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ORIGINAL ARTICLE

Three Energy Exergy Environmental (3E) analysis of three staged cascaded vapor compression refrigeration systems using hydrocarbons, HFO, and low GWP HFCs refrigerants

R. S. Mishra

Department of Mechanical Engineering, Delhi Technological University, Delhi, India.

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Abstract

Several alternatives are available in the literature for using HFC blends which for causing higher global warming potential without ozone depletion for replacing CFC refrigerants also have ultra-high global warming potential with ozone depletion. In this paper, thermodynamic energy-exergy performances of cascaded vapour compression refrigeration system for the ultra-low applications using ecofriendly low global warming potential GWP blends of HFC+HFO refrigerants in higher temperature cycle in the temperature range of 50ºC to -30ºC and also using blends of HFC+HFO refrigerants in low GWP in low temperature cycle have been investigated. It was observed that System44 gives highest thermodynamic first and second law performances. The lowest thermodynamic performances were observed by using ecofriendly low GWP R452A refrigerants in higher temperature cycle using ecofriendly R448A low GWP refrigerant in low temperature cycle in the cascaded of vapour compression refrigeration (system 41).

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1. Introduction

In recent years, environmentalists have shown concern about different issues that threaten the earth's existence. There are a lot of responsible factors that are accelerating the issue, is global warming(GWP) and ozone layer depletion (ODP). Studies have shown the significance of environment-friendly working fluids for existing systems. In refrigeration systems, the thermodynamic performance is evaluated using energy, exergy, and environmental analysis is used. The low temperatures for cryogenics range from -90 °C to -140°C, and its applications in the pharmaceuticals, chemical and petroleum industries. Also, the demand for refrigeration at ultra-low evaporation temperature applications increasing day by day, gives the importance of three staged cascaded vapor compression refrigeration systems,

A cascaded vapor compression refrigeration system combines two or more vapor compression refrigeration cycles. The thermodynamic performance is evaluated by considering both having higher and lower evaporator temperatures for finding the exergy of product and the exergy of fuel in terms of minimum electrical energy consumption for operating compressors. H.M.Getu and Bansal P.K [1] did the thermodynamic analysis of the carbon dioxide–ammonia (R744–R717) cascade refrigeration system and optimized the design and operating parameters such as condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature

Corresponding author: R. S. Mishra
Email Address: hod.mechanical.rsm@dtu.ac.in
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difference in a cascade heat exchanger using regression analysis to obtain optimum thermodynamic parameters.

Nikolaidis and Probert [2] studied the change in evaporator and condenser temperatures in the two-stage vapor compression refrigeration plant analytically using R22 to find the plant irreversibility Bhattacharyya et al [3] studied the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibilities.

Lee et al [4] studied thermodynamically a cascade refrigeration system that uses carbon dioxide and ammonia as refrigerants.

The ozone depletion and global warming due to the use of various refrigerants are severe for environmental degradation, which affect living human standard. Therefore, it is essential to search for and use new and low GWP and zero ODP eco-friendly refrigerants. Thermodynamic first and second law performances (energy-exergy efficiencies) of cascade vapor 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 [5]. The various combinations of using six different eco-friendly refrigerants used in the high-temperature cycle in the temperature range of from 50oC to 0°C for which other five ecofriendly low GWP refrigerants in the medium temperature range of from 0°C to-50°C & found that the first and second law performances of cascaded vapor 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 R1243zf in a 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 -50°C and also found the first and second law efficiencies are 3.24% lower than using R-1234yf in low-temperature cycle as compared to HFC-134a in a low-temperature cycle and R1234ze(Z) in high-temperature cycle with 5.2% decrement in the exergy destruction ratio.

CananCimsit [6] 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 ecofriendly 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 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 use of hydrocarbons can also be promising by taking appropriate safety measures because mostly 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 a 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 the high-temperature circuit and R1234yf in a low-temperature cycle. the thermodynamic performances of cascade vapor 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 [7]

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 517/2014to reduce mitigating climate change risk, environmental impact and deterioration. Therefore, refrigerant R1234yf could be a choice for vapor compression refrigeration cycle. However, the GWP and ODP rating of R1234yf are 4 and 0, which show the environment and nature-friendly behavior of refrigerant. Mishra [8] carried out the exergy analysis of three & four stages cascade refrigeration systems used for low-temperature applications using ecofriendly 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) have been optimized thermodynamically using of R1234yf and R1234ze in the high temperature circuits and mainly thirteen ecofriendly 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 [9]

The eco-friendly refrigeration technologies, are receiving more and more attention in the days by day of for solving energy and environmental problems. In this paper, it is suggested to phase out 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 is not many improvements in the thermodynamic performances using

R134a as compared with R410a in the first intermediate temperature circuit. [10].

