439	0.2812	0.2704
HTC compressor Work (Exergy of Fuel_HTC)	96.2	93.19	115.4	121.6	105.5	109.7
Exergy of product_HTC "kW"	29.65	29.65	29.65	29.07	29.07	29.07
LTC Condenser Heat Rejected"kW"	238.4	238.4	238.4	233.7	233.7	233.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.787	2.787	2.787	2.787	2.787
LTC First law Efficiency (COP_LTC)	2.979	2.979	2.979	2.979	2.979	2.979
Mass flow rate in high temperature cycle(Kg/sec)	2.993	3.099	3.046	4.177	2.68	2.869
Mass flow rate in medium temperature cycle(Kg/s)	1.828	1.828	1.828	1.828	1.828	1.828
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.6314	0.6314	0.6314	0.6314	0.6314
HTC compressor work "kW"	96.2	93.19	115.4	121.6	105.5	109.7
MTC compressor work "kW"	85.55	85.55	85.55	85.55	85.55	85.55
LTC compressor work "kW"	63.45	63.45	63.45	63.45	63.45	63.45
Power required to run three staged system "kW"	245.26	243.23	264.50	270.623	254.516	258.71
Power required to run two staged cascade system "kW"	181.723	178.72	201.0	207.134	190.99	195.225

2.3 Effect of HFO Blends in MT Cycle on thermal performances of Three staged VCRS

The ideal thermal performances of three staged VCR systems at various condenser temperatures (of 328 K) using R450A in HT cycle at evaporator temperature of 273K and using various HFO blends in MT cycle at evaporator temperature of 223K, R-513A in LT cycle at lowest evaporator temperature (of 183 K) are shown in Tables 5(a) and R-513A in low temperature cycle lowest evaporator temperature (of 183 K) are shown in using 5(b), respectively. It was found that the effect of eco-friendly HFO blended refrigerants in MT cycle at evaporator temperature of -223K, the System 7 (uses R450A in HT cycles, R513A in MT cycles, and R515A in LT cycles has the highest energy-exergy performances, and system-1 (using R450A in HT cycles, R454B in MT cycles, and R513A in LT cycles gives slightly lower energy-exergy performance than system-1 and higher than system- 8 (uses R450A in HT cycles, R454B in MT cycles, and R515A in LT cycles. Similarly, the lowest ideal thermodynamic performances of three staged VCRS systems was found in system- 9 at various condenser temperatures (of 328 K) using R450A in HT cycle at evaporator temperature of 273K and using HFO blends R-454C in MT cycle at evaporator temperature of 223K and R515A in LT cycle at lower evaporator temperature (of 183 K).

2.4 Effect of HFO Blends in LT Cycle on thermal performances of Three staged VCRS.

Table 6(a) to Table-6(d) shows the effect of low-temperature environmentally friendly HFO blended refrigerants at an evaporator temperature of 183 K on the ideal thermal energy-exergy performances of three staged VCR systems at various condenser temperatures (of 328 K), using R513A in HT cycle (at an evaporator temperature of 273 K) and using HFO blends

R-515A in MT cycle at evaporator temperature (of 223 K), and changing HFO blended refrigerants in LT is used by system 1 to system-14 and found that system-10 gives optimum COP in MT cycle, and R513A LT cycle and more than system-13 which provides the lowest energy-exergy performances while using R450A in HT cycles, R454B in HT cycles, and R454C in LT cycles. Similarly, system-12 using which uses R450A in and exergy efficiency using R450A in HT cycle, R513A in MT cycle, and R513A LT cycle and system-11 gives slightly lower COP and exergy efficiency (using R450A in HT cycle, R-454B HT cycle and R454B in MT cycle and R515A in LT cycle) gives higher energy-exergy performances than system-4 (using R450A in HT cycle, R513A in MT cycle, and R454B in LT cycle.

