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ORIGINAL ARTICLE

Thermodynamic (energy-exergy) analysis of three staged cascaded VCRS systems using HFO& HC refrigerants

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Abstract

With the increase in people aware of the global warming and ozone depleting effect, research on alternative refrigerants has gained more attention in current years. Many investigators have quoted the replacement of high GWP refrigerants & searching for the refrigerant alternative in LTC, MTC and HTC for cascaded refrigeration systems with ultra-low /zero ozone depletion potential (ODP) value and also an ultra-low global warming potential [GWP]. The thermodynamic performances of the three staged cascade vapour refrigeration systems operated by different refrigerant pairs have been computed using the energy-exergy concept. The use HFO refrigerants have been used in the ultra-low evaporator temperature cycle up to -150oC have been investigated. In this paper, zero ODP and low GWP value of HFO refrigerants have been used for three staged cascaded vapour compression refrigeration systems by considering different combinations using HFOs, and HCFOs to improve overall thermodynamic performances. It is found that HCFO-1233d(E), HFO-1336mzz(Z) and R1225ye(Z) give better results as compared with conventional three staged cascaded vapour compression refrigeration system using a low evaporator temperature of -90oC. The cascaded VCRS using R1233zd(E) in the high-temperature cycle & R1336mzz(Z) in the medium temperature cycle &R1225ye (Z) eco-friendly refrigerant in the low-temperature cycle gives the best thermodynamic performances up to (-150oC) low-temperature applications.

1. Introduction

In the present scenario, the energy, exergy, economy, environment and safety strategies are the most important issues being considered to assess the refrigeration cycles both having higher and lower evaporator temperatures. The low temperatures for cryogenics are around 90 °C, air conditioning around 0°C, industrial refrigeration is -35 to -50°C and its applications such as freeze drying, pharmaceuticals, chemical and petroleum industry use cascade refrigeration cycles. Also, the demand for refrigeration at ultralow evaporation temperature applications is increasing daily, ranging from high heat flux electronics to rapid freezing, frozen food and cold storage. A cascaded vapour compression refrigeration system combines two vapour compression refrigeration systems. Bansal P.K [1] carried out the thermodynamic analysis of the carbon dioxide–ammonia (R744–R717) cascade refrigeration system. Bhattacharyya et al. [2] studied the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibility. Lee et al. [3] studied a cascade refrigeration system thermodynamically using carbon dioxide and ammonia as

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refrigerants. The ozone depletion and global warming due to the use of various refrigerants are severe for environmental degradation, affecting living standards. Therefore, searching for and using new and low GWP and zero ODP eco-friendly refrigerants is essential. Thermodynamic first and second law performances (energy-exergy efficiencies) of cascade vapour compression refrigeration system using new HFO eco-friendly refrigerants for reducing global warming and ozone depletion performance parameters such as COP, exergetic efficiency and exergy destruction ratio and power required to run whole systems have been carried out by Mishra [4]. The various combinations of using six different eco-friendly refrigerants used in the high-temperature cycle in the temperature range of from 50oC to 0oC for which other five eco-friendly low GWP refrigerants in the medium temperature range of from 0oC to-50oC & found that the first and second law performances of cascaded vapour compression refrigeration system using R1234ze(Z) in higher temperature cycle and R1233zd(E) in the low-temperature cycle gives a best thermodynamic performance as compared to R1234ze(E) and R1224ze(Z) and R1243z in the high-temperature cycle. Moreover, the lowest performances were found by using R1234yf in high or low-temperature cycles as compared to other HFO refrigerants. The comparison was made between HFO-1234yf and HFC-134a in a low-temperature cycle up to a temperature of -50oC and also found the first and second law efficiencies are 3.24% lower than using R-1234yf in the low-temperature cycle as compared to HFC-134a in the low-temperature cycle and R1234ze(Z) in high-temperature cycle with 5.2% decrement in the exergy destruction ratio.

Canan Cimsit [5]studied energy & exergy analysis of a subcritical cascade refrigeration system using low global warming potential refrigerants and found a 13.05% improvement in the COP

The use of eco-friendly HFO refrigerants in the medium temperature range (up to -50°C) using Low GWP ecofriendly R245fa in Intermediate temperature cycle up to -95°C and R600a, R290 in ultra-low temperature (-155°C) of a cascade refrigeration system and it was found that Hydrocarbon R-600a gives best thermodynamic first and second law performances with lowest exergy destruction ratio in the ultra-low temperature between -110°C to -130°C. The thermodynamic first and second law performances of R32 and ethylene are nearly similar and less than R290. Therefore, the use of hydrocarbons can also be promising by taking appropriate safety measures because mainly hydrocarbons are flammable. R1234ze(z) gives the best/highest thermodynamic performances with the lowest exergy destruction ratio as compared to R1224yd(Z) and R1234ze(E) and R1243zf used in intermediate temperature for R1234ze(Z) /R1234ze(E) & R1243zf, R1233zd(E) in high-temperature cycle using R600a, R290 and R32 and Ethylene in ultra-low temperature ranges between -110°C to -130°C.However, the lowest performance was observed by using R134a in a high-temperature circuit and R1234yf in a low-temperature cycle. The thermodynamic performances of cascade vapour compression refrigeration systems were compared between HFC-134a and HFO-1234yf, and it was found that HFO-1236mzz(z) and R1225ye(Z) give similar results as compared with R134a used in intermediate temperature cycle up to -50°C of evaporator temperature [6]

The use of HFO refrigerant having zero ozone depleting potential (ODP) and low global warming potential (GWP), i.e. R1234yf, is strongly recommended by Regulation (EU) No 517/2014 to reduce mitigating climate change risk, environmental impact and deterioration. Therefore, refrigerant R1234yf could be a choice for the vapour compression refrigeration cycle. However, the GWP and ODP ratings of R1234yf are four, showing refrigerants' environment and nature-friendly behaviour. Mishra [3] carried out the exergy analysis of three & four stages cascade refrigeration systems used for low-temperature applications using eco-friendly refrigerants. The effect of performance parameters (i.e. approaches, condenser temperature, and temperature variations in the evaporators) on the thermal performances in terms of second law efficiency of the system (exergetic efficiency) and exergy destruction ratio (EDR) and first law efficiency (i.e. overall coefficient of performance) has been optimized thermodynamically using of R1234yf and R1234ze in the high-temperature circuits and mainly thirteen eco-friendly refrigerants in the intermediates circuits and ethane It was observed that in the low temperature (between -80 °C to -88°C) applications. It was observed that the best combination in terms of R1234ze-R134a-R410aethane gives better thermal performance than using R1234yf-R134a-R410a ethane [7]

Eco-friendly refrigeration technologies are receiving more and more attention day by day for solving energy and environmental problems. In this paper, it is suggested to phase out the presently most used refrigerant R-134a considering global warming and to use natural refrigerants such as ammonia, carbon dioxide and hydrocarbons in two stage cascade vapour compression refrigeration system for a sustainable environment. The thermodynamic performances in terms of COP and exergetic efficiency and system exergy destruction ratio (EDR) for very low-temperature application using ethane in the low-temperature circuits and R1234ze and R1234yf in higher temperature circuits, and observed that the use of R1234ze has ultra-low global warming potential (of GWP=6) gives better thermal performance than R1234yf (of GWP=6) in the higher temperature circuit of four stage cascade refrigeration system. Similarly, there are few improvements in the thermodynamic versions using R134a compared with R410a in the first intermediate temperature circuit. [8].

The second law efficiency using R600a in the low-temperature evaporator circuit performs better than R290 and R404a refrigerant in lower temperature circuit (LTC) [9].

Many studies are available in the literature on vapour compression cascaded three staged refrigeration cycles using CFC and HFC refrigerants, but thermodynamic performance evaluation using HFO+HFC blends is not available in the literature, so far. This paper mainly deals with the performance evaluation of the system using HFO and HFC+HFO blends.

2. Validation of thermodynamic Performances of cascaded vapour compression refrigeration systems at ultra-low temperature applications

Following systems h*a*ve been selected for numerical computations.

System-1: Cascaded Vapour compression refrigeration systems using R12, in HTC R22 in MTC and R13in LTC.

System-2: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC and R-1225ye(Z) in LTC R1336mzz(Z).

System-3: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC and R1336mzz(Z)) in LTC R1336mzz(Z).

System-4: Cascaded Vapour compression refrigeration systems using R1336mzz(Z)in HTC and R-1225ye(Z) in LTC R-1225ye(Z).

System-5: Cascaded Vapour compression refrigeration systems usingR-1225ye(Z) in HTC and R1336mzz(Z) in LTC.

System-6: Cascaded Vapour compression refrigeration systems using R1243zf, in HTC and R-1225ye (Z) in LTC.

System-7: Cascaded Vapour compression refrigeration systems using R1243zf, in HTC and R1336mzz(Z)in LTC.

System-8: Cascaded Vapour compression refrigeration systems using R-1234ze(E), in HTC and R-1225ye(Z) in LTC.

System-9: Cascaded Vapour compression refrigeration systems using R1234ze(E), in HTC and R-R1336mzz(Z)in LTC.

System-10: Cascaded Vapour compression refrigeration systems using R1234yf, in HTC and R-1225ye(Z) in LTC.

System-11: Cascaded Vapour compression refrigeration systems using R1234yf, in HTC and R1336mzz(Z)in LTC.

System-12: Cascaded Vapour compression refrigeration systems using R1234yf, in HTC and R1336mzz(Z)in LTC.

System-13: Cascaded Vapour compression refrigeration systems usingR1234yf, in HTC andR1233zd(E), in LTC.

System-14: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC and R-1225ye(Z) in LTC R1336mzz(Z).
Following input data have been taken for validation of numerical computed values.

Table-1(a): Input data used in thermal model for computing Thermodynamic Performance of system-1

S.No	Input parameter	Unit	Value
1	HTC condenser temperature	ºC	40ºC
2	HTC evaporator temperature	ºC	-22
3	MTC evaporator temperature	ºC	-60
4	LTC evaporator temperature ºC	ºC	-90
5	MTC approach (temp overlapping)	ºC	10
6	LTC approach (temp overlapping)	ºC	10
7	HTC compressor efficiency	(%)	100
8	MTC compressor efficiency	(%)	100
9	LTC compressor efficiency	(%)	100
10	LTC evaporator load	kW	175.0

It was found that developed thermal model predict nearly exact behaviour shown in t*a*ble-(b) respectively.

Table-1(b): Validation of computed results of system-1

Thermodynamic Performance Parameters	Ref [1]	Model	% Difference
$COP_{\_Cascade}$	0.858	0.875	(+)1.98
Total compressor work "kW"	204.0	201.0	(-)1.47
$COP_{\_HTC\_R12}$	2.88	3.018	(+)4.79
$COP_{\_MTC\_R22}$	3.70	3.681	(-)0.5135
$COP_{\_LTC\_R13}$	3.74	3.763	(+)0.615
HTC Mass Flow Rate(kg/sec)	2.72	2.741	(+)0.772
MTC Mass FlowRate(kg/sec)	1.15	1.157	(+)0.6087
LTC Mass Flow Rate(kg/sec)	1.5	1.509	(+)0.60
HTCcompressor Power "kW"	97.4	93.78	(-)3.717
MTCcompressor Power "kW"	59.8	60.45	(+)1.086
LTC compressor Power "kW"	46.8	46.73	(-)0.1496

Thermodynamic performances of sixteen systems have been computed and it was found that system-2 gives best thermodynamic performances and system-4 gives lowest thermodynamic performances

3. Results and Discussion

3.1 Effect of Blends of HFO+HFC refrigerants in three staged cascaded vapour compression refrigeration systems

Vapour compression systems have been computed with different combinations of cascaded VCRS using the following in the high-temperature cycle and following blends of HFO+HFC refrigerants in the medium temperature cycle & following eco-friendly refrigerants in the low-temperature cycle, also shown in table-2*(a)* respectively and it was found that the system cascaded VCRS using R454b in the high-temperature cycle & R515*a* in the medium temperature cycle &R513a eco-friendly refrigerant in the low-temperature cycle gives slightly lower thermodynamic performances than conventional three staged vapour compression refrigeration system.

3.2 Optimum (Best/highest) thermodynamic Performances of cascaded vapour compression refrigeration systems using HFO+HFC blends at low temperature applications

VCRS have been computed with different combinations of cascaded VCRS using the following in the high-temperature cycle and following blends of HFO+HFC refrigerants in the medium temperature cycle & following eco-friendly refrigerants in the low-temperature cycle, also shown in table-2(b) to table 2(c) respectively. It was found that the system cascaded VCRS using R454b in the high-temperature cycle &R515*a* in the medium temperature cycle & R513a eco-friendly refrigerant in the low-temperature cycle gives best thermodynamic performances. Similarly, the cascaded VCRS using R452*a* in the high-temperature cycle &R448*a* in the medium temperature cycle & R454c in the low-temperature cycle gives the lowest thermodynamic performances.

Table-1(c): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835 kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-22°C, $T_{\_Eva\text{-}MTC}$= - 60°C , $T_{\_Eva\ LTC}$= - 90°C, MTC temperature overlapping (Approach$_{_MTC}$)=10°C, LTC temperature overlapping (Approach$_{_LTC}$)=10°C, Compressor efficiency$_{_HTC}$=100%, Compressor efficiency$_{_MTC}$=100%, Compressor efficiency$_{_LTC}$=100%)

Refrigerant	System 1	System 2	System 3	System 4	System-5	System 6	System 7	System 8
COP_HTC	3.018	3.322	2.853	2.813	3.113	3.113	2.821	2.972
COP_MTC	3.681	3.738	3.738	3.738	3.671	3.689	3.738	3.738
COP_LTC	3.763	3.896	3.896	3.896	3.965	3.896	3.896	3.965
Three Stage COP_Cascade	0.875	0.9326	0.8687	0.8628	0.9048	0.9007	0.8640	0.8918
Three Stage Exergetic Efficiency	0.8202	0.7077	0.8334	0.8458	0.7601	0.7683	0.8434	0.7858
Three Stage Exergy Destruction Ratio (EDR)	0.5494	0.5856	0.5454	0.5418	0.5682	0.5655	0.5425	0.560
Three Stage Exergy of Fuel “kW”	201.0	188.5	202.4	203.8	193.4	195.2	203.5	197.2
Three Stage Exergy of Product “kW”	110.4	110.4	110.4	110.4	110.4	110.4	110.4	110.4
Two Stage COP_Cascade	1.443	1.541	1.405	1.393	1.468	1.468	1.395	1.441
Two Stage Exergy Destruction Ratio (EDR)	0.7378	0.6276	0.7850	0.8006	0.7080	0.7035	0.7976	0.7404
Two Stage Exergetic Efficiency	0.5754	0.6144	0.5602	0.5554	0.5855	0.5870	0.5563	0.5746
Two Stage Exergy of Fuel “kW”	154.2	143.4	157.3	158.7	150.0	150.1	158.4	152.8
Two Stage Exergy of Product “kW”	88.75	88.12	88.12	88.12	87.81	88.12	88.12	87.81
HTC Mass flow Rate (Kg/sec)	2.741	1.747	2.478	2.18	2.009	2.014	2.907	2.427
MTC Mass flow Rate (Kg/sec)	1.157	1.247	1.247	1.247	1.45	1.63	1.247	1.243
LTC Mass flow Rate (Kg/sec)	1.509	0.9868	0.9868	0.9868	1.114	0.9868	0.9868	1.114
Q_Cond_HTC“kW”	376.8	364.4	378.3	379.6	370.2	371.1	379.4	373.0
Q_Cond_MTC“kW”	283.0	280.1	280.1	280.1	280.2	280.9	280.1	279.1
Q_Cond_LTC“kW”	222.6	221.0	221.0	221.0	220.2	221.0	221.0	220.2
Q_EVA_LTC“kW”	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work“kW”	93.78	84.31	98.18	99.55	89.99	90.21	99.29	93.92
MTC compressor Work“kW”	60.45	59.11	59.11	59.11	58.98	45.13	45.13	58.9
LTC compressor Work“kW”	46.73	45.13	45.13	45.13	44.35	59.89	59.11	44.35
System compressor Work“kW”	201.0	188.5	202.4	203.8	193.4	195.2	203.5	197.2
$COP_{\_HTC}$	3.018	3.322	2.853	2.813	3.113	3.113	2.821	2.972
HTC Exergy Destruction Ratio (EDR)	0.7706	0.6087	0.8733	0.8994	0.7164	0.7164	0.8944	0.7982
HTC Exergetic Efficiency	0.5648	0.6216	0.5338	0.5418	0.5826	0.5826	0.5279	0.5561
HTC Exergy of Fuel “kW”	93.78	84.31	98.18	99.55	89.99	90.21	99.29	93.92
HTC Exergy of Product “kW”	46.73	52.41	52.41	52.41	52.43	52.56	52.41	52.23

Table-2(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ = - 22°C, $T_{\_Eva\text{-}MTC}$= - 90°C , $T_{\_Eva\ LTC}$= - 90°C, Compressor efficiency$_{_HTC}$=100%, Compressor efficiency$_{_MTC}$=100%, Compressor efficiency$_{_LTC}$=100%)