The second law efficiency using R600a in the low-temperature evaporator circuit gives better performance than using R290 and R404a refrigerant in lower temperature circuit (LTC) [10]. Many investigators have recommended a few hydrofluorocarbons and hydrocarbon-based refrigerants as replacements because they have minimal GWP and zero ODP. Pure hydrocarbon refrigerants are an intriguing option among the two. The main disadvantage of employing hydrocarbon refrigerants is their flammability. This issue, however, can be avoided by using safety as flammable refrigerants were formerly prohibited from use; current regulations allow the use of flammable fluids with additional safety measures. Despite the flammability issue, hydrocarbon-based re- refrigerants have several advantages over chlorofluorocarbon-based refrigerants [11]. R.S. Mishra [12,13,14,15,16] carried out a thermodynamic analysis of simple vapour compression refrigeration systems and cascaded vapour compression refrigeration systems using HFO+HFC blends in HTC & LTC cycles. Sun [17] carried out a thermodynamic (energy and exergy) analysis of hydrocarbon refrigerants' three staged cascade vapour compression refrigeration systems. for finding COP, total compressor work, exergy efficiency, total exergy destruction, mass flow rate and discharge temperatures of compressors, and component exergy destruction and suggested that at different evaporator temperatures, different hydrocarbon refrigerants on TCRS give higher COP and exergy efficiency. The highest COP and exergy efficiency at -100 ◦C evaporator temperature was found to be 0.5931 and 54.446%, respectively, which gives the utility of hydrocarbon refrigerants in three staged vapor compression refrigeration systems for ultra-low temperature applications without compromising the thermodynamic performances

This paper mainly deals with the performance evaluation of the three-staged cascaded vapor compression using HFOs, hydrocarbons(HC) & Low GWP ecofriendly HFC refrigerants in HTC, R170 and R41 in MTC for replacing R23 and R1150 for replacing R14 in LTC for finding maximum thermodynamic performance parameters.

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

Following systems have been selected for numerical computations. Cascaded Vapour compression refrigeration systems using R12, in HTC R22 in MTC and R13in LTC [18] The presented thermal model in this paper is compared with the input values. under the same operating conditions as shown in Table-1(a**)**. To validate the proposed study, the refrigerant pair is regarded the same. The simulation results differences as shown for the system has R12/R22/R13 combination, with the largest error being 1.98% for overall COP.as shown in Table-1(b**)**. It w**a**s found th**a**t developed therm**a**l model predict ne**a**rly ex**a**ct beh**a**vior shown in t**a**ble-1(b) respectively.

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

S.No	Input parameter [11]	Value
1	HTC condenser temperature (°C)	40
2	HTC evaporator temperature (°C)	-22
3	MTC evaporator temperature (°C)	-60
4	LTC evaporator temperature (°C)	-90
5	MTC approach (temperature overlapping) (°C)	10
6	LTC approach (temperature overlapping) (°C)	10
7	HTC compressor efficiency (%)	100
8	MTC compressor efficiency (%)	100
9	LTC compressor efficiency (%)	100
10	LTC evaporator load kW	175

Table-1(b): Validation of computed results of system [12]

Thermodynamic Performance Parameters	Ref [18]	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 Flow Rate (kg/sec)	1.15	1.157	(+)0.6087
LTC Mass Flow Rate (kg/sec)	1.5	1.509	(+)0.60
HTC compressor Power “kW”	97.4	93.78	(-)3.717
MTC compressor Power “kW”	59.8	60.45	(+)1.086
LTC compressor Power “kW”	46.8	46.73	(-)0.1496

2.1 Effect of ethylene (R1150) in low temperature cycle (LTC) on thermodynamic performances of three staged vapour compression refrigeration systems for replacing high global warming potential refrigerant used in R14 and R-170 & R41for replacing Options of low global warming potential refrigerants based on used in R23 in medium temperature cycle using R16

Thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-2(a), respectively. It was found that system-2 (using R161 in HTC, R170 in MTC, R1150 in LTC) gives the best thermodynamic performance and system-1 (using R161 in HTC, R41 in MTC, R1150 in LTC) gives slightly less thermodynamic performances than system-2. In contrast, system-3 (using R161 in HTC, R23 in MTC, R14 in LTC) gives lowest thermodynamic performances. Comparing thermodynamic performances between two cascaded vapour compression refrigeration systems (system-1 using R41 in MTC and & system-4 using R23 in MTC) and R1150 in LTC of both cascade vapour compression refrigeration systems using it was found that system-1 using R41 gives better thermodynamic performances than system-4 using R23 in medium temperature cycle. Therefore, it is concluded that R41 are suitable for replacing R23 in MTC. Similarly, system-2 using R170 in MTC and system-4 using R23 in MTC and R1150 in the low-temperature cycle in both cascade systems were compared with the thermodynamic performances, and it was found that system-2 using R41 in MTC gives better thermodynamic performances than system-4 using R23 in MTC. Therefore, it is concluded that R41 is suitable for replacing R23 in MTC using R1150 in the LTC cycle of both cascaded vapour compression refrigeration systems. The cascade system-4 using R1150 in LTC and system-3 using R14 in LTC for ultra-low temperature applications were compared for thermodynamic performances, and it was found that Ethylene (R-1150) in low temperature (LTC). It gives better performances than using R14 in LTC of system-3. Therefore, it is concluded that R1150 is replacing R14 in ultra-low temperature applications due to low electrical power consumed for replacing R14 in a low-temperature cycle (LTC cycle) for ultra-low temperature applications.