Table5(a): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K, Temperature_ Overlapping_ MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-1	System-2	System-3	System-4	System-5	System-6
HTC Refrigerant	R450A	R450A	R450A	R450A	R450A	R450A
MTC Refrigerant	R-454B	R-454C	R515A	R452A	R-448A	R-449A
LTC Refrigerant	R513A	R513A	R513A	R513A	R513A	R513A
Cascaded Three staged COP_Cascade_System)	0.7357	0.6928	0.7454	0.6984	0.7062	0.7063
Exergetic_Efficiency_Cascaded_Three_Staged	0.4620	0.4350	0.4680	0.4385	0.4434	0.4435
Exergy of Fuel_Total "kW"	237.9	252.6	234.8	250.6	247.8	247.8
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	412.9	427.6	409.8	425.6	422.8	422.8
HTC Evaporator cooling Load "kW"	318.3	329.7	316.0	328.1	326.0	326.0
Cascaded Two Staged COP_Cascade_MTC	1.297	1.199	1.32	1.211	1.229	1.229
Exergetic_Efficiency Cascaded_Two_Staged	0.4359	0.4029	0.4435	0.4072	0.4131	0.4131
Exergy of Fuel_Cascade_MTC_VCRS "kW"	179.7	194.5	176.7	192.4	189.7	189.7
Exergy of product_Cascade_ MTC_VCRS "kW"	78.35	78.35	78.35	78.35	78.35	78.35
MTC Condenser Heat Rejected"kW"	318.3	329.7	316.0	328.1	326.0	326.0
MTC Evaporator cooling Load "kW"	233.1	233.1	233.1	233.1	233.1	233.1
HTC First law Efficiency (COP_HTC)	3.368	3.368	3.368	3.368	3.368	3.368
HTC Exergetic Efficiency	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083
HTC compressor Work (Exergy of Fuel_HTC)	94.52	97.89	93.81	97.42	96.79	96.79
Exergy of product_HTC "kW"	29.14	30.18	28.92	30.03	29.84	29.84
LTC Condenser Heat Rejected"kW"	233.1	233.1	233.1	233.1	233.1	233.1
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.736	2.414	2.814	2.454	2.51	2.51
LTC First law Efficiency (COP_LTC)	3.011	3.011	3.011	3.011	3.011	3.011
Mass flow rate in high temperature cycle(Kg/sec)	2.94	3.046	2.919	3.031	3.011	3.011
Mass flow rate in medium temperature cycle(Kg/s)	1.04	1.591	1.796	1.99	1.459	1.459
Mass flow rate in low temperature cycle(Kg/sec)	1.037	1.037	1.037	1.037	1.037	1.037
HTC compressor work "kW"	94.52	97.89	93.81	97.42	96.79	96.79
MTC compressor work "kW"	85.22	96.59	82.84	95.01	92.88	92.86
LTC compressor work "kW"	58.13	58.13	58.13	58.13	58.13	58.13
Power required to run whole system "kW"	237.9	252.6	234.8	250.6	247.8	247.8
Power required to run two staged Cascade system"kW"	179.7	194.5	176.7	192.4	189.7	189.7

Table5(b): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-7	System-8	System-9	System-10	System-11	System-12
HTC Refrigerant	R450A	R450A	R450A	R450A	R450A	R450A
MTC Refrigerant	R513A	R454B	R-454C	R452A	R-448A	R-449A
LTC Refrigerant	R515A	R515A	R515A	R515A	R515A	R515A
Cascaded Three staged COP_Cascade_System)	0.7387	0.7324	0.6897	0.6953	0.7031	0.7032
Exergetic_Efficiency_Cascaded_Three_Staged	0.4639	0.4599	0.4331	0.4366	0.4415	0.4415
Power required for whole system(Exergy of Fuel_Total "kW"	236.9	238.9	253.7	251.7	248.9	248.9
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	411.9	413.9	428.7	426.7	423.9	423.9
HTC Evaporator cooling Load "kW"	317.6	319.2	330.6	329.0	326.9	326.8