Refrigerant in HTC	R12	R515A	R513A
Refrigerant in MTC	R22	R454B	R454B
Refrigerant in LTC	R13	R513A	R515A
COP_HTC	4.203	4.015	3.854
COP_MTC	2.904	2.736	2.736
COP_LTC	2.822	3.011	2.979
Three Stage COP_Cascade	0.7974	0.7860	0.771
Three Stage Exergy Destruction Ratio (EDR)	0.9974	1.026	1.066
Three Stage Exergetic Efficiency	0.5007	0.4935	0.4840
Three Stage Exergy of Fuel “kW”	220.5	223.7	228.1
Three Stage Exergy of Product “kW”	110.4	110.4	110.4

Two Stage COP_Cascade	1.506	1.417	1.389
Two Stage Exergy Destruction Ratio (EDR)	0.9760	1.10	1.142
Two Stage Exergetic Efficiency	0.5061	0.4763	0.4669
Two Stage Exergy of Fuel "kW"	158.2	165.3	169.10
Two Stage Exergy of Product "kW"	80.05	78.73	78.93
HTC Mass flow Rate (Kg/sec)	3.120	2.864	3.051
MTC Mass flow Rate (Kg/sec)	1.391	1.045	1.048
LTC Mass flow Rate (Kg/sec)	1.651	1.042	1.082
$Q_{\_Cond\_HTC}$"kW"	396.4	399.5	403.9
$Q_{\_Cond\_MTC}$"kW"	320.2	319.9	320.7
$Q_{\_Cond\_LTC}$"kW"	238.2	234.2	234.9
$Q_{\_EVA\_LTC}$"kW"	175.825	175.825	175.825
HTC compressor Work"kW"	76.18	79.68	83.20
MTC compressor Work"kW"	82.0	85.62	85.85
LTC compressor Work"kW"	62.34	58.4	59.02
System compressor Work"kW"	220.5	223.7	228.1
$COP_{\_HTC}$	4.203	4.015	3.854
HTC Exergy Destruction Ratio (EDR)	1.60	1.722	1.835
HTC Exergetic Efficiency	0.3847	0.3674	0.3528
HTC Exergy of Fuel "kW"	76.18	79.68	78.93
HTC Exergy of Product"kW"	29.30	29.28	29.35

Table-2(b): Thermodynamic performances of cascaded vapour compression refrigeration system using R452a ecofriendly low GWP refrigerants (Q_Eva=175.835 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ = - 22ºC, $T_{\_Eva\text{-}MTC}$= - 90ºC , $T_{\_Eva\ LTC}$= - 90ºC, MTC temperature overlapping (approach_MTC)=10ºC,LTC temperature overlapping (approach_LTC)=10ºC Compressor efficiency$_{_HTC}$=75%, Compressor efficiency$_{_MTC}$=75%, Compressor efficiency$_{_LTC}$=75%)

Refrigerant in HTC	R450a	R515a	R513a	R454b	R454c	R448a	R449a	R452a
Refrigerant in MTC	R454b	R454b	R454b	R515a	R515a	R515a	R515a	R515a
Refrigerants in LTC	R513a	R513a	R513a	R513a	R513a	R513a	R513a	R513a
Three Stage $COP_{\_Cascade}$	0.5734	0.5816	0.5694	0.5825	0.5426	0.5641	0.5574	0.5558
Three Stage Exergy Destruction Ratio (EDR)	1.777	1.738	1.797	1.735	1.935	1.823	1.857	1.972
Three Stage Exergetic Efficiency	0.3601	0.3652	0.3575	0.3657	0.3407	0.3542	0.350	0.3364
Three Stage Exergy of Fuel "kW"	306.6	302.3	308.8	301.9	324.1	311.7.8	315.5	328.2
$Q_{\_Cond\_HTC}$"kW"	482.5	478.2	474.7	477.7	499.9	487.5	491.3	504.0
$Q_{\_Cond\_LTC}$"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835

Table-2(c): Thermodynamic performances of cascaded vapour compression refrigeration system using R452a ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ = - 22ºC, $T_{\_Eva\text{-}MTC}$= - 90ºC, $T_{\_Eva\ LTC}$= - 90ºC, Compressor efficiency$_{_HTC}$=75%, Compressor efficiency$_{_MTC}$=75%, Compressor efficiency$_{_LTC}$=75%)

Refrigerant in HTC	R450a	R515a	R513a	R454b	R454c	R448a	R449a	R452a
Refrigerant in MTC	R454c	R454c	R454c	R454c	R448a	R454c	R454b	R448a
Refrigerants in LTC	R449a	R449a	R449a	R449a	R449a	R449a	R452a	R454c
Three Stage $COP_{\_Cascade}$	0.4924	0.4990	0.4902	0.490	0.4640	0.4756	0.4791	0.4577
Three Stage Exergy Destruction Ratio (EDR)	2.234	2.19	2.249	2.250	2.432	2.35	2.324	2.48
Three Stage Exergetic Efficiency	0.3092	0.3134	0.3078	0.3076	0.2914	0.2985	0.3008	0.2874
Three Stage Exergy of Fuel "kW"	357.1	352.3	358.7	358.9	378.9	369.8	367.0	382.2
$Q_{\_Cond\_HTC}$"kW"	532.9	528.2	534.5	534.7	554.8	545.6	542.9	560.6

3.3 Effect of HFO refrigerants in three staged cascaded vapour compression refrigeration systems

Following three staged cascaded vapour compression refrigeration systems have been considered

System-1: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC, R1233zd(E) in MTC and R-1225ye(Z) in LTC.

System-2: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC, R1233zd(E) in MTC and R1336mzz(Z) in LTC.

System-3: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC R1336mzz(Z) in MTC and R-1225ye(Z) in LTC .

System-4: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC R-1225ye(Z) in MTC and R1336mzz(Z) in LTC.

System-5: Cascaded Vapour compression refrigeration systems using R1243zf in HTC R1233zd(E) in MTC and R1336mzz(Z) in LTC.

System-6: Cascaded Vapour compression refrigeration systems using R1243zf in HTC R1233zd(E) in MTC and R-1225ye(Z) in LTC.

System-7: Cascaded Vapour compression refrigeration systems using R1243zf in HTC R1336mzz(Z) in MTC and R-1225ye(Z) in LTC.

System-8: Cascaded Vapour compression refrigeration systems using R1243zf in HTC R-1225ye(Z) in MTC and R1336mzz(Z) in LTC.

System-9: Cascaded Vapour compression refrigeration systems using R1336mzz(Z), in HTC R1233zd(E) in MTC and R-1225ye(Z) in LTC.

System-10: Cascaded Vapour compression refrigeration systems using R-1225ye(Z) in HTC R1233zd(E) in MTC and R- 1336mzz(Z), in LTC.

System-11: Cascaded Vapour compression refrigeration systems using R1233zd(E) in HTC R1336mzz(Z), in MTC and R- 1225ye(Z) in LTC.

System-12: Cascaded Vapour compression refrigeration systems using R1233zd(E) in HTC R1225ye(Z) in MTC and R-1336mzz(Z), in LTC.

System-13: Cascaded Vapour compression refrigeration systems using R1234yf in HTC R1233zd(E) in MTC and R-1336mzz(Z), in LTC.

System-14: Cascaded Vapour compression refrigeration systems using R1234yf in HTC R1233zd(E) in MTC and R-1225ye(Z) in LTC.

System-15: Cascaded Vapour compression refrigeration systems using R1234yf in HTC R-1225ye(Z) in MTC and R-1336mzz(Z), in LTC.

3.4 Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants for low temperature applications

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-3(a) respectively and it was found that the system cascaded VCRS using R1234ze(Z) in the high temperature cycle &R1233zd(E) in the medium temperature cycle &R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives higher thermodynamic performances than conventional cascaded vapour compression refrigeration system (system-7)for low temperature applications

Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-3(a) to Table-3(g) respectively. It was observed that HFO-1234yf used in HTC cycle gives slightly low thermodynamic performances than conventional systems in the low temperature applications.

Table-3(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ = - 22°C, $T_{\_Eva\text{-}MTC}$= - 60°C , $T_{\_Eva\ LTC}$= - 90°C, Compressor efficiency$_{_HTC}$=100%, Compressor efficiency$_{_MTC}$=100%, Compressor efficiency$_{_LTC}$=100%)

Refrigerant	System 1	System 2	System 3	System 4	System 5	System 6	System 7
HTC_Refrigerant	R1234ze(Z)	R1234 ze (Z)	R1234 ze (Z)	R1234 ze (Z)	R1234 ze (Z)	R1234 ze (Z)	R-12
MTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R225ye(Z)	R1234yf	R1234yf	R22
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R13
$COP_{\_ Three\ Stage\ \_Cascade}$	0.6456	0.6390	0.6347	0.6258	0.6203	0.6140	0.6029
($EDR_{Three\_Stage\ CVCRS}$)	1.467	1.492	1.509	1.545	1.568	1.594	1.641
Exergetic Efficiency$_{Three\ Stage\ CVCRS}$)	0.4054	0.4012	0.3985	0.3930	0.3895	0.3855	0.3786
Exergy of Fuel$_{Three\ Stage_CVCRS}$ “kW”	272.3	275.2	277.0	281.0	283.50	286.4	291.6
Exergy of Product$_{Three\ Stage}$ “kW”	110.4	110.4	110.4	110.4	110.4	110.4	110.4
COP_{HTC}	4.520	4.52	4.52	4.52	4.52	4.52	4.215
COP_{MTC}	2.215	2.215	2.143	2.128	2.052	2.052	2.178
COP_{LTC}	2.283	2.236	2.286	2.236	2.283	2.236	2.115
$COP_{Two\ Stage\_Cascade}$	1.295	1.295	1.264	1.258	1.225	1.295	1.242
($EDR_{\_Two\ Stage\_CRVS}$	1.298	1.298	1.354	1.366	1.425	1.298	1.396
Exergetic Efficiency$_{_\ Two\ Stage_CRVS}$	0.4351	0.4351	0.4249	0.4227	0.4117	0.4117	0.4174
Two Stage Exergy of Fuel “kW”	195.3	196.6	200.0	202.3	206.4	207.8	208.5
Two Stage Exergy of Product “kW”	84.99	85.52	84.99	85.52	84.99	85.52	87.03
HTC Mass flow Rate (Kg/sec)	2.119	2.133	2.141	2.160	2.172	2.186	3.345
MTC Mass flow Rate (Kg/sec)	1.61	1.62	1.916	2.181	2.166	2.18	1.512
LTC Mass flow Rate (Kg/sec)	1.186	1.059	1.186	1.059	1.186	1.059	1.651

Q_Cond_HTC"kW"	448.2	451.0	452.9	456.8	459.3	462.2	467.5
Q_Cond_MTC"kW"	367.0	369.3	370.8	374.1	376.1	378.5	377.8
Q_Cond_LTC"kW"	252.9	254.5	252.9	254.5	252.9	254.5	259.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.83	175.83	175.83	175.83
HTC compressor Work"kW"	81.19	81.7	82.04	82.75	83.20	83.72	89.64
MTC compressor Work"kW"	114.1	114.9	118.0	119.6	123.2	124.0	118.9
LTC compressor Work"kW"	77.03	78.62	77.03	78.62	77.03	78.62	83.12
System compressor Work"kW"	195.3	196.6	200.0	202.3	206.4	207.8	291.6
$COP_{\_HTC}$	4.50	4.50	4.50	4.50	4.50	4.50	4.215
HTC_EDR	1.417	1.417	1.417	1.417	1.417	1.417	1.592
HTC Exergetic Efficiency	0.4137	0.4137	0.4137	0.4137	0.4137	0.4137	0.3858
HTC Exergy of Fuel "kW"	81.19	81.7	82.04	82.75	83.20	83.72	89.64

Table-3(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ = 0.0°C, $T_{\_Eva\text{-}MTC}$= -50°C , $T_{\_Eva\ LTC}$= - 90°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Refrigerant	System-8	System-9	System-10	System-11	System-12	System-13	System-7
HTC Refrigerant	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R1224yd(Z)	R-12
MTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R225ye(Z)	R1234yf	R1234yf	R22
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R13
$COP_{\_Three\ Stage\ \_Cascade}$	0.6359	0.6294	0.6252	0.6165	0.6111	0.6065	0.6029
($EDR_{Three\_Stage\ CVCRS}$)	1.504	1.530	1.547	1.583	1.606	1.633	1.641
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3993	0.3952	0.3926	0.3871	0.3837	0.3799	0.3786
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	276.5	279.3	281.2	285.5	287.7	290.7	291.6
Exergy of $Product_{Three\ Stage}$ "kW"	110.4	110.4	110.4	110.4	110.4	110.4	110.4
COP_{HTC}	4.301	4.301	4.301	4.301	4.301	4.301	4.215
COP_{MTC}	2.215	2.215	2.143	2.126	2.052	2.052	2.178
COP_{LTC}	2.283	2.236	2.283	2.236	2.283	2.236	2.115
$COP_{Two\ Stage\_Cascade}$	1.268	1.268	1.238	1.232	1.20	1.20	1.242
$EDR_{\_Two\ Stage\_CRVS}$	1.347	1.347	1.403	1.415	1.479	1.479	1.396
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.4261	0.4261	0.4162	0.4140	0.4033	0.4033	0.4174
Two Stage Exergy of Fuel "kW"	199.5	200.7	204.2	206.6	210.7	212.0	208.5
Two Stage Exergy of Product "kW"	84.99	85.52	84.99	85.52	84.59	85.52	87.03
HTC Mass flow Rate (Kg/sec)	2.817	2.835	2.846	2.871	2.887	2.905	3.345
MTC Mass flow Rate (Kg/sec)	1.61	1.62	1.916	2.181	2.166	2.180	1.512
LTC Mass flow Rate (Kg/sec)	1.186	1.059	1.186	1.059	1.186	1.059	1.651
Q_Cond_HTC"kW"	452.3	455.2	457.1	461.0	463.6	466.5	467.5
Q_Cond_MTC"kW"	367.0	369.3	370.8	374.1	376.1	378.5	377.8
Q_Cond_LTC"kW"	252.9	254.5	252.9	254.5	252.9	254.5	259.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.83	175.83	175.83	175.835
HTC compressor Work"kW"	85.3	85.87	86.23	86.97	87.45	88.0	89.64
MTC compressor Work"kW"	114.1	114.9	118.0	119.6	123.2	124.0	118.9
LTC compressor Work"kW"	77.03	78.62	77.03	78.62	77.03	78.62	83.12
System compressor Work"kW"	276.5	279.3	281.2	285.5	287.7	290.7	291.6
$COP_{\_HTC}$	4.301	4.301	4.301	4.301	4.301	4.301	4.215
HTC_ EDR	1.54	1.54	1.54	1.54	1.54	1.54	1.592
HTC Exergetic Efficiency	0.3936	0.3936	0.3936	0.3936	0.3936	0.3936	0.3858
HTC Exergy of Fuel "kW"	85.3	85.87	86.23	86.97	87.45	88.0	89.64
HTC Exergy of Product "kW"	33.59	33.80	33.94	34.24	34.422	34.64	34.58

Table-3(c): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =0.0°C, $T_{\_Eva\text{-}MTC}$= -50°C , $T_{\_Eva\ LTC}$= - 90°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Refrigerant	System-14	System-15	System-16	System-17	System-18	System-19	System-7
HTC_Refrigerant	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)	R1234ze(E)	R-12
MTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R225ye(Z)	R1234yf	R1234yf	R22
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R13
$COP_{\_Three\ Stage\ \_Cascade}$	0.6267	0.6204	0.6162	0.6077	0.6024	0.5964	0.6029
($EDR_{Three\_Stage\ CVCRS}$)	1.541	1.567	1.585	1.621	1.644	1.671	1.641

Exergetic Efficiency$_{Three\ Stage\ CVCRS}$)	0.3935	0.3885	0.3869	0.3816	0.3782	0.3745	0.3786
Exergy of Fuel$_{Three\ Stage_CVCRS}$ "kW"	280.6	283.4	285.3	289.3	291.9	294.8	291.6
Exergy of Product$_{Three\ Stage}$ "kW"	110.4	110.4	110.4	110.4	110.4	110.4	110.4
COP_{HTC}	4.105	4.105	4.105	4.105	4.105	4.105	4.215
COP_{MTC}	2.215	2.215	2.143	2.181	2.052	2.052	2.178
COP_{LTC}	2.283	2.236	2.283	1.059	2.283	2.236	2.115
COP$_{Two\ Stage_Cascade}$	1.242	1.242	1.214	1.208	1.177	1.177	1.242
(EDR$_{_Two\ Stage_CRVS}$)	1.395	1.395	1.451	1.464	1.524	1.524	1.396
Exergetic Efficiency_$_{Two\ Stage_CRVS}$	0.4176	0.4176	0.408	0.4059	0.3955	0.3955	0.4174
Two Stage Exergy of Fuel "kW"	203.5	204.8	208.3	210.7	214.9	216.20	208.5
Two Stage Exergy of Product "kW"	84.99	85.52	84.99	85.52	84.94	85.52	87.03
HTC Mass flow Rate (Kg/sec)	2.857	2.857	2.887	2.912	2.928	2.946	3.345
MTC Mass flow Rate (Kg/sec)	1.610	1.620	1.196	2.181	2.166	2.180	1.512
LTC Mass flow Rate (Kg/sec)	1.186	1.059	1.186	1.059	1.186	1.059	1.651
Q_Cond_HTC"kW"	456.4	459.3	461.2	465.2	467.7	470.7	467.5
Q_Cond_MTC"kW"	367.0	369.3	370.8	374.1	376.1	378.5	377.8
Q_Cond_LTC"kW"	252.9	254.5	252.9	254.5	252.9	254.5	259.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	89.4	89.96	90.34	91.12	91.62	92.2	89.64
MTC compressor Work"kW"	114.1	114.9	118.0	119.6	123.2	124.0	118.9
LTC compressor Work"kW"	77.03	78.62	77.03	78.62	77.03	78.62	83.12
System compressor Work"kW"	280.6	283.4	285.3	289.3	291.9	294.8	291.6
COP$_{_HTC}$	4.105	4.105	4.105	4.105	4.105	4.105	4.215
HTC_EDR	1.662	1.662	1.662	1.662	1.662	1.662	1.592
HTC Exergetic Efficiency	0.3757	0.3757	0.3757	0.3757	0.3757	0.3757	0.3858
HTC Exergy of Fuel "kW"	89.4	89.96	90.34	91.12	91.62	92.2	89.64
HTC Exergy of Product "kW"	33.59	33.8	33.94	34.24	34.42	34.64	34.58