Table-2(a) Optimum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1250) in HTC, R-170 in MTC & R-1150 in LTC (Q_Eva=10.0kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -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%)

Three Staged Cascade system	System 1	System 2	System 3	System 4
Refrigerant in HTC	R161	R161	R161	R161
Refrigerant in MTC	R41	R170	R23	R23
Refrigerants in LTC	R1150	R1150	R14	R1150
COP_HTC	2.012	2.012	2.012	2.012
COP_MTC	1.43	1.428	1.391	1.391
COP_LTC	1.182	1.182	1.095	1.182
Three Stage COP_Cascade	0.2705	0.2703	0.2549	0.2666
Three Stage Exergy Destruction Ratio (EDR)	1.983	1.985	2.166	1.391
Three Stage Exergetic Efficiency	0.3352	0.335	0.3159	0.3304
Three Stage Exergy of Fuel "kW"	36.96	36.99	39.23	37.51
Three Stage Exergy of Product "kW"	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6476	0.6471	0.6356	0.6356
Two Stage Exergy Destruction Ratio (EDR)	1.459	1.461	1.506	1.506
Two Stage Exergetic Efficiency	0.4067	0.4063	0.3991	0.3991
Two Stage Exergy of Fuel "kW"	28.51	28.53	30.1	29.05
Two Stage Exergy of Product "kW"	11.59	11.59	12.01	11.59
HTC Mass flow Rate (Kg/sec)	0.1187	0.1188	0.1244	0.1201
MTC Mass flow Rate (Kg/sec)	0.05241	0.06071	0.1252	0.1209
LTC Mass flow Rate (Kg/sec)	0.02597	0.02597	0.1259	0.02597
Q_Cond_HTC"kW"	46.97	46.99	49.23	47.51
Q_Cond_MTC"kW"	31.28	31.39	32.88	31.74
Q_Cond_LTC"kW"	18.46	18.46	19.13	18.46
$Q_{_EVA}$_LTC"kW"	10	10	10	10
HTC compressor Work"kW"	15.59	15.6	16.34	15.77
MTC compressor Work"kW"	12.91	12.93	13.75	13.27
LTC compressor Work"kW"	8.463	8.463	9.13	8.463
System compressor Work"kW"	39.23	37.51	39.23	37.51
$COP_{\_HTC}$	2.012	2.012	2.012	2.012
HTC Exergy Destruction Ratio (EDR)	1.197	1.197	1.197	1.197
HTC Exergetic Efficiency	0.4551	0.4551	0.4551	0.4551
HTC Exergy of Fuel "kW"	36.96	36.99	16.34	15.77

2.2 Effect of ethylene (R1150) in low temperature cycle (LTC) on thermodynamic performances of three staged vapour compression refrigeration systems for replacing high global warming potential refrigerant used in R14 and R-170 & R41for replacing Options of low global warming potential refrigerants based on used in R23 in medium temperature cycle using R152a in the high temperature

Thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-2(b) respectively and it was found that system-9 (using R152a in HTC, R41 in MTC, R1150 in LTC) gives the best thermodynamic performances and system-6 (using R152a in HTC, R170 in MTC, R1150 in LTC) gives slightly less thermodynamic performances than system-5 while system-8 (using R152a in HTC, R23 in MTC, R14 in LTC) gives lowest thermodynamic performances.

Comparing thermodynamic performances between two cascaded vapor compression refrigeration systems (system-5 using R23 in MTC and & system-6 using R170 in MTC) it was found that it is concluded that system-6 using R170 in MTC gives better thermodynamic performances than system-5 using R23 in MTC for ultra-low temperature applications using Ethylene (R-1150) in low temperature (LTC). Similarly, with system-5 using R1150 used in LTC and system-8 using R14 in LTC, it was found that system-5 using R1150 used in LTC gives better thermodynamic performances than system-8 using R-14 in LTC. therefore, it is concluded that R1150 is replacing R14 in ultra-low-temperature applications. Similarly, system-8 using R23 in MTC and system-9 using R41 in MTC were compared with the thermodynamic performances, and it was found that system-9 using R41 in MTC gives the best performance than system-8 using R23 in MTC. Therefore, it is concluded that R41 & R170 are suitable for replacing R23 in MTC and R1150 are ideal for replacing R14 in LTC cycle.