Cascaded Two Staged First law Efficiency	1.312	1.297	1.199	-	-	-
Exergetic_Efficiency_Cascaded_Two_Staged	0.4410	0.4359	0.4029	0.4072	0.4131	0.4131
Exergy of Fuel_Cascade_MTC_VCRS “kW”	178.2	180.2	195.0	192.9	190.2	190.1
Exergy of product_Cascade_ MTC_VCRS “kW”	78.56	78.56	78.56	78.56	78.56	78.56
MTC Condenser Heat Rejected“kW”	317.6	319.2	330.6	329.0	326.9	326.8
MTC Evaporator cooling Load “kW”	233.7	233.7	233.7	233.7	233.7	233.7
HTC First law Efficiency (COP_HTC)	3.368	3.368	3.368	3.368	3.368	3.368
HTC Exergetic Efficiency	0.3083	0.3083	0.3083	0.3083	0.3083	0.3083
HTC compressor Work (Exergy of Fuel_HTC)	94.29	94.76	98.15	97.68	97.05	97.04
Exergy of product_HTC “kW”	29.07	29.21	30.26	30.11	29.92	29.91
LTC Condenser Heat Rejected“kW”	233.7	233.7	233.7	233.7	233.7	233.7
LTC Evaporator Heat cooling Load “kW”	175.0	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.736	2.414	2.454	2.51	2.51
LTC First law Efficiency (COP_LTC)	3.368	3.378	3.378	3.378	3.378	3.378
Mass flow rate in high temperature cycle(Kg/sec)	2.934		3.053	3.039	3.09	3.019
Mass flow rate in (Medium) temperature cycle(Kg/sec)	1.791	1.043	1.595	1.955	1.463	1.434
Mass flow rate in low temperature cycle(Kg/sec)	1.077	1.077	1.077	1.077	1.077	1.077
HTC compressor work “kW”	94.29	94.76	98.15	97.68	97.05	97.04
MTC compressor work “kW”	83.86	85.44	96.84	95.26	93.13	93.10
LTC compressor work “kW”	58.73	58.73	58.73	58.73	58.73	58.73
Power required to run whole system “kW”	236.9	238.9	253.7	251.7	248.9	248.9
Power required to run two staged Cascade system“kW”	178.2	180.2	195.0	192.9	190.2	190.1

Table-6(a): Effect of eco-friendly HFO blended refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 “kW”)

Performance Parameters of Cascade systems	System-1	System-2	System-3
HTC Refrigerant	R513A	R513A	R513A
MTC Refrigerant	R515A	R515A	R515A
LTC Refrigerant	R-454B	R-454C	R449A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.7117	0.6785	0.6789
Exergetic_Efficiency_Cascaded_Three_Staged	0.4469	0.4260	0.4263
Power required to run whole system (Exergy of Fuel_Total) “kW”	245.9	257.9	257.8
Exergy of product_Total “kW”	109.9	109.9	109.9
HTC Condenser Heat Rejected“kW”	420.9	432.9	432.8
HTC Evaporator cooling Load “kW”	323.2	332.4	332.3
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.307	1.307	1.307
Exergetic_Efficiency_Cascaded_Two_Staged	0.4393	0.4393	0.4393
Exergy of Fuel_Cascade_MTC_VCRS “kW”	182.4	187.7	187.6
Exergy of product_Cascade_ MTC_VCRS “kW”	80.14	82.83	82.40
MTC Condenser Heat Rejected“kW”	323.2	332.4	332.3
MTC Evaporator cooling Load “kW”	238.4	245.3	245.2
HTC First law Efficiency (COP_HTC)	3.308	3.308	3.308
HTC Exergetic Efficiency	0.3028	0.3028	0.3028
HTC compressor Work (Exergy of Fuel_HTC)	97.7	100.5	100.5
Exergy of product_HTC “kW”	29.58	30.42	30.41
LTC Condenser Heat Rejected“kW”	238.4	245.3	245.2
LTC Evaporator Heat cooling Load “kW”	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.814	2.814	2.814
LTC First law Efficiency (COP_LTC)	2.758	2.491	2.494
Mass flow rate in high temperature cycle(Kg/sec)	3.320	3.415	3.414
Mass flow rate in intermediate (Medium) temperature cycle(Kg/sec)	1.837	1.889	1.888
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.9410	0.8763
HTC compressor work “kW”	97.7	100.5	100.5
MTC compressor work “kW”	84.73	87.16	87.13
LTC compressor work “kW”	63.45	70.27	70.18
Power required to run two staged Cascade VCR system	182.4	187.7	187.6