Table-3(d): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40ºC, T_ambient=25ºC, T$_{_Eva\ HTC}$ = 0.0ºC, T$_{_Eva\text{-}MTC}$= -50ºC , T$_{_Eva\ LTC}$= - 90ºC, Temp_Overlaping$_{_MTC}$=10ºC, Temp_Overlaping$_{_LTC}$=10ºC, Compressor efficiency$_{_HTC}$=75%, Compressor efficiency$_{_MTC}$=75%, Compressor efficiency$_{_LTC}$=75%)

Refrigerant	System-20	System-21	System-22	System-23	System-24	System-25	System-27
HTC_Refrigerant	R1243zf	R1243zf	R1243zf	R1243zf	R1243zf	R1243zf	R-12
MTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)	R1234yf	R1234yf	R22
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R225ye(Z)	R1336mzz(Z)	R13
COP_$_{Three\ Stage\ _Cascade}$	0.6229	0.6166	0.6125	0.6040	0.5988	0.5928	0.6029
(EDR$_{Three_Stage\ CVCRS}$)	1.557	1.583	1.60	1.637	1.660	1.687	1.641
Exergetic Efficiency$_{Three\ Stage\ CVCRS}$)	0.3911	0.3872	0.3846	0.3793	0.3760	0.3722	0.3786
Exergy of Fuel$_{Three\ Stage_CVCRS}$ "kW"	282.3	282.3	285.2	287.1	293.7	296.6	291.6
Exergy of Product$_{Three\ Stage}$ "kW"	110.4	110.4	110.4	110.4	110.4	110.4	110.4
COP_{HTC}	4.028	4.028	4.028	4.028	4.028	4.028	4.215
COP_{MTC}	2.215	2.215	2.143	2.128	2.052	2.052	2.178
COP_{LTC}	2.283	2.236	2.283	2.236	2.283	2.236	2.115
COP$_{Two\ Stage_Cascade}$	1.232	1.232	1.204	1.198	1.167	1.167	1.242
EDR$_{_Two\ Stage_CRVS}$	1.415	1.415	1.472	1.484	1.549	1.549	1.396
Exergetic Efficiency_$_{Two\ Stage_CRVS}$	0.4140	0.4140	0.4046	0.4025	0.3923	0.3923	0.4174
Two Stage Exergy of Fuel "kW"	205.3	206.6	210.1	212.5	216.6	218.0	208.5
Two Stage Exergy of Product "kW"	84.99	85.52	84.99	85.52	84.99	85.52	87.03
HTC Mass flow Rate (Kg/sec)	2.575	2.591	2.602	2.604	2.639	2.655	3.345
MTC Mass flow Rate (Kg/sec)	1.610	1.620	1.916	2.181	2.166	2.18	1.512
LTC Mass flow Rate (Kg/sec)	1.186	1.059	1.186	1.059	1.186	1.059	1.651
Q_Cond_HTC"kW"	458.1	461.0	462.9	466.9	469.5	472.5	467.5
Q_Cond_MTC"kW"	367.0	369.3	370.8	374.1	376.1	378.5	377.8
Q_Cond_LTC"kW"	252.9	254.5	252.9	254.5	252.9	254.5	259.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	91.12	91.70	92.08	92.87	93.38	93.97	89.64
MTC compressor Work"kW"	114.1	114.9	118.6	119.6	123.2	124.0	118.9
LTC compressor Work"kW"	77.03	78.62	77.03	78.62	77.03	78.62	83.12
System compressor Work"kW"	282.3	282.3	285.2	287.1	291.9	294.8	291.6

COP_HTC	4.028	4.028	4.028	4.028	4.028	4.028	4.215
HTC_EDR	1.713	1.713	1.713	1.713	1.713	1.713	1.592
HTC Exergetic Efficiency	0.3686	0.3686	0.3686	0.3686	0.3686	0.3686	0.3858
HTC Exergy of Fuel "kW"	91.12	91.70	92.08	92.87	93.38	93.97	89.64
HTC Exergy of Product "kW"	33.59	33.8	33.94	34.24	34.42	33.64	34.58

Table-3(e): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, T_Eva HTC = 0.0°C, T_Eva-MTC= -50°C , T_Eva LTC= - 90°C, Temp_Overlaping_MTC=10°C, Temp_Overlaping_LTC=10°C, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System-26	System-27	System-28	System-29	System-30	System-31
HTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
MTC_Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1234yf	R1234yf	R1233zd(E)	R1234yf
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)
COP_ Three Stage _Cascade	0.6279	0.6191	0.6137	0.6075	0.6178	0.5939
(EDR Three_Stage CVCRS)	1.537	1.572	1.595	1.622	1.578	1.681
Exergetic Efficiency Three Stage CVCRS)	0.3942	0.3888	0.3853	0.3815	0.3879	0.3729
Exergy of Fuel Three Stage_CVCRS "kW"	280.0	284.0	286.5	289.4	284.60	296.0
Exergy of Product Three Stage "kW"	110.4	110.4	110.4	110.4	110.4	110.4
HTC First Law Efficiency (COP HTC)	4.361	4.361	4.105	4.105	4.025	4.025
MTC First Law Efficiency (COP MTC)	2.143	2.126	2.052	2.052	2.215	2.052
LTC First Law Efficiency (COP LTC)	2.283	2.236	2.283	2.236	2.236	2.236
COP Two Stage_Cascade	1.245	1.239	1.207	1.207	1.235	1.170
(EDR_Two Stage_CRVS)	1.389	1.401	1.465	1.465	1.409	1.542
Exergetic Efficiency_ Two Stage_CRVS	0.4186	0.4164	0.4057	0.4057	0.4152	0.3933
Two Stage Exergy of Fuel "kW"	203.0	205.4	209.5	210.8	206.0	205.4
Two Stage Exergy of Product "kW"	84.99	85.52	84.59	85.52	85.52	85.52
HTC Mass flow Rate (Kg/sec)	2.39	2.41	2.423	2.439	3.389	3.473
MTC Mass flow Rate (Kg/sec)	1.916	2.181	2.166	2.180	1.62	2.18
LTC Mass flow Rate (Kg/sec)	1.186	1.059	1.186	1.059	1.059	1.059
Q_Cond_HTC"kW"	455.90	459.8	462.4	465.3	460.4	471.9
Q_Cond_MTC"kW"	370.8	374.1	376.1	378.5	369.3	378.5
Q_Cond_LTC"kW"	252.9	254.5	252.9	254.5	254.5	254.5
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	85.04	85.77	86.24	86.79	91.14	93.40
MTC compressor Work"kW"	118.0	119.6	123.2	124.0	114.9	124.0
LTC compressor Work"kW"	77.03	78.62	77.03	78.62	78.62	78.62
System compressor Work"kW"	280.0	284.0	286.5	289.4	284.60	296.0
COP_HTC	4.361	4.361	4.361	4.361	4.052	4.052
HTC Exergy Destruction Ratio (EDR)	1.505	1.505	1.505	1.505	1.696	1.696
HTC Exergetic Efficiency	0.3991	0.3991	0.3991	0.399	0.3709	0.3709
HTC Exergy of Fuel "kW"	85.04	85.77	86.24	86.79	91.14	93.40
HTC Exergy of Product "kW"	33.94	34.24	34.422	34.64	33.80	34.64

Table-3(f): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, T_Eva HTC =0.0°C, T_Eva-MTC= -50°C , T_Eva LTC= - 90°C, Temp_Overlaping_MTC=10°C, Temp_Overlaping_LTC=10°C, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System-32	System-33	System-34	System-35	System-36	System-37
HTC Refrigerant	R1336mzz(Z)	R1336mzz(Z)	R1234yf	R1234yf	R1234yf	R1234yf
MTC_Refrigerant	R1233zd(E)	R1234yf	R1233zd(E)	R1233zd(E)	R1336mzz(Z)	R1225ye(Z)
LTC_Refrigerant	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP_ Three Stage _Cascade	0.6093	0.6340	0.6164	0.6102	0.6062	0.5978
(EDR Three_Stage CVCRS)	1.614	1.512	1.584	1.610	1.627	1.664
Exergetic Efficiency Three Stage CVCRS)	0.3826	0.3981	0.3871	0.3831	0.3806	0.3754
Exergy of Fuel Three Stage_CVCRS "kW"	288.6	277.3	285.2	288.2	290.1	294.1
Exergy of Product Three Stage "kW"	110.4	110.4	110.4	110.4	110.4	110.4
COP HTC	4.259	4.259	3.901	3.901	3.901	3.901
COP MTC	2.052	2.215	2.215	2.215	2.143	2.128
COP LTC	2.283	2.283	2.283	2.236	2.283	2.236
COP Two Stage_Cascade	1.195	1.262	1.214	1.214	1.187	1.181

($EDR_{Two\ Stage\_CRVS}$)	1.489	1.357	1.450	1.450	1.507	1.520
Exergetic Efficiency_ $_{Two\ Stage\_CRVS}$	0.3826	0.4243	0.4082	0.4082	0.3989	0.3969
Two Stage Exergy of Fuel “kW”	209.5	210.8	208.2	209.5	213.10	215.5
Two Stage Exergy of Product “kW”	84.99	84.99	84.99	85.52	84.99	85.52
HTC Mass flow Rate (Kg/sec)	2.855	2.786	3.388	3.409	3.424	3.453
MTC Mass flow Rate (Kg/sec)	2.166	1.610	1.61	1.62	1.916	2.181
LTC Mass flow Rate (Kg/sec)	1.186	1.186	1.186	1.059	1.186	1.059
Q_Cond_HTC“kW”	464.4	453.2	461.10	464.0	465.9	470.0
Q_Cond_MTC“kW”	376.1	367.0	367.0	369.3	370.8	370.1
Q_Cond_LTC“kW”	252.9	252.9	252.0	175.835	175.835	175.835
Q_EVA_LTC“kW”	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work“kW”	88.32	86.18	94.09	94.68	95.07	95.90
MTC compressor Work“kW”	123.2	114.10	114.1	114.9	118.0	119.6
LTC compressor Work“kW”	77.03	77.03	77.03	78.62	77.03	78.62
System compressor Work“kW”	288.6	277.3	285.2	288.2	290.1	294.1
$COP_{\_HTC}$	4.259	4.259	3.901	3.901	3.901	3.901
HTC Exergy Destruction Ratio (EDR)	1.566	1.566	1.801	1.801	1.801	1.801
HTC Exergetic Efficiency	0.3898	0.3898	0.357	0.357	0.357	0.357
HTC Exergy of Fuel “kW”	88.32	86.18	94.09	94.68	95.07	95.90
HTC Exergy of Product “kW”	34.42	33.59	33.59	33.80	33.94	34.42

Table-3(g): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =0.0°C, $T_{\_Eva-MTC}$= -50°C , $T_{\_Eva\ LTC}$= - 90°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, $Compressor\ efficiency_{\_HTC}$=75%, $Compressor\ efficiency_{\_MTC}$=75%, $Compressor\ efficiency_{\_LTC}$=75%)

Refrigerant	System 38	System 39	System-40	System 7
HTC_Refrigerant	R152*a*	R245*fa*	R32	R-12
MTC_Refrigerant	R245*fa*	R152*a*	R152*a*	R22
LTC_Refrigerant	R32	R32	R245*fa*	R13
COP_ $_{Three\ Stage\ \_Cascade}$	0.6075	0.6113	0.6204	0.6029
($EDR_{Three\_Stage\ CVCRS}$)	1.622	1.605	1.567	1.641
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3814	0.3838	0.3895	0.3786
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ “kW”	289.5	287.6	283.4	291.6
Exergy of $Product_{Three\ Stage}$ “kW”	110.4	110.4	110.4	110.4
COP_{HTC}	4.293	4.317	4.003	4.215
COP_{MTC}	2.202	2.222	2.222	2.178
COP_{LTC}	2.101	2.101	2.266	2.115
$COP_{Two\ Stage\_Cascade}$	1.261	1.273	1.231	1.242
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.359	1.338	1.417	1.396
Exergetic Efficiency_ $_{Two\ Stage\_CRVS}$	0.4239	0.4277	0.4138	0.4174
Two Stage Exergy of Fuel “kW”	205.8	204.0	205.8	208.5
Two Stage Exergy of Product “kW”	87.23	87.23	85.17	87.03
HTC Mass flow Rate (Kg/sec)	1.607	2.477	1.533	3.345
MTC Mass flow Rate (Kg/sec)	1.665	1.025	1.001	1.512
LTC Mass flow Rate (Kg/sec)	0.5151	0.5151	0.9164	1.651
Q_Cond_HTC“kW”	465.3	463.5	459.3	467.5
Q_Cond_MTC“kW”	377.4	376.3	367.5	377.8
Q_Cond_LTC“kW”	259.5	259.5	253.4	259.0
Q_EVA_LTC“kW”	175.835	175.835	175.835	175.835
HTC compressor Work“kW”	87.91	87.17	91.8	89.64
MTC compressor Work“kW”	117.9	116.8	114.0	118.9
LTC compressor Work“kW”	87.91	83.7	77.58	83.12
System compressor Work“kW”	289.5	287.6	283.4	291.6
$COP_{\_HTC}$	4.293	4.317	4.003	4.215
HTC Exergy Destruction Ratio (EDR)	1.545	1.531	1.730	1.592
HTC Exergetic Efficiency	0.3929	0.3951	0.3663	0.3858
HTC Exergy of Fuel “kW”	87.91	87.17	91.8	89.64
HTC Exergy of Product “kW”	34.54	34.44	33.63	34.58

3.5 Thermodynamic performances of cascaded vapour compression refrigeration system using low GWP ecofriendly HFO

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded VCRS system as shown in table-4a and it was found that the system cascaded VCRS using R1234ze(Z) in the high temperature cycle &R1233zd(E) in the medium temperature cycle &R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives higher thermodynamic performances than conventional cascaded vapour compression refrigeration system for ultra-low temperature applications.

Table 4a: Comparison of thermodynamic performances ofthree staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications

Refrigerant	HFO System	Conventional System
HTC_Refrigerant	R1234ze(Z)	R1234ze(Z)
MTC_Refrigerant	R1233zd(E)	R1233zd(E)
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)
$COP_{\_ Three\ Stage\ \_Cascade}$	0.3666	0.3383
($EDR_{Three\_Stage\ CVCRS}$)	1.881	2.122
$Efficiency_{\_Three\ Stage\ CVCRS}$)	0.3471	0.3203
Exergy of $Fuel_{\_3\ Stage\_CVCRS}$ "kW"	479.7	519.8
Exergy of $Product_{Three\ Stage}$ "kW"	166.5	166.5
COP_{HTC}	3.439	3.152
COP_{MTC}	1.725	1.70
COP_{LTC}	1.207	1.22
$COP_{Two\ Stage\_Cascade}$	0.9626	0.9157
($EDR_{\_Two\ Stage\_CRVS}$)	1.605	1.739
$Efficiency_{\_Two\ Stage\_CRVS}$	0.3838	0.365
Two Stage Exergy of Fuel "kW"	334.0	363.1
Two Stage Exergy "kW"	128.2	132.6
HTC Mass flow Rate (Kg/sec)	3.159	5.147
MTC Mass flow Rate (Kg/sec)	2.141	1.998
LTC Mass flow Rate (Kg/sec)	1.224	1.691
Q_Cond_HTC"kW"	655.5	695.6
Q_Cond_MTC"kW"	507.8	528.1
Q_Cond_LTC"kW"	321.5	332.5
Q_EVA_LTC"kW"	175.835	175.835
HTC compressor Work"kW"	147.7	167.5
MTC compressor Work"kW"	186.3	195.6
LTC compressor Work"kW"	145.7	156.6
System compressor Work"kW"	479.7	519.8
$COP_{\_HTC}$	3.439	3.152
HTC_EDR	2.177	2.466
HTC Exergetic Efficiency	0.3148	0.2885
HTC Exergy of Fuel "kW"	147.7	167.5
HTC Exergy of Product "kW"	46.48	48.33

Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle & other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-4(a) to Table-4(d) respectively. It was observed that HFO-1234yf used in HTC cycle gives slightly low thermodynamic performances than conventional systems in the low temperature applications.