Table-2(b) Optimum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R152a) in HTC, R-170, R23 &R41 in MTC & R-1150 & R14 in LTC (Q_Eva=11.0kW, T_Cond=40^{o}C, T_ambient=25^{o}C, $T_{\_Eva\ HTC}$ =-30^{o}C, $T_{\_Eva\text{-}MTC}$= -90^{o}C , $T_{\_Eva\ LTC}$= -140^{o}C, Temp_Overlaping$_{_MTC}$=10^{o}C, Temp_Overlaping$_{_LTC}$=10^{o}C, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three StagedCascade system	System 5	System 6	System 7	System 8	System 9
Refrigerant in HTC	R152a	R152a	R152a	R152a	R152a
Refrigerant in MTC	R23	R170	R170	R23	R41
Refrigerants in LTC	R1150	R1150	R14	R14	R14
COP_HTC	2.049	2.049	2.049	2.049	2.049
COP_MTC	1.391	1.428	1.428	1.391	1.43
COP_LTC	1.182	1.182	1.095	1.095	1.182
Three Stage COP_Cascade	0.2686	0.2724	0.2604	0.2568	0.2725
Three Stage Exergy Destruction Ratio (EDR)	2.004	1.963	2.099	2.142	1.961
Three Stage Exergetic Efficiency	0.3329	0.3375	0.3227	0.3183	0.3377
Three Stage Exergy of Fuel “kW”	37.23	36.71	38.4	38.93	36.69
Three Stage Exergy of Product “kW”	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6418	0.6535	0.6535	0.6418	0.6541
Two Stage Exergy Destruction Ratio (EDR)	1.481	1.437	1.437	1.481	1.435
Two Stage Exergetic Efficiency	0.403	0.4104	0.4104	0.403	0.4107
Two Stage Exergy of Fuel “kW”	28.77	28.25	29.27	29.8	28.23
Two Stage Exergy of Product “kW”	11.59	11.59	12.01	12.01	11.59
HTC Mass flow Rate (Kg/sec)	0.1487	0.1471	0.1524	0.1541	0.147
MTC Mass flow Rate (Kg/sec)	0.1209	0.06071	0.0629	0.1252	0.05241
LTC Mass flow Rate (Kg/sec)	0.02597	0.02597	0.1259	0.1259	0.02597
Q_Cond_HTC“kW”	47.23	46.71	48.4	48.93	46.69
Q_Cond_MTC“kW”	31.74	31.39	32.53	32.88	31.38
Q_Cond_LTC“kW”	18.46	18.46	19.13	19.13	18.46
Q_EVA_LTC“kW”	10	10	10	10	10
HTC compressor Work“kW”	15.49	15.32	15.88	16.02	15.31
MTC compressor Work“kW”	13.27	12.93	13.4	13.75	13.27
LTC compressor Work“kW”	8.463	8.463	9.13	9.13	8.463
System compressor Work“kW”	37.23	36.71	38.4	38.93	36.69
$COP_{\_HTC}$	2.049	2.049	2.049	2.049	2.049
HTC Exergy Destruction Ratio (EDR)	1.158	1.158	1.158	1.158	1.158
HTC Exergetic Efficiency	0.4634	0.4634	0.4634	0.4634	0.4634
HTC Exergy of Fuel “kW”	15.49	15.32	15.88	16.02	15.31
HTC Exergy of Product “kW”	7.179	7.101	7.357	7.438	7.097

2.3 *Effect of ethylene (R1150) in low temperature cycle (LTC) on thermodynamic performances of three staged vapour compression refrigeration systems for replacing high global warming potential refrigerant used in R14 and R-170 & R41for replacing Options of low global warming potential refrigerants based on used in R23 in medium temperature cycle using R717*

Thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-2(b) respectively and it was found that system-12 (using R717 in HTC, R41 in MTC, R1150 in LTC) gives best thermodynamic performances and system-11 (using R717 in HTC, R170 in MTC, R1150 in LTC) gives slightly less thermodynamic performances than system-11 while system-13 (using R R717 in HTC, R23 in MTC, R14 in LTC) gives lowest thermodynamic performances. Comparing thermodynamic performances between two cascaded vapour

compression refrigeration systems (system-10& system-11 & system-12) it was found that it is concluded that system-11 using R41 in MTC & system-11 using R170 used in MTC are suitable for replacing system-10 using R23 in MTC
Similarly system-10, system-11 & system-12 using R1150 in LTC were compared with the thermodynamic performances of system-13 & system-14 using R14 in the low temperature cycle LTC are suitable for replacing R14 in LTC cycle and it was found that cascade systems using R1150 in LTC gives better thermodynamic performances as compared with cascade systems using R14 in low temperature cycle ..