Table6(b): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-4	System-5	System-6
HTC Refrigerant	R515A	R515A	R515A
MTC Refrigerant	R513A	R513A	R513A
LTC Refrigerant	R-454B	R-454C	R-449A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.7226	0.6887	0.6891
Exergetic_Efficiency_Cascaded_Three_Staged	0.4537	0.4324	0.4327
Power required to run whole system (Exergy of Fuel_Total "kW"	242.3	254.1	254.0
Exergy of product_Total "kW"	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	417.2	429.1	429.1
HTC Evaporator cooling Load "kW"	324.0	333.3	333.1
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.334	1.334	1.334
Exergetic_Efficiency_Cascaded_Two_Staged_VCRS	0.4484	0.4484	0.4484
Exergy of Fuel_Cascade_MTC_VCRS "kW"	178.7	183.9	183.8
Exergy of product_Cascade_ MTC_VCRS "kW"	80.14	82.43	82.40
MTC Condenser Heat Rejected"kW"	324.0	333.3	333.1
MTC Evaporator cooling Load "kW"	238.4	245.3	245.2
HTC First law Efficiency (COP_HTC)	3.477	3.477	3.477
HTC Exergetic Efficiency	0.3182	0.3182	0.3182
HTC compressor Work (Exergy of Fuel_HTC)	93.19	95.86	95.82
Exergy of product_HTC "kW"	29.65	30.5	30.49
LTC Condenser Heat Rejected"kW"	238.4	245.3	245.2
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.787	2.787
LTC First law Efficiency (COP_LTC)	2.758	2.491	2.494
Mass flow rate in high temperature cycle(Kg/sec)	3.099	3.188	3.187
Mass flow rate in (medium temperature cycle(Kg/sec)	1.828	1.88	1.879
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.9410	0.8763
HTC compressor work "kW"	93.19	95.86	95.82
MTC compressor work "kW"	85.55	88.0	87.96
LTC compressor work "kW"	63.45	70.27	70.18
Power required to run three staged Cascade system"kW"	242.3	254.1	254.0
Power required to run two staged Cascade system"kW"	178.7	183.9	183.8

Table6(c): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-7	System-8	System-9	System-10
HTC Refrigerant	R450A	R450A	R450A	R450A
MTC Refrigerant	R513A	R513A	R513A	R513A
LTC Refrigerant	R-454B	R-454C	R-449A	R515A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.7137	0.6804	0.6808	0.7387
Exergetic_Efficiency_Cascaded_Three_Staged	0.4481	0.4272	0.4275	0.4639
Power required to run whole system (Exergy of Fuel_Total) "kW"	245.2	257.2	257.2	236.9
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	420.2	432.2	432.1	411.9
HTC Evaporator cooling Load "kW"	324.0	333.3	333.1	317.6
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.312	1.312	1.312	1.312
Exergetic_Efficiency_Cascaded_Two_Staged	0.4410	0.4410	0.4410	0.4410
Exergy of Fuel_Cascade_MTC_VCRS "kW"	181.7	186.9	186.9	178.2
Exergy of product of two staged Cascade system	80.14	82.43	82.40	78.56
MTC Condenser Heat Rejected"kW"	324.0	333.3	333.1	317.6
MTC Evaporator cooling Load "kW"	238.4	245.3	245.2	233.7
HTC First law Efficiency (COP_HTC)	3.308	3.308	3.308	3.308
HTC Exergetic Efficiency	0.3083	0.3083	0.3083	0.3083

HTC compressor Work (Exergy of Fuel_HTC)	96.2	98.95	98.91	94.29
Exergy of product_HTC "kW"	29.65	30.5	30.49	29.07
LTC Condenser Heat Rejected"kW"	238.4	245.3	245.2	233.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.787	2.787	2.787	2.787
LTC First law Efficiency (COP_LTC)	2.758	2.491	2.494	2.979
Mass flow rate in high temperature cycle(Kg/sec)	2.993	3.078	3.077	2.934
Mass flow rate in medium temperature cycle(Kg/sec)	1.828	1.880	1.879	1.791
Mass flow rate in low temperature cycle(Kg/sec)	0.6314	0.9410	0.8763	1.077
HTC compressor work "kW"	96.2	98.95	98.91	94.29
MTC compressor work "kW"	85.55	88.0	87.96	83.86
LTC compressor work "kW"	63.45	70.27	70.27	58.73
Power required to run three staged Cascaded system"kW"	245.2	257.2	257.2	236.9
Power required for two staged Cascaded_HTC-MTC system"kW"	181.7	186.9	186.9	178.2