3.6 Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants for ultra-low temperature applications

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-5 respectively and it was found that the system cascaded VCRS using R1233zd(E)in the high temperature cycle & R1336mzz(Zin the medium temperature cycle & R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives higher thermodynamic performances than conventional cascaded vapour compression refrigeration system for low temperature applications. Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-5(a) to Table-5(b) respectively. It was observed that HFO-1234yf used in HTC cycle gives slightly low thermodynamic performances than conventional systems in the ultra-low temperature applications.

3.7 Thermodynamic performances of cascaded vapour compression refrigeration system using ultralow GWP ecofriendly HFO refrigerants for ultra-low temperature applications

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-5 respectively and it was found that the system cascaded VCRS using R1234ze(E) in the high temperature cycle &R1233zd(E) in the medium temperature cycle &R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives higher thermodynamic performances than conventional cascaded vapour compression refrigeration system (system-7)for low temperature applications

Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-6. It was observed that HFO-1234yf used in HTC cycle gives slightly low thermodynamic performances than conventional systems in the ultra-low temperature applications

3.8 Thermodynamic performances of cascaded vapour compression refrigeration system using low GWP ecofriendly HFC/HC refrigerants

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-7(a) respectively and it was found that the system cascaded VCRS using R717in the high temperature cycle &R41 in the medium temperature cycle &R1150ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances than other cascaded vapour compression refrigeration system for ultra-low temperature applications.

Table-4(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =0.0ºC, $T_{\_Eva\text{-}MTC}$= -60ºC , $T_{\_Eva\ LTC}$= - 120ºC, $Temp\_Overlaping_{\_MTC}$=10ºC, $Temp\_Overlaping_{\_LTC}$=10ºC, $Compressor\ efficiency_{\_HTC}$=75%, $Compressor\ efficiency_{\_MTC}$=75%, $Compressor\ efficiency_{\_LTC}$=75%)

Refrigerant	System 1	System 2	System 3	System 4	System-5	System 6	System 7	System 8
HTC_Refrigerant	R1234 ze(Z)	R1234 ze(Z)	R1234 ze(Z)	R1234 ze(Z)	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)
MTC_Refrigerant	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R225 ye(Z)
LTC_Refrigerant	R1225 ye(Z)	R1336 mzz(Z)	R225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R225 ye(Z)	R1336 mzz(Z)
$COP_{\_ Three\ Stage\ \_Cascade}$	0.3666	0.3568	0.3593	0.3491	0.3513	0.3420	0.3445	0.3348
($EDR_{Three\_Stage\ CVCRS}$)	1.881	1.961	1.939	2.025	2.006	2.088	2.066	2.155
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3471	0.3378	0.3402	0.3305	0.3326	0.3238	0.3261	0.3170
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	479.7	492.9	489.3	503.7	500.5	514.0	510.4	525.2
Exergy of $Product_{Three\ Stage}$ "kW"	166.5	166.5	166.5	166.5	166.5	166.5	166.5	166.5
COP_{HTC}	3.439	3.439	3.439	3.439	3.014	3.014	3.014	3.014
COP_{MTC}	1.725	1.725	1.659	1.653	1.725	1.725	1.659	1.653
COP_{LTC}	1.207	1.156	1.207	1.156	1.207	1.156	1.207	1.156
$COP_{Two\ Stage\_Cascade}$	0.9626	0.9626	0.9335	0.9330	0.9061	0.9061	0.8813	0.8790
$EDR_{\_Two\ Stage\_CRVS}$	1.605	1.605	1.681	1.688	1.768	1.768	1.845	1.853
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.3838	0.3838	0.3731	0.3721	0.3613	0.3613	0.3515	0.3505
Two Stage Exergy of Fuel "kW"	334.0	340.7	343.7	351.5	354.8	362.0	364.8	373.1
Two Stage Exergy of Product "kW"	128.2	130.8	128.2	130.8	128.2	130.8	128.2	130.8
HTC Mass flow Rate (Kg/sec)	3.159	3.222	3.205	3.274	4.467	4.557	4.532	4.63
MTC Mass flow Rate (Kg/sec)	2.141	2.184	2.572	2.954	2.141	2.184	2.572	2.954
LTC Mass flow Rate (Kg/sec)	1.224	1.097	1.224	1.097	1.224	1.097	1.224	1.097
Q_Cond_HTC"kW"	655.5	668.7	665.1	679.5	676.3	689.9	686.3	701.1
Q_Cond_MTC"kW"	507.8	518.1	515.3	526.4	507.8	518.1	515.3	526.4
Q_Cond_LTC"kW"	321.5	328.0	321.5	328.0	321.5	328.0	321.5	328.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	147.7	150.6	149.8	153.1	168.5	171.9	171.0	174.6
MTC compressor Work"kW"	186.3	190.1	193.8	198.5	186.3	190.1	193.8	198.5
LTC compressor Work"kW"	145.7	152.1	145.7	152.1	145.7	152.1	145.7	152.1
System compressor Work"kW"	479.7	492.9	489.3	503.7	500.5	514.0	510.4	525.2
$COP_{\_HTC}$	3.439	3.439	3.439	3.439	3.014	3.014	3.014	3.014
HTC_EDR	2.177	2.177	2.177	2.177	2.625	2.625	2.625	2.625
HTC Exergetic Efficiency	0.3148	0.3148	0.3148	0.3148	0.2759	0.2759	0.2759	0.2759
HTC Exergy of Fuel "kW"	147.7	150.6	149.8	153.1	168.5	171.9	171.0	174.6
HTC Exergy of Product "kW"	46.48	47.42	47.16	48.18	46.48	47.42	47.16	48.18

Table-4(c): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =0.0ºC, $T_{\_Eva\text{-}MTC}$= -60ºC , $T_{\_Eva\ LTC}$= - 120ºC, $Temp\_Overlaping_{\_MTC}$=10ºC, $Temp\_Overlaping_{\_LTC}$=10ºC, $Compressor\ efficiency_{\_HTC}$=75%, $Compressor\ efficiency_{\_MTC}$=75%, $Compressor\ efficiency_{\_LTC}$=75%)

Refrigerant	System 1	System 2	System 3	System 4	System-5	System 6	System 7	System 8
HTC_Refrigerant	R1224 yd(Z)	R1224 yd(Z)	R1224 yd(Z)	R1224 yd(Z)	R1243 zf	R1243 zf	R1243 zf	R1243 zf
MTC_Refrigerant	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)
LTC_Refrigerant	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)

COP_ Three Stage _Cascade	0.3595	0.3449	0.3524	0.3424	0.3496	0.3404	0.3428	0.3332
(EDR Three_Stage CVCRS)	1..938	2.019	1..997	2.084	2.021	2.103	2.081	2.17
Exergetic Efficiency Three Stage CVCRS)	0.3404	0.3313	0.3337	0.3242	0.3310	0.3222	0.3246	0.3154
Exergy of Fuel Three Stage_CVCRS "kW"	489.10	502.5	498.9	513.5	502.9	516.6	512.9	527.8
Exergy of Product Three Stage "kW"	166.5	166.5	166.5	166.5	166.5	166.5	166.5	166.5
COP_{HTC}	3.232	3.232	3.232	3.232	2.971	2.971	2.971	2.971
COP_{MTC}	1.725	1.725	1.659	1.653	1.725	1.725	1.659	1.653
COP_{LTC}	1.156	1.207	1.207	1.156	1.207	1.156	1.207	1.156
COP Two Stage_Cascade	0.936	0.936	0.9101	0.9077	0.8998	0.8998	0.8753	0.8731
EDR_Two Stage_CRVS	1.679	1.679	1.755	1.763	1.783	1.783	1.865	1.872
Exergetic Efficiency_ Two Stage_CRVS	0.3733	0.3733	0.3629	0.3620	0.3588	0.3588	0.3491	0.3482
Two Stage Exergy of Fuel "kW"	343.5	350.4	353.3	361.3	357.3	364.5	367.3	175.7
Two Stage Exergy of Product "kW"	128.2	130.8	128.2	130.8	128.2	130.8	128.2	130.8
HTC Mass flow Rate (Kg/sec)	4.287	4.373	4.35	4.444	4.005	4.086	4.064	4.152
MTC Mass flow Rate (Kg/sec)	2.141	2.184	2.572	2.954	2.141	2.184	2.572	2.954
LTC Mass flow Rate (Kg/sec)	1.224	1.097	1.224	1.097	1.224	1.097	1.224	1.097
Q_Cond_HTC"kW"	665.0	678.4	674.5	689.3	678.8	692.4	688.8	703.6
Q_Cond_MTC"kW"	507.8	518.1	515.3	526.4	507.8	518.1	515.3	526.4
Q_Cond_LTC"kW"	321.5	328.0	321.5	328.0	321.5	328.0	321.5	328.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	157.1	160.3	159.4	162.9	170.9	174.4	173.5	177.2
MTC compressor Work"kW"	186.3	190.1	193.8	198.5	186.3	190.1	193.8	198.5
LTC compressor Work"kW"	145.7	152.1	145.7	152.1	145.7	152.1	145.7	152.1
System compressor Work"kW"	489.10	502.5	498.9	513.5	502.9	516.6	512.9	527.8
COP_HTC	3.232	3.232	3.232	3.232	2.971	2.971	2.971	2.971
HTC Exergy Destruction Ratio (EDR)	2.381	2.381	2.381	2.381	2.878	2.878	2.878	2.878
HTC Exergetic Efficiency	0.2958	0.2958	0.2958	0.2958	0.2719	0.2719	0.2719	0.2719
HTC Exergy of Fuel "kW"	157.1	160.3	159.4	162.9	170.9	174.4	173.5	177.2

Table-4(d): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50°C, T_ambient=25°C, T_Eva HTC =0.0°C, T_Eva-MTC= -60°C , T_Eva LTC= - 120°C, Temp_Overlaping_MTC=10°C, Temp_Overlaping_LTC=10°C, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System 1	System 2	System 3	System 4	System-5	System 6	System 7	
HTC_Refrigerant	R123yf	R123yf	R123yf	R123yf	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)
MTC_Refrigerant	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)
LTC_Refrigerant	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)
COP_ Three Stage _Cascade	0.3425	0.3335	0.3359	0.3265	0.3548	0.3448	0.3580	0.340
(EDR Three_Stage CVCRS)	2.084	2.167	2.145	2.235	1.977	2.106	1.951	2.106
Exergetic Efficiency Three Stage CVCRS)	0.3243	0.3157	0.3180	0.3091	0.3380	0.3264	0.3389	0.3219
Exergy of Fuel Three Stage_CVCRS "kW"	513.4	527.3	523.5	538.60	495.6	510.0	491.2	517.10
Exergy of Product Three Stage "kW"	166.5	166.5	166.5	166.5	166.5	166.5	166.5	166.5
COP_{HTC}	2.80	2.80	2.80	2.80	3.302	3.302	3.190	2.962
COP_{MTC}	1.725	1.725	1.725	1.725	1.659	1.653	1.725	1.725
COP_{LTC}	1.207	1.156	1.207	1.156	1.207	1.156	1.207	1.156
COP Two Stage_Cascade	0.8742	0.8742	0.8508	0.8486	0.9189	0.9165	0.9303	0.8986
Exergy Destruction Ratio (EDR_Two Stage_CRVS)	1.868	1.868	1.948	1.955	1.729	1.736	1.695	1.791
Exergetic Efficiency_ Two Stage_CRVS	0.3486	0.3486	0.3393	0.3384	0.3664	0.3655	0.3710	0.3583
Two Stage Exergy of Fuel "kW"	367.7	375.1	377.9	386.5	349.9	357.9	345.6	365.0
Two Stage Exergy of Product "kW"	128.2	130.8	128.2	130.8	128.2	130.8	128.2	130.8
HTC Mass flow Rate (Kg/sec)	5.441	5.551	5.521	5.64	3.616	3.694	4.267	5.40
MTC Mass flow Rate (Kg/sec)	2.141	2.184	2.572	2.954	2.572	2.954	2.141	2.184
LTC Mass flow Rate (Kg/sec)	1.224	1.097	1.224	1.097	1.224	1.097	1.224	1.097
Q_Cond_HTC"kW"	689.2	703.1	699.4	714.5	671.4	685.8	667.1	692.9
Q_Cond_MTC"kW"	507.8	518.10	515.3	526.4	515.3	526.4	507.8	518.10
Q_Cond_LTC"kW"	321.5	328.0	321.5	328.0	321.5	328.0	321.5	328.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835

HTC compressor Work"kW"	181.4	185.0	184.10	188.0	156.0	159.4	159.2	174.9
MTC compressor Work"kW"	186.3	190.1	193.8	198.5	193.8	198.5	186.3	190.1
LTC compressor Work"kW"	145.7	152.1	145.7	152.1	145.7	152.1	145.7	152.1
System compressor Work"kW"	513.4	527.3	523.5	538.60	495.6	510.0	491.2	517.10
$COP_{\_HTC}$	2.80	2.80	2.80	2.80	3.302	3.302	3.190	2.962
HTC Exergy Destruction Ratio (EDR)	2.903	2.903	2.903	2.903	2.309	2.309	2.426	2.688
HTC Exergetic Efficiency	0.2562	0.2562	0.2562	0.2562	0.3022	0.3022	0.2919	0.2711

Table-5(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW kW, T_Cond=50°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =0.-30°C, $T_{\_Eva\text{-}MTC}$= -75°C , $T_{\_Eva\ LTC}$=-130°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Refrigerant	System 1	System 2	System 3	System 4	System-5	System 6	System 7	System 8
HTC_Refrigerant	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1243 zf	R1243 zf	R1243 zf
MTC_Refrigerant	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R225 ye(Z)	R1234 yf	R1234 yf
LTC_Refrigerant	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)
$COP_{\_\ Three\ Stage\ \_Cascade}$	0.2763	2.692	0.2744	0.2688	0.2761	0.2690	0.2742	0.2686
($EDR_{Three\_Stage\ CVCRS}$)	2.343	2.431	2.366	2.436	2.345	2.433	2.368	2.438
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.2991	0.2914	0.2971	0.2910	0.2990	0.2913	0.2969	0.2909
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	636.9	653.3	640.9	654.3	636.8	653.6	641.2	654.6
Exergy of $Product_{Three\ Stage}$ "kW"	190.4	190.41	190.4	190.4	190.4	190.4	190.4	190.4
COP_{HTC}	1.357	1.357	1.357	1.357	1.356	1.356	1.356	1.356
COP_{MTC}	2.197	2.197	2.159	2.188	2.197	2.197	2.159	2.188
COP_{LTC}	1.208	1.155	1.208	1.155	1.208	1.155	1.208	1.155
$COP_{Two\ Stage\_Cascade}$	0.6547	0.6547	0.6489	0.6534	0.6543	0.6543	0.6485	0.6530
Exergy Destruction Ratio ($EDR\__{Two\ Stage\_CRVS}$)	2.027	2.027	2.054	2.033	2.028	2.028	2.056	2.034
Exergetic $Efficiency\__{\ Two\ Stage\_CRVS}$	0.3304	0.3304	0.3275	0.3298	0.3303	0.3303	0.3273	0.3296
Two Stage Exergy of Fuel "kW"	490.9	501.1	495.3	502.1	491.2	501.4	495.6	502.4
Two Stage Exergy of Product "kW"	162.2	165.6	165.6	165.6	162.2	165.6	162.2	165.6
HTC Mass flow Rate (Kg/sec)	5.054	5.159	5.082	5.165	4.38	4.471	4.404	4.476
MTC Mass flow Rate (Kg/sec)	1.818	1.856	2.121	2.416	1.818	1.856	2.121	2.416
LTC Mass flow Rate (Kg/sec)	1.147	1.017	1.147	1.017	1.147	1.017	1.147	1.017
Q_Cond_HTC"kW"	812.6	829.1	816.7	830.10	812.6	829.4	817.0	830.4
Q_Cond_MTC"kW"	467.7	477.4	470.2	477.9	467.7	477.4	470.2	477.9
Q_Cond_LTC"kW"	321.4	328.0	321.4	328.0	321.4	328.0	321.4	328.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	344.6	351.7	346.5	352.2	344.9	352.0	346.8	352.2
MTC compressor Work"kW"	146.3	149.3	148.8	149.9	146.3	149.9	148.8	149.9
LTC compressor Work"kW"	145.6	152.2	145.6	152.2	145.6	152.2	145.6	152.2
System compressor Work"kW"	636.9	653.3	640.9	654.3	636.8	653.6	641.2	654.6
$COP_{\_HTC}$	1.357	1.357	1.357	1.357	1.356	1.356	1.356	1.356
HTC Exergy Destruction Ratio (EDR)	2.257	2.257	2.257	2.257	2.260	2.260	2.260	2.260
HTC Exergetic Efficiency	0.3070	0.3070	0.3070	0.3070	0.3067	0.3067	0.3067	0.3067
HTC Exergy of Fuel "kW"	344.6	351.7	346.5	352.2	344.9	352.0	346.8	352.2
HTC Exergy of Product "kW"	105.8	108.0	106.4	108.1	105.8	108.0	106.4	108.1