Table-2(c) Optimum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-717) in HTC, R-170 ,R23& R41in MTC & R-1150 & R14 in LTC (Q_Eva=10.0kW, T_Cond=40°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%)

Three StagedCascade system	System10	System11	System12	System13	System-14
Refrigerant in HTC	R717	R717	R717	R717	R717
Refrigerant in MTC	R23	R170	R41	R23	R41
Refrigerants in LTC	R1150	R1150	R1150	R14	R14
COP_HTC	2.057	2.057	2.057	2.057	2.057
COP_MTC	1.391	1.428	1.43	1.391	1.43
COP_LTC	1.182	1.182	1.182	1.095	1.095
Three Stage COP_Cascade	0.2691	0.2728	0.273	0.2573	0.261
Three Stage Exergy Destruction Ratio (EDR)	1.999	1.958	1.956	2.137	2.092
Three Stage Exergetic Efficiency	0.3334	0.3381	0.3383	0.3188	0.3235
Three Stage Exergy of Fuel “kW”	37.16	36.65	36.63	38.87	38.31
Three Stage Exergy of Product “kW”	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6433	0.655	0.6555	0.6433	0.6555
Two Stage Exergy Destruction Ratio (EDR)	1.476	1.431	1.429	1.476	1.429
Two Stage Exergetic Efficiency	0.4039	0.4113	0.4116	0.4039	0.4116
Two Stage Exergy of Fuel “kW”	28.7	28.19	28.16	29.74	29.18
Two Stage Exergy of Product “kW”	11.59	11.59	11.59	11.59	12.01
HTC Mass flow Rate (Kg/sec)	0.03073	0.0304	0.03038	0.03184	0.03148
MTC Mass flow Rate (Kg/sec)	0.1209	0.06071	0.05241	0.1252	0.0543
LTC Mass flow Rate (Kg/sec)	0.02597	0.02597	0.02597	0.1259	0.1259
Q_Cond_HTC“kW”	47.16	46.65	46.63	48.87	48.31
Q_Cond_MTC“kW”	31.74	31.39	31.38	32.88	32.51
Q_Cond_LTC“kW”	18.46	18.46	18.46	19.13	19.13
Q_EVA_LTC“kW”	10	10	10	10	10
HTC compressor Work“kW”	15.43	15.26	15.25	15.98	15.8
MTC compressor Work“kW”	13.27	12.93	12.91	13.75	13.38
LTC compressor Work“kW”	8.463	8.463	8.463	9.13	9.13
System compressor Work“kW”	37.16	36.65	36.63	38.87	38.31
$COP_{\_HTC}$	2.057	2.057	2.057	2.057	2.057
HTC Exergy Destruction Ratio (EDR)	1.149	1.149	1.149	1.149	1.149
HTC Exergetic Efficiency	0.4657	0.4657	0.4657	0.4657	0.4657
HTC Exergy of Fuel “kW”	15.43	15.26	15.25	15.98	15.8
HTC Exergy of Product “kW”	7.179	7.101	7.357	7.438	7.097

2.4 *Effect of ethylene (R1150) in low temperature cycle (LTC) on thermodynamic performances of three staged vapour compression refrigeration systems for replacing high global warming potential refrigerant used in R14 and R-170 & R41for replacing Options of low global warming potential refrigerants based on used in R23 in medium temperature cycle using propylene (R1270)*

Thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-2(b) respectively and it was found that system-15 (using R1270 in HTC, R170 in MTC, R1150 in LTC) gives best thermodynamic performances and system-19 (using R1270 in HTC, R41 in MTC, R1150 in LTC) gives slightly less thermodynamic performances than system-15 while system-18 (using R1250 in HTC, R23 in MTC, R14 in LTC) gives lowest thermodynamic performance. Comparing thermodynamic performances between two cascaded vapour compression refrigeration systems system-15, using R1150 in LTC were compared with the thermodynamic performances of system-17 using R14 in the low temperature cycle(LTC) it was found that cascade systems using R1150 in LTC gives better thermodynamic performances as compared with cascade systems using R14 in low temperature cycle

Similarly system-19 using R41 in MTC & system-15& system-16 using R170 in MTC were compared with system-17 & system-18 using R23 in MTC it was found that it is concluded that using R41 & R170 used in MTC are suitable for replacing R23 in MTC therefore, it is concluded that R41 & R170 are suitable for replacing R23 in MTC and R1150 are suitable for replacing R14 in LTC cycle..