Table 6(d): Effect of eco-friendly HFO blends, HFO & HCFO refrigerants and low GWP eco-friendly HFC refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-11	System-12	System-13	System-14
HTC Refrigerant	R450A	R450A	R450A	R450A
MTC Refrigerant	R-454B	R-454B	R-454B	R-454B
LTC Refrigerant	R-513A	R515A	R-454C	R-449A
Cascaded Three staged First law Efficiency (COP_Cascade_System)	0.7357	0.7324	0.6747	0.6751
Exergetic_Efficiency_Cascaded_Three_Staged	0.4620	0.4599	0.4237	0.4239
Power required to run whole system (Exergy of Fuel_Total "kW"	237.9	238.9	259.4	259.2
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	412.9	413.9	434.4	434.2
HTC Evaporator cooling Load "kW"	318.3	319.2	334.9	334.8
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.297	1.297	1.297	1.297
Exergetic_Efficiency_Cascaded_Two_Staged	0.4359	0.4359	0.4359	0.4359
Exergy of Fuel_Cascade_MTC_VCRS "kW"	179.7	180.2	189.1	189.0
Exergy of product_Cascade_ MTC_VCRS "kW"	78.35	78.56	82.43	82.40
MTC Condenser Heat Rejected"kW"	318.3	319.2	334.9	334.8
MTC Evaporator cooling Load "kW"	233.1	233.7	245.3	245.2
HTC First law Efficiency (COP_HTC)	3.368	3.368	3.368	3.368
HTC Exergetic Efficiency	0.3083	0.3083	0.3083	0.3083
HTC compressor Work (Exergy of Fuel_HTC)	94.52	94.76	99.44	99.40
Exergy of product_HTC "kW"	29.14	29.21	30.65	30.64
LTC Condenser Heat Rejected"kW"	233.1	233.7	245.3	245.2
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.736	2.736	2.736	2.736
LTC First law Efficiency (COP_LTC)	3.011	2.979	2.491	2.494
Mass flow rate in high temperature cycle(Kg/sec)	2.94	2.948	3.094	3.092
Mass flow rate in medium temperature cycle(Kg/sec)	1.04	1.043	1.095	1.094
Mass flow rate in low temperature cycle(Kg/sec)	1.037	1.077	0.941	0.8763
HTC compressor work "kW"	94.52	94.76	99.44	99.40
MTC compressor work "kW"	85.22	85.44	89.55	89.62
LTC compressor work "kW"	58.13	58.73	70.27	70.18
Power required to run three staged Cascade system	237.9	238.9	259.4	259.2
Power required to run two staged Cascade system"kW"	179.7	180.2	189.1	189.0

2.5 Comparison of actual thermal performances of blends of eco-friendly HFO refrigerants, in three staged VCRS systems

Table-7(a) to Table-7(b) show the comparison the actual thermal performances of blends of eco-friendly HFO refrigerants, in three staged VCR systems at different temperature of condenser (of 328 K) using R454B in *HT* cycle at evaporator temperature of 273K and HFO blends in *MT* cycle at evaporator temperature of 213K and using HFO blends in in *LT* cycle lowest evaporator temperature (of 183 K) and it was found that system-1 has somewhat highest energy-exergy performances with R450A in *HT* cycles,R-515A in the *MT* cycle and R513A in the *LT* cycle. The lowest energy-exergy performances are achieved by system-3, which uses R450A in *HT* cycles, R454B in *MT* cycles, and R454C in *LT* cycles. Similarly, system-8 uses R-454B in *HT* cycles R513A in *MT* cycle and R515A in *LT* cycle delivers slightly lower energy-exergy performances than system 1 and higher than using system-2 (using R450A *HT* cycles at condenser temperature of 55°C, R513A in *MT* cycle and R515A in *MT* cycle) and system-5 using R-450A in *HT* cycles R-454B in MT cycle and R515A in *LT* cycle.