Table-5(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =0.-30°C, $T_{\_Eva\text{-}MTC}$= -75°C , $T_{\_Eva\ LTC}$=-130°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Refrigerant	System 9	System 10	System 11	System 12	System-13	System 14	System 15	System 16
HTC_Refrigerant	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1234 yf	R1234 yf	R1234 yf	R1234 yf
MTC_Refrigerant	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1225 ye(Z)	R1225 ye(Z)
LTC_Refrigerant	R1225	R1336	R1225	R1336	R1225	R1336	R1225	R1336

	ye(Z)	mzz(Z)	ye(Z)	mzz(Z)	ye(Z)	mzz(Z)	ye(Z)	mzz(Z)
COP_ Three Stage _Cascade	0.2956	0.2894	0.2862	0.2671	0.2597	0.2532	0.2580	0.2528
(EDRThree_Stage CVCRS)	2.125	2.191	2.227	2.458	2.556	2.648	2.580	2.654
Exergetic EfficiencyThree Stage CVCRS)	0.320	0.3134	0.3099	0.2892	0.2812	0.2741	0.2793	0.2737
Exergy of FuelThree Stage_CVCRS "kW"	594.9	607.5	614.3	658.3	677.0	694.6	681.6	695.6
Exergy of ProductThree Stage "kW"	190.4	190.4	190.4	190.4	190.4	190.4	190.4	190.4
COP_{HTC}	1.565	1.565	1.46	1.338	1.215	1.215	1.215	1.215
COP_{MTC}	2.159	2.188	2.197	2.197	2.197	2.197	2.159	2.188
COP_{LTC}	1.208	1.155	1.208	1.155	1.208	1.155	1.208	1.155
COPTwo Stage_Cascade	0.7153	0.7205	0.6857	0.6482	0.6048	0.6048	0.5996	0.6037
Exergy Destruction Ratio (EDR_Two Stage_CRVS)	1.770	1.750	1.890	2.057	2.276	2.276	2.305	2.282
Exergetic Efficiency_ Two Stage_CRVS	0.3610	0.3636	0.3460	0.3271	0.3052	0.3052	0.3026	0.3047
Two Stage Exergy of Fuel "kW"	449.3	455.3	468.8	506.1	531.4	542.4	536.0	544.4
Two Stage Exergy of Product "kW"	162.2	165.6	162.2	165.6	162.2	165.6	162.2	165.6
HTC Mass flow Rate (Kg/sec)	3.884	3.947	4.856	6.067	6.365	6.496	6.399	6.504
MTC Mass flow Rate (Kg/sec)	2.121	2.416	1.818	1.856	1.818	1.856	2.121	2.416
LTC Mass flow Rate (Kg/sec)	1.147	1.017	1.147	1.017	1.147	1.017	1.147	1.017
Q_Cond_HTC"kW"	770.7	783.4	790.2	834.2	852.8	870.4	857.4	871.5
Q_Cond_MTC"kW"	470.2	477.9	467.7	477.4	467.7	477.4	470.2	477.9
Q_Cond_LTC"kW"	321.4	328.8	321.4	328.0	321.4	328.0	321.4	328.0
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	300.5	305.4	322.5	356.8	385.1	393.1	387.2	393.5
MTC compressor Work"kW"	148.8	149.9	146.3	149.3	146.3	149.3	148.8	149.9
LTC compressor Work"kW"	145.6	152.2	145.6	152.2	145.6	152.2	145.6	152.2
System compressor Work"kW"	594.9	607.5	614.3	658.3	677.0	694.6	681.6	695.6
COP_HTC	1.565	1.565	1.450	1.338	1.215	321.4	321.4	321.4
HTC Exergy Destruction Ratio (EDR)	1.825	1.825	2.048	2.304	2.64	321.4	321.4	321.4
HTC Exergetic Efficiency	0.3540	0.3540	0.3281	0.3026	0.2747	321.4	321.4	321.4
HTC Exergy of Fuel "kW"	300.5	305.4	322.5	356.8	385.1	393.1	387.2	393.5
HTC Exergy of Product "kW"	106.4	108.1	105.8	108.0	105.8	108.0	106.4	108.1

Table-6: Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50ºC, T_ambient=25ºC, T_Eva HTC =-30ºC, T_Eva-MTC= -90ºC , T_Eva LTC= - 140ºC, Temp_Overlaping_MTC=10ºC, Temp_Overlaping_LTC=10ºC, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
HTC_Refrigerant	R1234 ze(E)	R1234 ze(E)	R1243z f	R1243 zf	R1233 zd(E)	R1233 zd(E)	R1234 yf	R1234 yf
MTC_Refrigerant	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)
LTC_Refrigerant	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)
COP_ Three Stage _Cascade	0.2267	0.2238	0.2266	0.2237	0.2435	0.2404	0.2136	0.2110
(EDRThree_Stage CVCRS)	2.560	2.605	2.562	2.607	2.314	2.357	2.326	2.825
Exergetic EfficiencyThree Stage CVCRS)	0.2809	0.2774	0.2808	0.2772	0.3017	0.2979	0.2647	0.2614
Exergy of FuelThree Stage_CVCRS "kW"	775.7	785.6	776.1	786.0	722.2	731.5	823.2	833.5
Exergy of ProductThree Stage "kW"	217.90	217.90	217.90	217.90	217.90	217.90	217.90	217.90
COP_{HTC}	1.357	1.357	1.356	1.356	1.565	1.565	1.215	1.215
COP_{MTC}	1.441	1.476	1.441	1.476	1.441	1.476	1.441	1.476
COP_{LTC}	1.191	1.141	1.191	1.141	1.191	1.141	1.191	1.141
COPTwo Stage_Cascade	0.5149	0.5226	0.5146	0.5223	0.5629	0.5715	0.4788	0.4857
Exergy Destruction Ratio (EDR_Two Stage_CRVS)	2.093	2.048	2.095	2.049	1.829	1.786	2.326	2.279
Exergetic Efficiency_ Two Stage_CRVS	0.3233	0.3281	0.3231	0.3279	0.3535	0.3589	0.3006	0.305
Two Stage Exergy of Fuel "kW"	628.10	631.5	628.50	631.8	574.6	577.3	675.6	679.4
Two Stage Exergy of Product "kW"	203.10	207.2	203.10	207.2	203.1	207.2	203.1	207.2
HTC Mass flow Rate (Kg/sec)	5.921	5.982	5.131	5.184	4.525	4.572	7.456	7.533
MTC Mass flow Rate (Kg/sec)	2.28	2.578	2.28	2.578	2.28	2.578	2.280	2.578
LTC Mass flow Rate (Kg/sec)	1.083	0.9459	1.083	0.9459	1.083	0.9459	1.083	0.9459
Q_Cond_HTC"kW"	951.6	961.5	959.9	961.8	898.0	907.3	999.0	1000.9
Q_Cond_MTC"kW"	547.9	553.6	547.9	553.6	547.9	553.6	547.9	553.9

Q_Cond_LTC“kW”	323.4	330.0	323.4	330.0	323.4	330.0	323.4	330.0
Q_{EVA}_LTC“kW”	175.835	175.835	175.835	175.83	175.835	175.835	175.835	175.835
HTC compressor Work“kW”	403.7	407.9	404.0	408.2	350.1	353.8	451.1	455.8
MTC compressor Work“kW”	224.4	223.6	224.4	223.6	224.4	223.6	224.4	223.6
LTC compressor Work“kW”	147.6	154.10	147.6	154.10	147.6	154.1	147.6	154.1
System compressor Work“kW”	775.7	785.6	776.10	786.0	722.2	731.5	823.2	833.5
$COP_{\_HTC}$	1.357	1.357	1.356	1.356	1.565	1.565	1.215	1.215
HTC Exergy Destruction Ratio (EDR)	2.257	2.257	2.260	2.260	1.825	1.825	2.64	2.64

Table-7(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-12ºC, $T_{\_Eva-MTC}$= -60ºC , $T_{\_Eva\ LTC}$= - 100ºC, $Temp\_Overlaping_{MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=5ºC, Compressor efficiency$_{_HTC}$=75%, Compressor efficiency$_{_MTC}$=75%, Compressor efficiency$_{_LTC}$=75%)

Refrigerant	System 1	System 2	System 3	System 4	System 5	System 6
HTC_Refrigerant	R717	R-152*a*	R161	R717	R-152*a*	R161
MTC_Refrigerant	R41	R41	R41	R41	R41	R41
LTC_Refrigerant	R1150	R1150	R1150	R1150	R1150	R1150
$COP_{\_\ Three\ Stage\ \_Cascade}$	0.6128	0.6105	0.6063	0.6022	0.60	0.5959
($EDR_{Three\_Stage\ CVCRS}$)	1.261	1.269	1.24	1.30	1.309	1.325
Exergetic Efficiency$_{Three\ Stage\ CVCRS}$)	0.4428	0.4408	0.4377	0.4347	0.4337	43.02
Exergy of Fuel$_{Three\ Stage_CVCRS}$ “kW”	57.29	57.6	58.0	58.4	58.61	59.02
Exergy of Product$_{Three\ Stage}$ “kW”	25.39	25.39	25.39	25.39	25.39	25.39
COP_{HTC}	3.239	3.208	3.151	3.239	3.208	3.151
COP_{MTC}	2.40	2.40	2.40	2.314	2.314	2.314
COP_{LTC}	2.383	2.383	2.383	2.383	2.383	2.383
$COP_{Two\ Stage\_Cascade}$	1.171	1.165	1.154	1.144	1.138	1.128
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.142	1.152	1.172	1.192	1.203	1.223
Exergetic Efficiency$_{_\ Two\ Stage_CRVS}$	0.4424	0.4646	0.4604	0.4561	0.4539	0.4498
Two Stage Exergy of Fuel “kW”	42.64	42.85	43.24	43.65	43.86	44.26
Two Stage Exergy of Product “kW”	19.91	19.91	19.91	19.91	19.91	19.91
HTC Mass flow Rate (Kg/sec)	0.06687	0.3123	0.2532	0.616	0.3157	0.2560
MTC Mass flow Rate (Kg/sec)	0.1464	0.1464	0.1464	0.1695	0.1695	0.1695
LTC Mass flow Rate (Kg/sec)	0.0969	0.0969	0.0969	0.0969	0.0969	0.0969
Q_Cond_HTC“kW”	92.56	92.77	93.17	93.57	93.78	94.18
Q_Cond_MTC“kW”	70.72	70.72	70.72	71.49	71.49	71.49
Q_Cond_LTC“kW”	49.92	49.92	49.92	49.92	49.92	49.92
Q_EVA_LTC“kW”	35.167	35.167	35.167	35.167	35.167	35.167
HTC compressor Work“kW”	21.84	22.08	22.45	22.07	22.25	22.69
MTC compressor Work“kW”	20.8	20.8	20.8	21.57	21.57	21.57
LTC compressor Work“kW”	14.75	14.75	14.75	14.75	14.75	14.75
System compressor Work“kW”	57.29	57.6	58.0	58.4	58.61	59.02
$COP_{\_HTC}$	3.239	3.208	3.151	3.239	3.208	3.151
HTC Exergy Destruction Ratio (EDR)	1.179	1.179	1.179	1.179	1.20	1.24
HTC Exergetic Efficiency	0.4589	0.4589	0.4589	0.4589	0.4545	0.4464
HTC Exergy of Fuel “kW”	21.84	22.08	22.45	22.07	22.25	22.69
HTC Exergy of Product “kW”	10.02	10.02	10.02	10.13	10.13	10.13

Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-7(b) respectively. It was observed that HC-290 used in HTC cycle R170 in the medium temperature cycle &R1150 ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances for the ultra-low temperature applications.

3.9 Comparison of thermodynamic performances of cascaded vapour compression refrigeration system using low GWP ecofriendly HFO &HC refrigerants for ultra-low temperature applications

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-8(a) to table-8(b) respectively and it was found that the system cascaded VCRS using R1233zd(E)in the high temperature cycle &R1336mzz(Z)in the medium temperature cycle &R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances than other cascaded vapour compression refrigeration system for ultra-low temperature applications

Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other HFO refrigerants in the medium temperature cycle &other ecofriendly HFO refrigerants in the low temperature cycle is shown in Table-8(a) to Table-8(b) respectively. It was observed that HC-290 used in HTC cycle R170 in the medium temperature cycle &R1150 ecofriendly refrigerant in the low temperature cycle gives lowest thermodynamic performances for the ultra-low temperature applications.

Table-7(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-12°C, $T_{\_Eva\text{-}MTC}$= -60°C , $T_{\_Eva\ LTC}$= - 100°C, $Temp\_Overlaping_{\_MTC}$=5°C, $Temp\_Overlaping_{\_LTC}$=5°C, Compressor efficiency$_{_HTC}$=75%, Compressor efficiency$_{_MTC}$=75%, Compressor efficiency$_{_LTC}$=75%)

Refrigerant	System-7	System-8	System-9	System-10
HTC_Refrigerant	R1270	R-290	R404a	R600a
MTC_Refrigerant	R170	R170	R23	R170
LTC_Refrigerant	R1150	R1270	R14	R1150
$COP_{\_Three\ Stage\ \_Cascade}$	0.5845	0.6014	0.4758	0.5924
($EDR_{Three\_Stage\ CVCRS}$)	1.37	1.303	1.911	1.338
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.4218	0.4218	0.4218	0.4276
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	60.17	58.47	73.92	59.37
Exergy of $Product_{Three\ Stage}$ "kW"	25.39	25.39	25.39	25.39
COP_{HTC}	2.998	2.991	2.998	2.998
COP_{MTC}	2.314	2.314	2.314	2.314
COP_{LTC}	2.383	2.541	2.383	2.383
$COP_{Two\ Stage\_Cascade}$	1.009	1.098	1.017	1.1119
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.354	1.284	1.466	1.241
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.4248	0.4238	0.4055	0.4462
Two Stage Exergy of Fuel "kW"	45.41	44.64	54.08	44.61
Two Stage Exergy of Product "kW"	19.91	19.54	21.93	19.91
HTC Mass flow Rate (Kg/sec)	0.2735	0.2770	0.7964	0.2955
MTC Mass flow Rate (Kg/sec)	0.1695	0.1664	0.3834	0.1695
LTC Mass flow Rate (Kg/sec)	0.0969	0.08844	0.5906	0.0969
Q_Cond_HTC"kW"	95.34	93.64	109.1	94.54
Q_Cond_MTC"kW"	71.49	70.18	71.2	71.49
Q_Cond_LTC"kW"	49.92	49.0	55.0	49.92
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167
HTC compressor Work"kW"	23.84	23.46	29.88	23.04
MTC compressor Work"kW"	21.57	21.17	24.20	21.57
LTC compressor Work"kW"	14.75	13.84	19.83	14.75
System compressor Work"kW"	60.17	58.47	73.92	59.37
$COP_{\_HTC}$	2.998	2.991	2.65	3.103
HTC Exergy Destruction Ratio (EDR)	1.354	1.359	1.663	1.275
HTC Exergetic Efficiency	0.4248	0.4238	0.3755	0.4396
HTC Exergy of Fuel "kW"	23.84	23.46	29.88	23.04
HTC Exergy of Product "kW"	10.13	9.943	11.22	10.13

Table-8(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=17.5835kW, T_Cond=50°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva\text{-}MTC}$= -90°C, $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Refrigerant	System-1	System-2	System-3	System-4	System-5
HTC_Refrigerant	R-1250	R-600a	R-290	R1233zd(E)	R1233zd(E)
MTC_Refrigerant	R170	R170	R170	R1336mzz(Z)	R1225ye(Z)
LTC_Refrigerant	R1150	R1150	R1150	R1225ye(Z)	R1336mzz(Z)
$COP_{\_Three\ Stage\ \_Cascade}$	0.2635	0.2662	0.2624	0.2951	0.2913
($EDR_{Three\_Stage\ CVCRS}$)	2.062	2.032	2.075	1.735	1.771
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3266	0.3298	0.3252	0.3656	0.3609
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	66.72	66.07	67.0	59.59	60.37
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	21.79	21.79	21.79	21.79
COP_{HTC}	1.896	1.940	1.878	2.049	2.049
COP_{MTC}	1.428	1.428	1.428	1.537	1.574
COP_{LTC}	1.182	1.182	1.182	1.271	1.217
$COP_{Two\ Stage\_Cascade}$	0.6262	0.6343	0.6229	0.6867	0.6976