Table-2(d) Optimum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1250) in HTC, R-170, R23 &R41 in MTC & R-1150 & R14 in LTC (Q_Eva=10.0kW, T_Cond=40°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%)

Three staged cascade system	System15	System16	System17	System18	System-19	System 20
Refrigerant in HTC	R1270	R1270	R1270	R1270	R1270	R1270
Refrigerant in MTC	R170	R170	R23	R23	R41	R23
Refrigerants in LTC	R1150	R14	R14	R1150	R14	R13
COP_HTC	1.896	1.896	1.896	1.896	1.896	1.896
COP_MTC	1.428	1.428	1.430	1.391	1.391	1.391
COP_LTC	1.182	1.095	1.095	1.095	1.182	1.259
Three Stage COP_Cascade	0.2635	0.2520	0.2522	0.2486	0.2599	0.2694
Three Stage Exergy Destruction Ratio (EDR)	2.062	2.202	2.20	2.246	2.105	1.995
Three Stage Exergetic Efficiency	0.3266	0.3123	0.3125	0.3081	0.3221	0.3339
Three Stage Exergy of Fuel “kW”	37.95	39.68	39.65	40.23	38.481	37.12
Three Stage Exergy of Product “kW”	12.39	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6262	0.6262	0.6267	0.6152	0.6152	0.6152
Two Stage Exergy Destruction Ratio (EDR)	1.543	1.543	1.541	1.589	1.589	1.589
Two Stage Exergetic Efficiency	0.3932	0.3932	0.3935	0.3863	0.3863	0.3863
Two Stage Exergy of Fuel “kW”	29.48	30.55	30.52	31.10	30.01	29.17
Two Stage Exergy of Product “kW”	11.59	12.01	12.01	12.01	11.59	11.27
HTC Mass flow Rate (Kg/sec)	0.1259	0.1338	0.1338	0.1352	0.1305	0.1269
MTC Mass flow Rate (Kg/sec)	0.06071	0.0629	0.0543	0.1252	0.3863	0.1175
LTC Mass flow Rate (Kg/sec)	0.02597	0.1259	0.1259	0.1259	0.02597	0.08054
Q_Cond_HTC“kW”	47.95	49.68	49.65	50.23	48.48	47.12
Q_Cond_MTC“kW”	31.39	32.53	32.51	32.88	31.74	30.85
Q_Cond_LTC“kW”	18.46	19.13	19.13	19.13	18.46	17.94
Q_EVA_LTC“kW”	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work“kW”	16.27	17.15	17.15	17.34	16.74	16.27
MTC compressor Work“kW”	12.93	13.40	13.38	13.75	13.27	12.9
LTC compressor Work“kW”	8.463	9.13	9.13	9.13	8.463	7.945
System compressor Work“kW”	37.95	39.68	39.65	40.23	38.481	37.12
$COP_{\_HTC}$	1.896	1.896	1.896	1.896	1.896	1.896
HTC Exergy Destruction Ratio (EDR)	1.332	1.332	1.332	1.332	1.332	1.332
HTC Exergetic Efficiency	0.4289	0.4289	0.4289	0.4289	0.4289	0.4289
HTC Exergy of Fuel “kW”	16.27	17.15	17.15	17.34	16.74	16.27
HTC Exergy of Product “kW”	7.10	7.357	7.354	7.438	7.179	6.977

2.5 Dynamic performances evolution of cascaded vapour compression refrigeration systems.

The dynamic thermal performance using variations in different condenser and evaporators hve been discussed in details and the effect on thermodynamic performances were presented in the following sections.

2.5.1 Effect of varying LTC evaporator temperature in three staged cascade system on thermodynamic performances of three staged cascaded vapour compression refrigeration system using R1270 in high temperature cycle(HTC), R170 in medium temperature cycle (MTC) nd R1150 in the low temperature cycle

The effect of varying LTC evaporator temperature in three staged cascade system on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-3(a) respectively and it was found that when LTC evaporator temperature is increasing, the first law cascaded efficiency ($COP_{\_cascade}$) and first law cycle efficiency ($COP_{\_LTC}$) is increasing, and electrical energy consumption (power required to run three compressors) is decreasing.

Table-3(a) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1250) in HTC, R-170 in MTC & R-1150 in LTC (Q_Eva=175.835 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-22ºC, $T_{\_Eva-MTC}$= -80ºC , $T_{\_Eva\ LTC}$= -120ºC, $Temp\_Overlaping_{\_MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=5ºC, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%, Compressor $efficiency_{\_LTC}$=100%)