Table7(a): Effect of eco-friendly HFO & HCFO refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=313K, T_HTC_eva=248K, T_MIT_eva=218K, T_LIT_eva=183K Temperature_Overlapping_MTC=10, Temperature_ Overlapping_LTC =10, compressors isentropic efficiency_HTC= 80%, compressors isentropic efficiency_MTC= 80%, compressors isentropic efficiency_LTC= 80%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-1	System-2	System-3	System-4	System-5
HTC Refrigerant	R450A	R450A	R450A	R450A	R450A
MTC Refrigerant	R-515A	R513A	R-454B	R513A	R-454B
LTC Refrigerant	R513A	R-515A	R-454c	R-454B	R515A
Cascaded Three staged (COP_Cascade_System)	0.5548	0.5497	0.5302	0.5326	0.5473
Exergetic_Efficiency_Cascaded_Three_Staged	0.3484	0.3451	0.3323	0.3344	0.3437
Power required to run whole system (Exergy of Fuel_Total "kW"	315.4	318.4	330.1	328.6	319.7
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	490.4	493.4	505.1	503.6	494.7
HTC Evaporator cooling Load "kW"	357.7	359.8	386.4	367.3	360.8
Cascaded Two Staged First law Efficiency (COP_Cascade_MTC)	1.020	1.014	1.040	1.020	1.002
Exergetic_Efficiency_Cascaded_Two_Staged	0.3229	0.3409	0.3409	0.3429	0.3369
Exergy of Fuel_Cascade_MTC_VCRS "kW"	242.7	245.0	250.8	249.3	247.1
Exergy of product_Cascade_ MTC_VCRS "kW"	83.24	83.49	85.47	85.47	83.24
MTC Condenser Heat Rejected"kW"	357.7	359.8	386.4	367.3	360.8
MTC Evaporator cooling Load "kW"	247.7	248.4	254.3	254.3	247.7
HTC First law Efficiency (COP_HTC)	2.694	2.694	2.694	2.694	2.694
HTC Exergetic Efficiency	0.2466	0.2466	0.2466	0.2466	0.2466
HTC compressor Work (Exergy of Fuel_HTC)	132.7	133.5	136.7	136.3	133.9
Exergy of product_HTC "kW"	32.74	32.93	33.71	33.61	33.02.
LTC Condenser Heat Rejected"kW"	247.7	248.4	254.3	254.3	247.7
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.251	2.23	2.23	2.251	2.189
LTC First law Efficiency (COP_LTC)	2.409	2.384	2.207	2.207	2.409
Mass flow rate in high temperature cycle(Kg/sec)	3.304	3.324	3.402	3.392	3.333
Mass flow rate in medium temperature cycle(Kg/sec)	1.907	1.904	1.949	1.959	1.105
Mass flow rate in low temperature cycle(Kg/sec)	1.037	1.077	0.6314	0.6314	1.037
HTC compressor work "kW"	132.7	133.5	136.7	136.3	133.9
MTC compressor work "kW"	110.0	111.4	114.1	113.0	113.2
LTC compressor work "kW"	72.66	73.42	79.31	79.31	72.66
Power required to run three staged Cascade system"kW"	315.4	318.4	330.1	328.6	319.7
Power required to run two staged Cascade system "kW"	242.7	245.0	250.8	249.3	247.1

Table-7(b): Effect of eco-friendly HFO blended refrigerants and low GWP eco-friendly HFO blended refrigerants on thermal energy-exergy performances of three staged VCR systems (T_HTC_Cond=328K, T_HTC_eva=263K, T_MIT_eva=213K, T_LIT_eva=178K Temperature_Overlapping_MTC=10, Temperature_Overlapping_LTC=10, compressors isentropic efficiency_HTC= 100% compressors isentropic efficiency_MTC= 100%, compressors isentropic efficiency_LTC= 100%, Load on LTC Evaporator (Q_LTC_EVA= 175 "kW")