Exergy Destruction Ratio (EDR_$_{\text{Two Stage_CRVS}}$)	1.543	1.511	1.428	1.319	1.289
Exergetic Efficiency_ $_{\text{Two Stage\_CRVS}}$	0.3932	0.3983	0.3911	0.4312	0.4380
Two Stage Exergy of Fuel “kW”	51.84	51.18	52.12	45.76	45.92
Two Stage Exergy of Product “kW”	20.38	20.38	20.38	19.73	20.11
HTC Mass flow Rate (Kg/sec)	0.227	0.253	0.2375	0.3877	0.3916
MTC Mass flow Rate (Kg/sec)	0.1068	0.1068	0.1068	0.2215	0.2503
LTC Mass flow Rate (Kg/sec)	0.04566	0.04566	0.04566	0.1083	0.09459
Q_Cond_HTC“kW”	84.31	83.65	84.59	77.18	77.95
Q_Cond_MTC“kW”	55.20	55.20	55.20	51.86	52.38
Q_Cond_LTC“kW”	32.46	32.46	32.46	31.42	32.03
Q_EVA_LTC“kW”	17.5835	17.5835	17.5835	17.5835	17.5835
HTC compressor Work“kW”	29.21	28.45	29.39	25.32	25.57
MTC compressor Work“kW”	22.73	22.73	22.73	20.44	20.35
LTC compressor Work“kW”	14.88	14.88	14.88	13.84	14.45
System compressor Work“kW”	66.72	66.07	67.0	59.59	60.37
COP_$_{\text{HTC}}$	1.856	1.94	1.878	2.049	2.049
HTC Exergy Destruction Ratio (EDR)	1.332	1.279	1.354	1.158	1.158
HTC Exergetic Efficiency	0.4289	0.4388	0.4248	0.4634	0.4634
HTC Exergy of Fuel “kW”	29.21	28.45	29.39	25.32	25.57
HTC Exergy of Product “kW”	12.49	12.49	12.49	11.73	11.85

Table-8(b)Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50°C, T_ambient=25°C, T_$_{\text{Eva HTC}}$ =-30°C, T_$_{\text{Eva-MTC}}$= -75°C , T_$_{\text{Eva LTC}}$= - 130°C, Temp_Overlaping_$_{\text{MTC}}$=10°C, Temp_Overlaping_$_{\text{LTC}}$=10°C, Compressor efficiency_$_{\text{HTC}}$=75%, Compressor efficiency_$_{\text{MTC}}$=75%, Compressor efficiency_$_{\text{LTC}}$=75%)

Refrigerant	System 6	System 7	System 8	System 9
HTC_Refrigerant	R-1243zf	R-1243zf	R-1234 ze(E)	R-1234 ze(E)
MTC_Refrigerant	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)
LTC_Refrigerant	R1225ye(Z)	R1336mzz(Z)	R1225ye(Z)	R1336mzz(Z)
COP_ $_{\text{Three Stage \_Cascade}}$	0.2812	0.2777	0.2825	0.279
(EDR$_{\text{Three_Stage CVCRS}}$)	1.869	1.906	1.856	1.893
Exergetic Efficiency$_{\text{Three Stage CVCRS}}$)	0.3485	0.3441	0.3501	0.3457
Exergy of Fuel$_{\text{Three Stage_CVCRS}}$ “kW”	62.52	63.33	62.23	63.03
Exergy of Product$_{\text{Three Stage}}$ “kW”	21.79	21.79	21.79	21.79
COP_{HTC}	1.836	1.836	1.855	1.855
COP_{MTC}	1.537	1.574	1.537	1.574
COP_{LTC}	1.271	1.217	1.217	1.217
COP$_{\text{Two Stage_Cascade}}$	0.6454	0.6554	0.6493	0.6594
EDR_$_{\text{Two Stage_CRVS}}$)	1.468	1.430	1.453	1.415
Exergetic Efficiency_ $_{\text{Two Stage\_CRVS}}$	0.4053	0.4115	0.4077	0.4140
Two Stage Exergy of Fuel “kW”	48.68	48.88	48.39	48.58
Two Stage Exergy of Product “kW”	19.73	20.11	19.73	20.11
HTC Mass flow Rate (Kg/sec)	0.3877	0.3916	0.4833	0.4882
MTC Mass flow Rate (Kg/sec)	0.2215	0.2503	0.2215	0.2503
LTC Mass flow Rate (Kg/sec)	0.1083	0.09459	0.1083	0.09459
Q_Cond_HTC“kW”	80.11	80.91	79.82	80.62
Q_Cond_MTC“kW”	51.86	52.38	51.86	52.38
Q_Cond_LTC“kW”	31.42	32.03	31.42	32.03
Q_EVA_LTC“kW”	17.5835	17.5835	17.5835	17.5835
HTC compressor Work“kW”	28.24	28.53	27.95	28.23
MTC compressor Work“kW”	20.44	20.35	20.44	20.35
LTC compressor Work“kW”	13.84	14.45	13.84	14.45
System compressor Work“kW”	62.52	63.33	62.23	63.03
COP_$_{\text{HTC}}$	1.855	1.855	1.855	1.855
HTC_EDR	1.383	1.383	1.383	1.383
HTC Exergetic Efficiency	0.4197	0.4197	0.4197	0.4197
HTC Exergy of Fuel “kW”	28.24	28.53	27.95	28.23
HTC Exergy of Product “kW”	11.73	11.85	11.73	11.85

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded VCRS for ultra-low temperature applications using refrigerant (R-717), HFC-152a, R161 in the high temperature cycle using HFC41 & R170 in medium temperature cycle and R1150 in ultra-low temperature cycle also shown in table-8(a) respectively and it was found that the system cascaded VCRS using R-717 in the high temperature cycle &R41 the medium temperature cycle & R1150 ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances than other cascaded VCRS using R152a & R161in the high temperature cycle and R41, R170 in the medium temperature cycle &R1150 refrigerant. Similarly, the cascaded VCRS using was observed that R-161 used in HTC cycle R170 in the medium temperature cycle & R1150 gives lowest thermodynamic performances.

Table-8(c): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva-MTC}$= -75°C , $T_{\_Eva\ LTC}$= - 130°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, $Compressor\ efficiency_{\_HTC}$=75%, $Compressor\ efficiency_{\_MTC}$=75%, $Compressor\ efficiency_{\_LTC}$=75%)

Refrigerant	System-10	System-11	System-12	System-13	System-14	System-15
HTC Refrigerant	R717	R152*a*	R161	R717	R152*a*	R161
MTC_Refrigerant	R41	R41	R41	R170	R170	R170
LTC_Refrigerant	R1150	R1150	R1150	R1150	R1150	R1150
$COP_{\_Three\ Stage\ \_Cascade}$	0.3048	0.3040	0.3020	0.3030	0.3022	0.3002
($EDR_{Three\_Stage\ CVCRS}$)	1.647	1.654	1.672	1.663	1.670	1.688
Exergetic Efficiency $_{Three\ Stage\ CVCRS}$	0.3778	0.3768	0.3742	0.3756	0.3746	0.372
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	115.4	115.70	116.5	116.1	116.4	117.2
Exergy of $Product_{\_Three\ Stage}$ "kW"	43.58	43.58	43.58	43.58	43.58	43.58
COP_{HTC}	2.495	2.478	2.434	2.495	2.478	2.434
COP_{MTC}	1.752	1.752	1.752	1.730	1.730	1.730
COP_{LTC}	1.058	1.058	1.058	1.058	1.058	1.058
$COP_{Two\ Stage\_Cascade}$	0.8331	0.830	0.8222	0.8261	0.8231	0.8153
$EDR_{\_Two\ Stage\_CRVS}$	1.208	1.216	1.237	1.227	1.235	1.256
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.4529	0.4529	0.4555	0.4491	0.4474	0.4432
Two Stage Exergy of Fuel "kW"	82.12	82.42	83.2	82.81	83.12	83.91
Two Stage Exergy of Product "kW"	37.19	37.19	37.19	37.19	37.19	37.19
HTC Mass flow Rate (Kg/sec)	0.1029	0.490	0.3963	0.1034	0.4923	0.3942
MTC Mass flow Rate (Kg/sec)	0.1940	0.1940	0.1940	0.2235	0.2235	0.2235
LTC Mass flow Rate (Kg/sec)	0.0944	0.0944	0.0944	0.0944	0.0944	0.0955
Q_Cond_HTC"kW"	150.5	150.8	151.6	151.2	151.5	151.3
Q_Cond_MTC"kW"	107.5	107.5	107.5	108.0	108.0	108.0
Q_Cond_LTC"kW"	68.41	68.41	68.41	68.41	68.41	68.41
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC compressor Work"kW"	43.06	43.06	44.15	43.26	43.57	44.36
MTC compressor Work"kW"	39.05	39.05	39.05	39.55	39.55	39.55
LTC compressor Work"kW"	33.24	33.24	33.24	33.24	33.24	33.24
System compressor Work"kW"	115.4	115.70	116.5	116.1	116.4	117.20
$COP_{\_HTC}$	2.495	2.478	2.434	2.495	2.478	2.434
HTC Exergy Destruction Ratio (EDR)	1.146	1.156	1.196	1.141	1.156	1.196
HTC Exergetic Efficiency	0.4670	0.4638	0.4555	0.4670	0.4638	0.4555
HTC Exergy of Fuel "kW"	43.06	43.06	44.15	43.26	43.57	44.36
HTC Exergy of Product "kW"	20.11	20.11	20.11	20.20	20.20	20.20

3.10 Comparison of thermodynamic performances of cascaded vapour compression refrigeration system using low GWP ecofriendly HFO &HC refrigerants

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications using low GWP ecofriendly HFO &HC refrigerants in HTC also shown in table-8(d) respectively and it was found that the system cascaded VCRS using R1250 in the high temperature cycle & R170in the medium temperature cycle & R1150ecofriendly refrigerant in the low temperature cycle gives slightly lower thermodynamic performances than other cascaded vapour compression refrigeration system for ultra-low temperature applications

Similarly, the cascaded VCRS using other cascaded systems in the other HC refrigerants in the high temperature cycle &HC-170, R41 refrigerants in the medium temperature cycle &other ecofriendly R1150 refrigerant in the low temperature cycle gives better thermodynamic performances. than R-161 used in HTC cycle R23 in the medium temperature cycle &R14 ecofriendly refrigerant in the low temperature cycle gives lowest thermodynamic performances for the ultra-low temperature applications. It is concluded that three staged cascaded vapour compression systems using R-1150 can replace R 14 in low temperature cycle (LTC) and R41 & R170 can replace R23 in medium temperature cycle (LTC).

3.11 Comparison of thermodynamic performances of cascaded vapour compression refrigeration system using low GWP ecofriendly HFO refrigerants in high temperature cycle for -130°C

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with gives highest thermodynamic performances than other cascaded vapour compression refrigeration system.
Similarly, the cascaded VCRS using other cascaded systems in the other HFO refrigerants in the high temperature cycle &other R-41 and R170 refrigerants in the medium temperature cycle &other ecofriendly R1150 refrigerant in the low temperature cycle is shown in Table-8(e) to Table-8(f) respectively. It was observed that three staged cascaded vapour conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-8(e) to table-8(f) respectively and it was found that the system cascaded VCRS using R1233zd(E)in the high temperature cycle &R170 in the medium temperature cycle &R1150 ecofriendly refrigerant in the low temperature cycle

compression systems using HFO refrigerants in the high temperature cycle cycle and R170 in the medium temperature cycle &R1150 ecofriendly refrigerant in the low temperature cycle gives better thermodynamic performances than HFO refrigerants in the high temperature cycle cycle and R41 in the medium temperature cycle &R1150 ecofriendly refrigerant in the low temperature cycle.

Table-8(d): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva\text{-}MTC}$= -75°C , $T_{\_Eva\ LTC}$= - 130°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Refrigerant	System-1	System-2	System-3	System-4	System-5	System-6	System-7	System-8
HTC_Refrigerant	R1250	R1250	R290	R600a	R600*a*	R717	R152a	R161
MTC_Refrigerant	R170	R170	R41	R41	R170	R23	R23	R23
LTC_Refrigerant	R1150	R1150	R1150	R1150	R1150	R14	R14	R14
$COP_{\_Three\ Stage\ \_Cascade}$	0.2939	0.2957	0.2949	0.2989	0.2971	0.2954	0.2946	0.2769
($EDR_{Three\_Stage\ CVCRS}$)	1.746	1.729	1.736	1.70	1.716	1.732	1.739	1.905
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3642	0.3661	0.3655	0.3701	0.3682	0.3661	0.3651	0.343
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	119.6	118.9	119.2	117.7	118.4	119.0	119.4	127.0
Exergy of $Product_{Three\ Stage}$ "kW"	43.58	43.58	43.58	43.58	43.58	43.58	43.58	43.58
COP_{HTC}	2.304	2.304	2.290	2.370	2.370	2.495	2.478	2.434
COP_{MTC}	1.730	1.752	1.752	1.752	1.730	1.909	1.909	1.909
COP_{LTC}	1.058	1.058	1.058	1.058	1.058	0.9484	0.9484	0.9484
$COP_{Two\ Stage\_\_Cascade}$	0.7918	0.7983	0.7956	0.8105	0.8038	0.8814	0.8781	0.8032
$EDR\__{Two\ Stage\_CRVS}$	1.319	1.304	1.312	1.27	1.289	1.087	1.095	1.29
Exergetic $Efficiency\__{\ Two\ Stage\_CRVS}$	0.4312	0.4340	0.4325	0.4406	0.437	0.4791	0.4773	0.4366
Two Stage Exergy of Fuel "kW"	86.40	85.69	85.99	84.40	85.11	81.97	82.82	89.95
Two Stage Exergy of Product "kW"	37.19	37.19	37.19	37.19	37.19	37.19	37.19	37.19
HTC Mass flow Rate (Kg/sec)	0.4294	0.4274	0.4445	0.4699	0.4721	0.1054	0.5020	0.4240
MTC Mass flow Rate (Kg/sec)	0.2235	0.1940	0.1940	0.1940	0.2235	0.5557	0.5557	0.4745
LTC Mass flow Rate (Kg/sec)	0.0944	0.0944	0.0944	0.0944	0.0944	0.4777	0.4777	0.4777
Q_Cond_HTC"kW"	154.8	154.1	154.4	152.8	153.5	154.2	154.5	162.2
Q_Cond_MTC"kW"	108.0	107.5	107.5	107.5	108.0	110.1	110.1	115.0
Q_Cond_LTC"kW"	68.41	68.41	68.41	68.41	68.41	72.25	72.25	72.25
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC compressor Work"kW"	46.85	46.64	46.93	45.35	45.56	44.12	44.43	47.23
MTC compressor Work"kW"	39.55	39.05	39.05	39.05	39.55	37.85	37.85	42.71
LTC compressor Work"kW"	33.24	33.24	33.24	33.24	33.24	37.08	37.08	37.08
System compressor Work"kW"	119.6	118.9	119.2	117.7	118.4	119.0	119.4	127.0
$COP_{\_HTC}$	2.304	2.304	2.290	2.370	2.370	2.495	2.478	2.434
HTC Exergy Destruction Ratio (EDR)	1.319	1.319	1.334	1.225	1.225	1.141	1.156	1.196
HTC Exergetic Efficiency	0.4312	0.4312	0.4285	0.4435	0.4358	0.4670	0.4638	0.4555
HTC Exergy of Fuel "kW"	46.85	46.64	46.93	45.35	45.56	44.12	44.43	47.23
HTC Exergy of Product "kW"	20.21	20.11	20.11	20.11	20.20	20.60	20.60	21.51

Table-8(e): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=175.835kW, T_Cond=50ºC, T_ambient=25ºC, T_Eva HTC =-30ºC, T_Eva-MTC= -75ºC , T_Eva LTC= - 130ºC, Temp_Overlaping_MTC=10ºC, Temp_Overlaping_LTC=10ºC, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System-1	System-2	System-3	System-4	System-5	System-6
HTC_Refrigerant	R1243zf	R1233zd(E)	R1243zf	R1233zd(E)	R1336mzz (Z)	R1225ye(Z)
MTC_Refrigerant	R41	R41	R170	R170	R170	R170
LTC_Refrigerant	R1150	R1150	R1150	R1150	R1150	R1150
COP_ Three Stage _Cascade	0.2929	0.3046	0.2912	0.3024	0.2975	0.2915
(EDRThree_Stage CVCRS)	1.755	1.649	1.771	1.665	1.713	1.768
Exergetic EfficiencyThree Stage CVCRS)	0.3630	0.3776	0.3606	0.3752	0.3687	0.3612
Exergy of FuelThree Stage_CVCRS "kW"	120.0	115.4	120.8	116.1	118.2	120.6
Exergy of ProductThree Stage "kW"	43.58	43.58	43.58	43.58	43.58	43.58
COPHTC	2.251	2.491	2.251	2.491	2.377	2.257
COPMTC	1.752	1.752	1.73	1.73	1.73	1.73
COPLTC	1.058	1.058	1.058	1.058	1.058	1.058
COPTwo Stage_Cascade	0.7881	0.8322	0.7817	0.8253	0.8252	0.7828
EDR_Two Stage_CRVS	1.374	1.210	1.353	1.229	1.285	1.350
Exergetic Efficiency_ Two Stage_CRVS	0.4284	0.4524	0.4212	0.4486	0.4377	0.4255
Two Stage Exergy of Fuel "kW"	86.6	82.2	87.52	82.09	84.96	87.39
Two Stage Exergy of Product "kW"	37.19	37.19	37.19	37.19	37.19	37.19
HTC Mass flow Rate (Kg/sec)	0.8402	0.7706	0.8402	0.7742	0.9389	1.121
MTC Mass flow Rate (Kg/sec)	0.1940	0.1940	0.2235	0.2235	0.2235	0.2235
LTC Mass flow Rate (Kg/sec)	0.0944	0.0944	0.0944	0.0944	0.0944	0.0944
Q_Cond_HTC"kW"	155.2	150.6	155.9	151.3	153.4	155.8
Q_Cond_MTC"kW"	107.5	107.5	108.0	108.0	108.0	108.0
Q_Cond_LTC"kW"	68.41	68.41	68.41	68.41	68.41	68.41
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC compressor Work"kW"	47.75	43.15	47.97	43.35	45.41	47.84
MTC compressor Work"kW"	39.05	39.05	39.55	39.55	39.55	39.55
LTC compressor Work"kW"	33.24	33.24	33.24	33.24	33.24	33.24
System compressor Work"kW"	120.0	115.4	120.8	116.1	118.2	120.6
COP_HTC	2.251	2.491	2.251	2.491	2.377	2.257
HTC_ EDR	1.374	1.145	1.374	1.145	1.248	1.368
HTC Exergetic Efficiency	0.4212	0.4661	0.4212	0.4661	0.4449	0.4223
HTC Exergy of Fuel "kW"	47.75	43.15	47.97	43.35	45.41	47.84
HTC Exergy of Product "kW"	20.11	20.11	20.20	20.20	20.20	20.20

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-8(f) respectively and it was found that the system cascaded VCRS using R1233zd(E)in the high temperature cycle &R1336mzz(Z)in the medium temperature cycle &R1225ye(Z) ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances than other cascaded vapour compression refrigeration system.