LTC evaporator temperature in three Staged cascade system	-150	-145	-140	-135	-130	-125	-120	-115	-110
COP_HTC	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
COP_MTC	2.632	2.632	2.632	2.632	2.632	2.632	2.632	2.632	2.632
COP_LTC	0.9501	1.125	1.322	1.56	1.843	2.187	2.609	3.141	3.827
Three Stage COP_Cascade	0.3303	0.3687	0.4088	0.4504	0.4935	0.5378	0.5834	0.6302	0.678
Three Stage Exergy Destruction Ratio	1.13	1.044	0.9738	0.9169	0.8716	0.8364	0.8104	0.7926	0.7824
Three Stage Exergetic Efficiency	0.4691	0.4892	0.5066	0.521	0.5341	0.5445	0.5521	0.5578	0.561
Three Stage Exergy of Fuel “kW”	532.3	476.8	430.1	390.4	356.3	326.9	301.4	279	259.3
Three Stage Exergy of Product “kW”	249.1	233.1	217.9	203.6	190.1	178.1	166.1	155.1	145.1
Two Stage COP_Cascade	1.039	1.039	1.039	1.039	1.039	1.039	1.039	1.039	1.039
Two Stage Exergy Destruction Ratio	0.7699	0.7699	0.7699	0.7699	0.7699	0.7699	0.7699	0.7699	0.7699
Two Stage Exergetic Efficiency	0.565	0.565	0.565	0.565	0.565	0.565	0.565	0.565	0.565
Two Stage Exergy of Fuel “kW”	347.2	320	297	277.6	260.9	246.5	234	223	213.4
Two Stage Exergy of Product “kW”	196.2	180.8	167.9	156.9	147.4	137.3	132.2	126	120.6
HTC Mass flow Rate (Kg/sec)	2.048	1.888	1.753	1.638	1.539	1.454	1.38	1.316	1.259
MTC Mass flow Rate (Kg/sec)	1.093	1.007	0.9352	0.8738	0.8213	0.776	0.7365	0.702	0.6716
LTC Mass flow Rate (Kg/sec)	0.4872	0.4794	0.472	0.4649	0.4581	0.4516	0.4454	0.4395	0.4339
Q_Cond_HTC“kW”	708.2	652.7	605.9	566.2	532.2	502.8	477.2	454.9	435.2
Q_Cond_MTC“kW”	498	459	426.1	398.2	374.3	353.6	335.6	319.9	305
Q_Cond_LTC“kW”	360.9	332.6	308.8	288.6	271.2	256.2	243.2	231.8	221.8
Q_EVA_LTC“kW”	175.84	175.84	175.84	175.84	175.84	175.84	175.84	175.84	175.84
HTC compressor Work“kW”	210.1	193.7	179.8	168	157.9	149.2	141.6	135	129.1
MTC compressor Work“kW”	102.6	126.4	117.3	109.6	103	97.35	92.4	88.07	84.26
LTC compressor Work“kW”	102.6	126.4	117.3	109.6	103	97.35	67.38	55.99	45.95
System compressor Work“kW”	532.3	476.8	430.1	390.4	356.3	326.9	301.4	279	259.3
$COP_{\_HTC}$	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
HTC Exergy Destruction Ratio (EDR)	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652
HTC Exergetic Efficiency	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361
HTC Exergy of Fuel “kW”	210.1	193.7	179.8	168	157.9	149.2	141.6	135	129.1
HTC Exergy of Product “kW”	112.7	103.8	96.39	90.07	84.66	79.98	75.92	72.36	69.23

2.5.2 *Effect of varying MTC evaporator temperature in three staged cascade system on thermodynamic performances of three staged cascaded vapour compression refrigeration system using R1270 in high temperature cycle(HTC), R170 in medium temperature cycle (MTC) nd R1150 in the low temperature cycle*

The effect of varying MTC evaporator temperature in three staged cascade system on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-3(b) respectively and it was found that when MTC evaporator temperature is decreasing, the first law cascaded efficiency ($COP_{\_cascade}$) and first law cycle efficiency ($COP_{\_MTC}$) is increasing, and electrical energy consumption (power required to run three compressors) is decreasing.

2.5.3 *Effect of varying HTC evaporator temperature in three staged cascade system on thermodynamic performances of three staged cascaded vapour compression refrigeration systems using R1270 in high temperature cycle(HTC), R170 in medium temperature cycle (MTC) nd R1150 in the low temperature cycle*

The effect of varying HTC evaporator temperature in three staged cascade system on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-3(c) respectively and it was found that when MTC evaporator temperature is increasing , the first law cascaded efficiency ($COP_{\_cascade}$) and first law cycle efficiency ($COP_{\_MTC}$) is decreasing, and electrical energy consumption (power required to run three compressors) is decreasing and exergetic efficiency is, also decreasing, *Table-3(b) Optimum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1250) in HTC, R-170 in MTC & R-1150 in LTC (Q_Eva=175.835kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-22ºC, $T_{\_Eva\text{-}MTC}$= -80ºC , $T_{\_Eva\ LTC}$= -120ºC, $Temp\_Overlaping_{\_MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=5ºC, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%, Compressor $efficiency_{\_LTC}$=100%)*