Performance Parameters of Cascade systems	System-6	System-7	System-8	System-9	System--10
HTC Refrigerant	R450A	R-454B	R-454B	R513A	R-515A
MTC Refrigerant	R-454B	R515A	R513A	R-454B	R-454B
LTC Refrigerant	R-515A	R513A	R-515A	R-515A	R513A
Cascaded Three staged (COP_Cascade_System)	0.5447	0.5406	0.5546	0.5415	0.5365
Exergetic_Efficiency_Cascaded_Three_Staged	0.3420	0.3395	0.3482	0.340	0.3369
Exergy of Fuel_Total "kW"	321.2	323.7	315.5	323.2	326.2
Exergy of product_Total "kW"	109.9	109.9	109.9	109.9	109.9
HTC Condenser Heat Rejected"kW"	496.2	498.7	490.5	498.2	501.2
HTC Evaporator cooling Load "kW"	361.9	361.9	360.8	357.7	359.8
Cascaded Two Staged First law Efficiency	1.002	0.9926	1.02	0.9885	0.9828

Exergetic_Efficiency_Cascaded_Two_Staged	0.3369	0.3336	0.3427	0.3322	0.3303
Exergy of Fuel_Cascade_MTC_VCRS "kW"	247.8	250.3	242.9	250.5	252.8
Exergy of product_Cascade_ MTC_VCRS "kW"	83.49	83.49	83.24	83.24	83.49
MTC Condenser Heat Rejected"kW"	361.9	361.9	360.8	357.7	359.8
MTC Evaporator cooling Load "kW"	248.4	248.4	247.7	247.7	248.4
HTC First law Efficiency (COP_HTC)	2.694	2.646	2.781	2.545	2.545
HTC Exergetic Efficiency	0.2466	0.2422	0.2546	0.2230	0.2330
HTC compressor Work (Exergy of Fuel_HTC)	134.3	136.8	129.7	140.6	141.4
Exergy of product_HTC "kW"	33.13	33.13	33.02	32.74	32.93
LTC Condenser Heat Rejected"kW"	248.4	248.4	247.7	247.7	248.4
LTC Evaporator Heat cooling Load "kW"	175.0	175.0	175.0	175.0	175.0
MTC First law Efficiency (COP_MTC)	2.189	2.189	2.189	2.251	2.230
LTC First law Efficiency (COP_LTC)	2.384	2.384	2.409	2.409	2.384
Mass flow rate in high temperature cycle(Kg/sec)	3.343	3.718	3.451	2.224	2.238
Mass flow rate in medium temperature cycle(Kg/sec)	1.109	1.109	1.105	1.907	1.904
Mass flow rate in low temperature cycle(Kg/sec)	1.077	1.077	1.037	1.037	1.017
HTC compressor work "kW"	134.3	136.8	129.7	140.6	141.4
MTC compressor work "kW"	113.5	113.5	113.2	110.0	111.4
LTC compressor work "kW"	73.42	73.42	72.66	72.66	73.42
Power required to run whole system "kW"	321.2	323.7	315.5	323.2	326.2
Power required to run two staged Cascade system "kW"	247.8	250.3	242.9	250.5	252.8

3. Conclusions & Recommendations

Following analysis of the thermodynamic performances of the three-stage cascade VCR system using various HFO blended refrigerants and consideration of environmental effect concerns, the following conclusions were drawn:

(i) A three-stage cascade VCR system running on various HFO-blend refrigerants—R450A for high temperature cycles, R515A for medium temperatures, and R513A for low temperatures—gives the best energy efficiency (COP) and exergy efficiency when compared to systems running on R-454B for high temperature cycles, R513A for medium temperatures, and R515A for low temperatures cycle at -90°C. The lowest energy-exergy performances are provided by a three-stage cascade VCR system using R-450A in high temperature cycles, R513A in medium temperature cycles, and R454b in low temperature cycles.

(ii)Exergy-energy analysis has shown that using R450A in high temperature cycles, R513A in medium temperature cycles, and R515A in low temperature cycles results in the highest energy-exergy performances for the refrigerant couple in the low temperature cycle of a three-stage cascaded VCR system (COP_Cascade).

(iii) The three stage cascade VCR system provides the optimum thermal performance with zero ODP and a low GWP value. The highest energy-exergy performances are achieved utilizing R450A in *HT* cycles, R515A in *MT* cycles, and R513A in *LT* cycles at 183K evaporator temperature.

(iv)The three-stage cascaded vapour compression refrigeration system using R450A in the *HT* cycle, R513A in the *MT* cycle, and R515A in the *LT* cycle gives the best thermodynamic performance with zero ODP and a low GWP value.

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