Table-8(f): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.165kW, T_Cond=50ºC, T_ambient=25ºC, T_Eva HTC =-30ºC, T_Eva-MTC= -75ºC , T_Eva LTC= - 130ºC, Temp_Overlaping_MTC=10ºC, Temp_Overlaping_LTC=10ºC, Compressor efficiency_HTC=75%, Compressor efficiency_MTC=75%, Compressor efficiency_LTC=75%)

Refrigerant	System-7	System-8	System-9	System-10
HTC_Refrigerant	R1233zd(E)	R1233zd(E)	R1243zf	R1243zf
MTC_Refrigerant	R1336mzz (Z)	R1225ye(Z)	R1336mzz (Z)	R1225ye(Z)
LTC_Refrigerant	R1225ye(Z)	R1336mzz (Z)	R1225ye(Z)	R1336mzz (Z)
COP_ Three Stage _Cascade	0.3317	0.3243	0.3187	0.3116
(EDRThree_Stage CVCRS)	1.433	1.589	1.532	1.589
Exergetic EfficiencyThree Stage CVCRS)	0.4110	0.4018	0.3948	0.3862
Exergy of FuelThree Stage_CVCRS "kW"	106.0	108.5	110.3	112.8
Exergy of ProductThree Stage "kW"	43.58	43.58	43.58	43.58
COPHTC	2.491	2.491	2.251	2.251
COPMTC	1.878	1.909	1.878	1.909

COP_{LTC}	1.150	1.096	1.150	1.096
$COP_{Two\ Stage\_Cascade}$	0.8711	0.8805	0.824	0.8326
($EDR\__{Two\ Stage\_CRVS}$)	1.112	1.089	1.232	1.209
Exergetic Efficiency_ $_{Two\ Stage\_CRVS}$	0.4736	0.4786	0.4480	0.4526
Two Stage Exergy of Fuel "kW"	75.46	76.38	79.77	80.76
Two Stage Exergy of Product "kW"	35.74	36.56	35.74	36.56
HTC Mass flow Rate (Kg/sec)	0.7224	0.7348	0.7877	0.8012
MTC Mass flow Rate (Kg/sec)	0.4546	0.5173	0.4546	0.5173
LTC Mass flow Rate (Kg/sec)	0.2224	0.1956	0.2224	0.1956
Q_Cond_HTC"kW"	141.2	143.6	145.5	148.0
Q_Cond_MTC"kW"	100.7	102.5	100.7	102.5
Q_Cond_LTC"kW"	65.74	67.25	65.74	67.25
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167
HTC compressor Work"kW"	40.45	41.15	44.76	45.53
MTC compressor Work"kW"	35.01	35.23	35.01	35.23
LTC compressor Work"kW"	30.57	32.08	30.57	32.08
System compressor Work"kW"	106.0	108.5	110.3	112.8
$COP\__{HTC}$	2.491	2.491	2.251	2.251
HTC_EDR	1.145	1.145	1.374	1.374
HTC Exergetic Efficiency	0.4661	0.4661	0.4212	0.4212

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-8(g) respectively and it was found that the system cascaded VCRS using R717& R152a in the high temperature cycle gives best thermodynamic performances than other cascaded vapour compression refrigeration system using R161in the high temperature cycle for ultra-low temperature applications.

Table-8(g): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.165kW, T_Cond=50°C, T_ambient=25°C, $T\__{Eva\ HTC}$ =-30°C, $T\__{Eva-MTC}$= -75°C , $T\__{Eva\ LTC}$= - 130°C, $Temp\_Overlaping\__{MTC}$=10°C, $Temp\_Overlaping\__{LTC}$=10°C, Compressor $efficiency\__{HTC}$=75%, Compressor $efficiency\__{MTC}$=75%, Compressor $efficiency\__{LTC}$=75%)

Refrigerant	System-11	System-12	System-13
HTC_Refrigerant	R717	R152a	R161
MTC_Refrigerant	R23	R23	R23
LTC_Refrigerant	R14	R14	R14
COP_ $_{Three\ Stage\ \_Cascade}$	0.2954	0.2946	0.2769
($EDR_{Three\_Stage\ CVCRS}$)	1.732	1.739	1.915
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3661	0.3651	0.3430
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	119.0	119.4	127.0
Exergy of $Product_{Three\ Stage}$ "kW"	43.58	43.58	43.58
COP_{HTC}	2.495	2.478	2.434
COP_{MTC}	1.909	1.909	1.909
COP_{LTC}	0.9484	0.9484	0.9484
$COP_{Two\ Stage\_Cascade}$	0.8814	0.8781	0.8032
Exergy Destruction Ratio ($EDR\__{Two\ Stage\_CRVS}$)	1.087	1.095	1.290
Exergetic Efficiency_ $_{Two\ Stage\_CRVS}$	0.4791	0.4773	0.4366
Two Stage Exergy of Fuel "kW"	81.97	82.28	89.95
Two Stage Exergy of Product "kW"	39.27	39.27	39.27
HTC Mass flow Rate (Kg/sec)	0.1054	0.5020	0.4240
MTC Mass flow Rate (Kg/sec)	0.5557	0.5557	0.5557
LTC Mass flow Rate (Kg/sec)	0.4777	0.4777	0.4777
Q_Cond_HTC"kW"	154.2	154.5	162.2
Q_Cond_MTC"kW"	110.1	110.1	110.1
Q_Cond_LTC"kW"	72.25	72.25	72.25
Q_EVA_LTC"kW"	35.167	35.167	35.167
HTC compressor Work"kW"	44.12	44.43	47.23
MTC compressor Work"kW"	37.85	37.85	37.85
LTC compressor Work"kW"	37.08	37.08	37.08
System compressor Work"kW"	119.0	119.4	127.0
$COP\__{HTC}$	2.495	2.478	2.434
HTC Exergy Destruction Ratio (EDR)	1.141	1.156	1.196

3.12 Comparison of thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants

Following seven three staged cascaded vapour compression systems have been considered for comparison

System-1: Cascaded Vapour compression refrigeration systems using R290 in HTC R-170in MTC and R-1150in LTC

System-2: Cascaded Vapour compression refrigeration systems using R600a in HTC R170 in MTC and R-1150 in LTC

System-3: Cascaded Vapour compression refrigeration systems using R1270 in HTC R-170in MTC and R-1150in LTC

System-4: Cascaded Vapour compression refrigeration systems using R1270 in HTC R170in MTC and R-14 in LTC

System-5: Cascaded Vapour compression refrigeration systems using R290 in HTC R-41in MTC and R-14in LTC

System-6: Cascaded Vapour compression refrigeration systems using R404a in HTC R-41in MTC and R-14in LTC

System-7: Cascaded Vapour compression refrigeration systems using R404a in HTC R-23in MTC and R-14in LTC

The thermodynamic performances of three staged cascaded vapour compression systems have been compared with conventional cascaded vapour compression refrigeration system for ultra-low temperature applications also shown in table-8(f) and it was found that the system cascaded VCRS using R600a in the high temperature cycle & HTC R170 in the medium temperature cycle & R-1150 ecofriendly refrigerant in the low temperature cycle gives highest thermodynamic performances than other cascaded vapour compression refrigeration system for ultra-low temperature applications The lowest thermodynamic performances than other cascaded vapour compression refrigeration using R R404a in the high temperature cycle & HTC R-23in the medium temperature cycle & R-14 ecofriendly refrigerant in the low temperature cycle gives lowest thermodynamic performances it can be concluded that R1150 can replace R14 in LTC R41 & R170 cn replace R23 in MTC and R717, R152a,R161, R600a, R290, R1270 cn replace R404a in High temperature cycle

Table-8(f)Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.165kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva\text{-}MTC}$= -80°C , $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=75%, Compressor $efficiency_{\_MTC}$=75%, Compressor $efficiency_{\_LTC}$=75%)

Cascaded Vapour compression refrigeration systems	System 1	System 2	System 3	System 4	System 5	System 6	System 7
$COP_{\_\ Three\ Stage\ \_Cascade}$	0.2575	0.2608	0.2581	0.2336	0.2368	0.2244	0.2195
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3192	0.3232	0.3198	0.2898	0.2931	0.2781	0.272

3.13 Effect of LTC evaporator temperature on thermodynamic performances of cascaded VCRS using low GWP R1270 refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of LTC evaporator temperature (°C) on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-9 and it was found that the increasing LTC evaporator temperature of cascaded VCRS, the cascaded three staged first law efficiency (COP) is increasing while exergetic efficiency is decreasing

Table-9: Effect of LTC evaporator temperature (°C) on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R1250 refrigerant in HTC R1250 refrigerant in HTC (Q_Eva=17.5835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva\text{-}MTC}$= -80°C, $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)

LTC Evaporator temperature (°C)	-140	-135	-130	-125	-120
$COP_{\_\ Three\ Stage\ \_Cascade}$	0.2581	0.2852	0.3134	0.3427	0.3730
($EDR_{Three\_Stage\ CVCRS}$)	2.127	2.028	1.947	1.882	1.832
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3198	0.3303	0.3393	0.3469	0.3531
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	68.14	61.66	56.11	51.31	47.15
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	20.36	19.04	17.8	16.65
COP_{HTC}	2.424	2.424	2.424	2.424	2.424
COP_{MTC}	1.464	1.464	1.464	1.464	1.464
COP_{LTC}	0.9519	1.117	1.311	1.543	1.823
$COP_{Two\ Stage\_Cascade}$	0.7260	0.7260	0.7260	0.7260	0.7260
Exergy Destruction Ratio ($EDR\__{Two\ Stage\_CRVS}$)	1.534	1.534	1.534	1.534	1.534
Exergetic $Efficiency\__{\ Two\ Stage\_CRVS}$	0.3947	0.3947	0.3947	0.3947	0.3947
Two Stage Exergy of Fuel "kW"	49.66	45.91	42.69	39.92	37.5
Two Stage Exergy of Product "kW"	19.6	18.12	16.85	15.75	14.80
HTC Mass flow Rate (Kg/sec)	0.2394	0.2213	0.2058	0.1924	0.1808
MTC Mass flow Rate (Kg/sec)	0.1270	0.1114	0.1092	0.1021	0.09588
LTC Mass flow Rate (Kg/sec)	0.04887	0.04811	0.04738	0.046690	0.04602
Q_Cond_HTC"kW"	85.72	79.24	73.69	68.9	64.73
Q_Cond_MTC"kW"	60.68	56.1	52.17	48.78	45.82

Q_Cond_LTC"kW"	36.06	33.33	31.0	28.98	27.23
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	25.03	23.14	21.52	20.12	18.9
MTC compressor Work"kW"	24.63	22.77	21.17	19.8	18.6
LTC compressor Work"kW"	18.47	15.75	13.41	11.40	9.643
System compressor Work"kW"	68.14	61.66	56.11	51.31	47.15
$COP_{\_HTC}$	2.424	2.424	2.424	2.424	2.424
HTC Exergy Destruction Ratio (EDR)	1.321	1.321	1.321	1.321	1.321
HTC Exergetic Efficiency	0.4309	0.4309	0.4309	0.4309	0.4309
HTC Exergy of Fuel "kW"	25.03	23.14	21.52	20.12	18.9
HTC Exergy of Product "kW"	10.79	9.972	9.274	8.67	8.146

3.14 Effect of MTC evaporator temperature on thermodynamic performances of cascaded VCRS system using ecofriendly low GWP propylene (R1270) refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of MTC evaporator temperature (°C) on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-10 and it was found that by the increasing *MTC evaporator temperature* of cascaded VCRS, the cascaded three staged first law efficiency (COP) is increasing and reaching to maximum value and then decreasing. The optimum value of MTC evaporator temperature was found to be -82°C to -83°C while exergetic efficiency is also increasing and reaching to maximum value and then decreasing

Table-10: Effect of MTC evaporator temperature (°C) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP* R1250 *refrigerant* in HTC R1250 *refrigerant* in HTC *(Q_Eva=17.5835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva-MTC}$= -80°C , $T_{\_Eva\ LTC}$= - 140°C, temperature _Overlaping$_{_MTC}$=10°C, temperature _Overlaping$_{_LTC}$=10°C, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)*

MTC Evaporator temperature (°C)	-100	-95	-90	-85	-80	-75
$COP_{\_Three\ Stage\ \_Cascade}$	0.2518	0.2549	0.2570	0.2580	0.2581	0.2571
($EDR_{Three\_Stage\ CVCRS}$)	2.205	2.166	2.14	2.127	2.127	2.139
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.312	0.3159	0.3184	0.3198	0.3198	0.3185
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	69.84	68.99	68.42	68.14	68.14	68.414
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	21.79	21.79	21.79	21.79	21.79
COP_{HTC}	2.424	2.424	2.424	2.424	2.424	2.424
COP_{MTC}	0.8967	1.012	1.142	1.292	1.464	1.664
COP_{LTC}	1.506	1.328	1.182	1.058	0.9519	0.8601
$COP_{Two\ Stage\_Cascade}$	0.5031	0.5528	0.6063	0.6639	0.7260	0.7929
Exergy Destruction Ratio ($EDR\__{Two\ Stage\_CRVS}$)	1.753	1.686	1.627	1.576	1.534	1.499
Exergetic Efficiency_ $_{Two\ Stage\_CRVS}$	0.3632	0.3724	0.3807	0.3882	0.3947	0.4001
Two Stage Exergy of Fuel "kW"	58.16	55.75	53.54	51.52	49.66	47.96
Two Stage Exergy of Product "kW"	21.12	20.76	20.38	20.0	19.60	19.19
HTC Mass flow Rate (Kg/sec)	0.2442	0.2418	0.2402	0.2395	0.2394	0.2402
MTC Mass flow Rate (Kg/sec)	0.112	0.11540	0.119	0.1228	0.1270	0.1314
LTC Mass flow Rate (Kg/sec)	0.0429	0.04423	0.04566	0.04720	0.04887	0.0507
Q_Cond_HTC"kW"	87.43	86.57	86.01	85.73	85.72	85.99
Q_Cond_MTC"kW"	61.89	61.29	60.89	60.69	60.68	60.87
Q_Cond_LTC"kW"	29.26	30.82	32.46	34.21	36.06	38.03
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	25.53	25.28	25.12	25.04	25.03	25.11
MTC compressor Work"kW"	32.63	30.47	28.42	26.48	24.63	22.85
LTC compressor Work"kW"	11.68	13.24	14.88	16.62	18.47	20.44
System compressor Work"kW"	69.84	68.99	68.42	68.14	68.14	68.414
$COP_{\_HTC}$	2.424	2.424	2.424	2.424	2.424	2.424
HTC Exergy Destruction Ratio (EDR)	1.321	1.321	1.321	1.321	1.321	1.321
HTC Exergetic Efficiency	0.4309	0.4309	0.4309	0.4309	0.4309	0.4309
HTC Exergy of Fuel "kW"	25.53	25.28	25.12	25.04	25.03	25.11
HTC Exergy of Product "kW	11.0	10.893	10.82	10.79	10.79	10.82

Table-11: Effect of MTC evaporator temperature (°C) on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R1250 refrigerant in HTC R1250 refrigerant in HTC (Q_Eva=17.5835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva-MTC}$= -80°C , $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)

MTC Evaporator temperature (°C)	-80	-81	-82	-83	-84	-85
$COP_{\_Three\ Stage\ \_Cascade}$	0.2581	0.2581	0.2582	0.2582	0.2581	0.2580
($EDR_{Three\_Stage\ CVCRS}$)	2.127	2.126	2.126	2.126	2.126	2.127
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3198	0.3199	0.3199	0.3199	0.3199	0.3198
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	68.14	68.12	68.11	68.11	68.12	68.14
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	21.79	21.79	21.79	21.79	21.79
COP_{HTC}	2.424	2.424	2.424	2.424	2.424	2.424
COP_{MTC}	1.464	1.427	1.392	1.392	1.324	1.292
COP_{LTC}	0.9519	0.9719	0.9927	0.9927	1.035	1.058
$COP_{Two\ Stage\_Cascade}$	0.7260	0.7132	0.7006	0.7006	0.6760	0.6639
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.534	1.542	1.550	1.550	1.567	1.576
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.3947	0.3934	0.3922	0.3922	0.3895	0.3882
Two Stage Exergy of Fuel "kW"	49.66	50.02	50.39	50.39	51.14	51.52
Two Stage Exergy of Product "kW"	19.60	19.68	19.76	19.76	19.92	20.0
HTC Mass flow Rate (Kg/sec)	0.2394	0.2394	0.2394	0.2394	0.2394	0.2395
MTC Mass flow Rate (Kg/sec)	0.1270	0.1261	0.1253	0.1253	0.1236	0.1228
LTC Mass flow Rate (Kg/sec)	0.04887	0.04853	0.04819	0.04819	0.04752	0.0472
Q_Cond_HTC"kW"	85.72	85.70	85.69	85.69	85.70	85.73
Q_Cond_MTC"kW"	60.68	60.67	60.66	60.66	60.67	60.69
Q_Cond_LTC"kW"	36.06	35.68	35.30	35.30	34.57	34.21
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	25.03	25.03	25.03	25.03	25.03	25.04
MTC compressor Work"kW"	24.63	24.99	25.36	25.36	26.11	26.48
LTC compressor Work"kW"	18.47	18.09	17.72	17.72	16.98	16.62
System compressor Work"kW"	68.14	68.12	68.11	68.11	68.12	68.14
$COP_{\_HTC}$	2.424	2.424	2.424	2.424	2.424	2.424
HTC Exergy Destruction Ratio (EDR)	1.321	1.321	1.321	1.321	1.321	1.321
HTC Exergetic Efficiency	0.4309	0.4309	0.4309	0.4309	0.4309	0.4309
HTC Exergy of Fuel "kW"	25.03	25.03	25.03	25.03	25.03	25.04
HTC Exergy of Product "kW"	10.79	10.78	10.78	10.78	10.79	10.79

3.15 Effect of HTC condenser temperature on thermodynamic performances of cascaded VCRS system using ecofriendly low GWP propylene (R1270) refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of HTC evaporator temperature (°C) on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-12 and it was found that by the decreasing *HTC* condenser *temperature* of cascaded VCRS, the cascaded three staged first law efficiency (COP) is increasing.

Table-12: Effect of HTC condenser temperature (°C) on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R1250 refrigerant in HTC R1250 refrigerant in HTC (Q_Eva=17.5835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva-MTC}$= -80°C , $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)

HTC condenser temperature (°C)	60	55	50	45	40
$COP_{\_Three\ Stage\ \_Cascade}$	0.2077	0.2209	0.2336	0.2460	0.2581
($EDR_{Three\_Stage\ CVCRS}$)	2.885	2.653	2.454	2.281	2.127
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.2574	0.2738	0.2895	0.3048	0.3198
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	86.54	79.59	75.26	71.48	68.14
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	21.79	21.79	21.79	21.79
COP_{HTC}	1.460	1.663	1.887	2.138	2.424
COP_{MTC}	1.464	1.464	1.464	1.464	1.464
COP_{LTC}	0.9519	0.9519	0.9519	0.9519	0.9519
$COP_{Two\ Stage\_Cascade}$	0.5448	0.590	0.6349	0.6802	0.7260
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	2.376	2.353	1.897	1.705	1.534
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.2962	0.3207	0.3452	0.3697	0.3947
Two Stage Exergy of Fuel "kW"	66.18	61.2	56.79	53.01	49.66

Two Stage Exergy of Product "kW"	19.60	19.60	19.60	19.60	19.60
HTC Mass flow Rate (Kg/sec)	0.3141	0.2904	0.2706	0.2539	0.2394
MTC Mass flow Rate (Kg/sec)	0.1270	0.1270	0.1270	0.1270	0.1270
LTC Mass flow Rate (Kg/sec)	0.04887	0.04887	0.04887	0.04887	0.04887
Q_Cond_HTC"kW"	102.2	97.17	92.84	89.07	85.72
Q_Cond_MTC"kW"	60.68	60.68	60.68	60.68	60.68
Q_Cond_LTC"kW"	36.06	36.06	36.06	36.06	36.06
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	41.55	36.49	32.16	28.38	25.03
MTC compressor Work"kW"	24.63	24.63	24.63	24.63	24.63
LTC compressor Work"kW"	18.47	18.47	18.47	18.47	18.47
System compressor Work"kW"	86.54	79.59	75.26	71.48	68.14
$COP_{\_HTC}$	1.460	1.663	1.887	2.138	2.424
HTC Exergy Destruction Ratio (EDR)	2.852	2.382	1.981	1.631	1.321
HTC Exergetic Efficiency	0.2596	0.2956	0.3354	0.3801	0.4309
HTC Exergy of Fuel "kW"	41.55	36.49	32.16	28.38	25.03
HTC Exergy of Product "kW"	10.79	10.79	10.79	10.79	10.79

3.16 Effect of HTC evaporator temperature on thermodynamic performances of cascaded VCRS system using ecofriendly low GWP propylene (R1270) refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of MTC evaporator temperature (°C) on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-13 and it was found that by the increasing *HTC evaporator temperature* of the cascaded three staged VCRS, the cascaded first law efficiency (COP) & exergetic efficiency (both) are decreasing

Table-13: Effect of HTC evaporator temperature (°C) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP* R1250 *refrigerant* in HTC R1250 *refrigerant* in HTC *(Q_Eva=17.5835kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-20°C, $T_{\_Eva\text{-}MTC}$= -80°C , $T_{\_Eva\ LTC}$= - 140°C, $Temp\_Overlaping_{\_MTC}$=10°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)*

HTC Evaporator temperature (°C)	-20	-15	-10	-5	0	5
$COP_{\_Three\ Stage\ \_Cascade}$	0.2581	0.2537	0.2476	0.2395	0.2291	0.2160
($EDR_{Three\_Stage\ CVCRS}$)	2.205	2.180	2.259	2.369	2.522	2.736
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3198	0.3144	0.3069	0.2968	0.2839	0.2677
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ "kW"	69.84	69.3	71.01	73.41	76.74	81.41
Exergy of $Product_{Three\ Stage}$ "kW"	21.79	21.79	21.79	21.79	21.79	21.79
COP_{HTC}	2.424	2.763	3.172	3.674	4.304	5.118
COP_{MTC}	1.464	1.30	1.152	1.017	0.8906	0.7711
COP_{LTC}	0.9519	0.9519	0.9519	0.9519	0.9519	0.9519
$COP_{Two\ Stage\_Cascade}$	0.7260	0.7094	0.6863	0.6563	0.6188	0.5729
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.534	1.593	1.680	1.803	1.973	2.211
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.3947	0.3856	0.3731	0.3568	0.3364	0.3114
Two Stage Exergy of Fuel "kW"	49.66	50.83	52.54	54.94	58.27	62.94
Two Stage Exergy of Product "kW"	19.60	19.60	19.60	19.60	19.60	19.60
HTC Mass flow Rate (Kg/sec)	0.2394	0.2468	0.2558	0.2667	0.2805	0.2986
MTC Mass flow Rate (Kg/sec)	0.1270	0.1348	0.1439	0.1550	0.1687	0.1863
LTC Mass flow Rate (Kg/sec)	0.04887	0.04887	0.04887	0.04887	0.04887	0.04887
Q_Cond_HTC"kW"	85.72	86.88	88.59	90.99	94.32	98.99
Q_Cond_MTC"kW"	60.68	63.79	67.36	71.52	76.54	82.81
Q_Cond_LTC"kW"	36.06	36.06	36.06	36.06	36.06	36.06
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	25.03	23.09	21.24	19.47	17.78	16.18
MTC compressor Work"kW"	24.63	27.74	31.30	35.97	40.48	46.76
LTC compressor Work"kW"	18.47	18.47	18.47	18.47	18.47	18.47
System compressor Work"kW"	69.84	69.3	71.01	73.41	76.74	81.41
$COP_{\_HTC}$	2.424	2.763	3.172	3.674	4.304	5.729
HTC Exergy Destruction Ratio (EDR)	1.321	1.336	1.371	1.433	1.539	1.718
HTC Exergetic Efficiency	0.4309	0.4281	0.4218	0.4110	0.3939	0.368
HTC Exergy of Fuel "kW"	25.53	23.09	21.24	19.47	19.47	16.18
HTC Exergy of Product "kW"	10.79	9.885	8.959	8.002	7.005	5.954

3.17 Effect of MTC temperature overlapping on thermodynamic performances of cascaded VCRS system using ecofriendly low GWP propylene (R1270) refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of temperature overlapping on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-14 and it was found that by the increasing HTC evaporator temperature of the cascaded three staged VCRS, the cascaded first law efficiency (COP) & exergetic efficiency (both) are decreasing

Table-14: Effect of MTC temperature overlaping (ºC) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP* R1250 *refrigerant* in HTC R1250 *refrigerant* in HTC *(Q_Eva=17.5835kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-20ºC, $T_{\_Eva-MTC}$= -80ºC , $T_{\_Eva\ LTC}$= - 140ºC, $Temp\_Overlaping_{\_MTC}$=10ºC, $Temp\_Overlaping_{\_LTC}$=10ºC, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)*

MTC temperature overlaping (ºC)	0	5	10	15
$COP_{\_Three\ Stage\ \_Cascade}$	0.2896	0.2737	0.2581	0.2424
($EDR_{Three\_Stage\ CVCRS}$)	1.787	1.948	2.205	2.329
Exergetic $Efficiency_{Three\ Stage\ CVCRS}$)	0.3588	0.3392	0.312	0.3004
Exergy of $Fuel_{Three\ Stage\_CVCRS}$ “kW”	60.73	64.24	69.84	72.53
Exergy of $Product_{Three\ Stage}$ “kW”	21.79	21.79	21.79	21.79
COP_{HTC}	2.424	2.424	2.424	2.424
COP_{MTC}	1.86	1.649	1.464	1.30
COP_{LTC}	0.9519	0.9519	0.9519	0.9519
$COP_{Two\ Stage\_Cascade}$	0.8533	0.7879	0.7260	0.6670
Exergy Destruction Ratio ($EDR_{\_Two\ Stage\_CRVS}$)	1.156	1.335	1.534	1.758
Exergetic $Efficiency_{\_\ Two\ Stage\_CRVS}$	0.4639	0.4283	0.3947	0.3625
Two Stage Exergy of Fuel “kW”	42.25	45.76	49.66	54.06
Two Stage Exergy of Product “kW”	19.60	19.60	19.60	19.60
HTC Mass flow Rate (Kg/sec)	0.2187	0.2285	0.2394	0.2517
MTC Mass flow Rate (Kg/sec)	0.1144	0.1203	0.1270	0.1348
LTC Mass flow Rate (Kg/sec)	0.04887	0.04887	0.04887	0.04887
Q_Cond_HTC“kW”	78.31	81.82	85.72	90.11
Q_Cond_MTC“kW”	55.44	57.92	60.68	63.79
Q_Cond_LTC“kW”	36.06	36.06	36.06	36.06
Q_EVA_LTC“kW”	17.5834	17.5834	17.5834	17.5834
HTC compressor Work“kW”	22.87	23.9	25.03	26.32
MTC compressor Work“kW”	19.38	21.87	24.63	27.74
LTC compressor Work“kW”	18.47	18.47	18.47	18.47
System compressor Work“kW”	60.73	64.24	69.84	72.53
$COP_{\_HTC}$	2.424	2.424	2.424	2.424
HTC Exergy Destruction Ratio (EDR)	1.321	1.321	1.321	1.321
HTC Exergetic Efficiency	0.4309	0.4309	0.4309	0.4309
HTC Exergy of Fuel “kW”	22.87	23.9	25.03	26.32
HTC Exergy of Product “kW”	9.855	10.30	10.79	11.34

3.18 Effect of LTC temperature overlapping on thermodynamic performances of cascaded VCRS system using ecofriendly low GWP propylene (R1270) refrigerant in HTC ethane (R170) refrigerant in MTC and ethylene (R1150) refrigerant in LTC

The Effect of LTC temperature overlapping on thermodynamic performances of three staged cascaded vapour compression systems for ultra-low temperature applications have been shown in Table-15 and it was found that by the increasing LTC temperature overlapping of the cascaded three staged VCRS, the cascaded first law efficiency (COP) & exergetic efficiency (both) are decreasing

Table-15: Effect of LTC temperature overlapingon thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP R1250 *refrigerant* in HTC R1250 *refrigerant* in HTC *(Q_Eva=17.5835kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-20ºC, $T_{\_Eva-MTC}$= -80ºC , $T_{\_Eva\ LTC}$= - 140ºC, $Temp\_Overlaping_{\_MTC}$=10ºC, $Temp\_Overlaping_{\_LTC}$=10ºC, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)*

LTC temperature overlaping (ºC)	0	5	10	15
$COP_{\_Three\ Stage\ \_Cascade}$	0.295	0.2759	0.2581	0.2415
($EDR_{Three\_Stage\ CVCRS}$)	1.735	1.925	2.205	2.342

Exergetic Efficiency$_{\text{Three Stage CVCRS}}$)	0.3656	0.3419	0.312	0.2992
Exergy of Fuel$_{\text{Three Stage_CVCRS}}$ "kW"	59.60	63.74	69.84	72.82
Exergy of Product$_{\text{Three Stage}}$ "kW"	21.79	21.79	21.79	21.79
COP_{HTC}	2.424	2.424	2.424	2.424
COP_{MTC}	1.464	1.464	1.464	1.464
COP_{LTC}	1.182	1.058	0.9519	0.8601
$COP_{\text{Two Stage\_Cascade}}$	0.7260	0.7260	0.7260	0.7260
Exergy Destruction Ratio (EDR_$_{\text{Two Stage_CRVS}}$)	1.534	1.534	1.534	1.534
Exergetic Efficiency_ $_{\text{Two Stage\_CRVS}}$	0.3947	0.3947	0.3947	0.3947
Two Stage Exergy of Fuel "kW"	44.72	47.12	49.66	52.38
Two Stage Exergy of Product "kW"	17.65	18.60	19.60	20.67
HTC Mass flow Rate (Kg/sec)	0.2156	0.2272	0.2394	0.2525
MTC Mass flow Rate (Kg/sec)	0.1143	0.1205	0.1270	0.1339
LTC Mass flow Rate (Kg/sec)	0.04566	0.04720	0.04887	0.0507
Q_Cond_HTC"kW"	77.18	81.32	85.72	90.41
Q_Cond_MTC"kW"	54.64	57.57	60.68	64.0
Q_Cond_LTC"kW"	32.46	34.21	36.06	38.03
Q_EVA_LTC"kW"	17.5834	17.5834	17.5834	17.5834
HTC compressor Work"kW"	22.54	23.75	25.03	26.32
MTC compressor Work"kW"	22.18	23.37	24.63	27.74
LTC compressor Work"kW"	14.88	16.62	18.47	18.47
System compressor Work"kW"	59.60	63.74	69.84	72.82
COP_$_{HTC}$	2.424	2.424	2.424	2.424
HTC Exergy Destruction Ratio (EDR)	1.321	1.321	1.321	1.321
HTC Exergetic Efficiency	0.4309	0.4309	0.4309	0.4309
HTC Exergy of Fuel "kW"	22.54	23.75	25.03	26.32
HTC Exergy of Product "kW"	9.713	10.23	10.79	11.38

4. Conclusions

The following conclusions were made from thermodynamic performances of vapour compression cascaded refrigeration systems

- HFO and HFC refrigerants and blends of HFO+HFC refrigerants are more suitable for replacing high GWP refrigerants such as R404, R34 and R125 for low-temperature applications
- Cascaded VCRS using R454b in the high-temperature cycle & R515a in the medium temperature cycle &R513a eco-friendly refrigerant in the low-temperature cycle gives the best thermodynamic performances up to (-90°C) low-temperature applications
- The cascaded VCRS using R452a in the high-temperature cycle & R448a in the medium temperature cycle &R454c eco-friendly refrigerant in the low-temperature cycle gives slightly lowest thermodynamic performances up to (-90°C) low-temperature applications
- The cascaded VCRS using R1233zd(E) in the high-temperature cycle & R1336mzz(Z) in the medium temperature cycle &R1225ye(Z) eco-friendly refrigerant in the low-temperature cycle gives the best thermodynamic performances up to (-150°C) low-temperature applications
- Three staged cascaded vapour compression systems using HFOs in the high-temperature cycle upto (-30°C) using R-1150 can replace R 14 in low-temperature cycle (LTC) up to (-140°C), and R41 & R170 can replace R23 in medium temperature cycle (MTC) up to (-90°C)
- Three staged cascaded vapour compression systems using R-1150 can replace R 14 in the low-temperature cycle (LTC), and R41 & R170 can replace R23 in the medium temperature cycle (LTC).

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