MTC evaporator temperature in three Staged cascade system	-45	-50	-55	-60	-65	-70	-75	-80	-85
COP_HTC	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
COP_MTC	10.03	7.69	6.134	5.026	4.199	3.558	3.047	2.632	2.288
COP_LTC	1.154	1.282	1.427	1.592	1.784	2.009	2.279	2.609	3.023
Three Stage COP_Cascade	0.5214	0.5377	0.5517	0.5632	0.5722	0.5786	0.5824	0.5834	0.5816
Three Stage Exergy Destruction Ratio	1.026	0.9643	0.9146	0.8754	0.8458	0.8253	0.8135	0.8104	0.816
Three Stage Exergetic Efficiency	0.4936	0.5091	0.5221	0.5332	0.5418	0.5476	0.5511	0.5521	0.5501
Three Stage Exergy of Fuel "kW"	337.3	327	318.7	311.53	307.3	303.9	301.9	301.4	302.3
Three Stage Exergy of Product "kW"	166.1	166.1	166.1	166.1	166.1	166.1	166.1	166.1	166.1
Two Stage COP_Cascade	1.774	1.648	1.53	1.419	1.315	1.217	1.125	1.039	0.9584
Two Stage Exergy Destruction Ratio	0.8371	0.8055	0.8652	0.7674	0.759	0.7569	0.7606	0.7699	0.7846
Two Stage Exergetic Efficiency	0.5443	0.5539	0.561	0.5658	0.5685	0.5692	0.568	0.565	0.5603
Two Stage Exergy of Fuel "kW"	185	189.9	195.5	201.8	208.7	216.4	228.4	234	244.2
Two Stage Exergy of Product "kW"	100.7	105.2	109.7	114.2	118.7	123.2	127.7	132.2	136.8
HTC Mass flow Rate (Kg/sec)	1.484	1.454	1.43	1.412	1.397	1.387	1.382	1.38	1.383
MTC Mass flow Rate (Kg/sec)	0.9024	0.9643	0.8421	0.8167	0.7937	0.7773	0.7539	0.7365	0.7206
LTC Mass flow Rate (Kg/sec)	0.5846	0.5581	0.5346	0.5132	0.4939	0.4764	0.4602	0.4454	0.4316
Q_Cond_HTC"kW"	513.1	502.8	494.6	488	483.1	479.7	477.7	477.2	478.2
Q_Cond_MTC"kW"	360.9	353.6	347.8	343.2	339.8	337.4	336	335.6	336.3
Q_Cond_LTC"kW"	328.1	327	299.1	286.3	274.4	263.3	253.2	243.2	234.2
Q_EVA_LTC"kW"	175.84	175.84	175.84	175.84	175.84	175.84	175.84	175.84	175.84
HTC compressor Work"kW"	152.2	149.2	146.7	144.8	143.4	142.3	141.8	141.6	141.9
MTC compressor Work"kW"	32.71	40.69	48.75	56.96	65.36	74.02	83.01	92.4	102.3
LTC compressor Work"kW"	152.3	137.1	123.2	110.4	98.58	87.51	77.14	67.38	58.17
System compressor Work"kW"	337.3	327	318.7	311.53	307.3	303.9	301.9	301.4	302.3
$COP_{\_HTC}$	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
Exergy Destruction Ratio ($EDR_{\_\ HTC}$)	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652	0.8652
HTC Exergetic Efficiency	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361	0.5361
HTC Exergy of Fuel "kW"	152.2	149.2	146.7	144.8	143.4	142.3	141.8	141.6	141.9
HTC Exergy of Product "kW"	81.662	79.99	78.68	77.64	76.86	76.31	76	75.92	76.02

Table-3(c): Effect of varying HTC evaporator temperature in three staged cascade system *thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1250) in HTC, R-170 in MTC & R-1150 in LTC (Q_Eva=175.835kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-22ºC, $T_{\_Eva\text{-}MTC}$= -80ºC , $T_{\_Eva\ LTC}$= -120ºC, $Temp\_Overlaping_{\_MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=5ºC, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%, Compressor $efficiency_{\_LTC}$=100%)*

HTC evaporator temperature in three Staged cascade system	-30	-20	-10	0
COP_HTC	2.37	3.03	3.965	5.38
COP_MTC	2.632	2.061	1.625	1.271
COP_LTC	2.609	2.609	2.609	2.609
Three Stage COP_Cascade	0.5834	0.5772	0.5561	0.5178
Three Stage Exergy Destruction Ratio (EDR)	0.8104	0.8298	0.8992	1.04
Three Stage Exergetic Efficiency	0.552	0.5466	0.5265	0.49
Three Stage Exergy of Fuel "kW"	301.4	304.6	316.2	339.6
Three Stage Exergy of Product "kW"	166.1	166.1	166.1	166.1
Two Stage COP_Cascade	1.039	1.025	0.9776	0.8935
Two Stage Exergy Destruction Ratio (EDR)	0.7699	0.7942	0.8817	1.059
Two Stage Exergetic Efficiency	0.565	0.5573	0.5314	0.4858
Two Stage Exergy of Fuel "kW"	234	237.2	248.8	272.2
Two Stage Exergy of Product "kW"	132.2	132.2	132.2	132.2

HTC Mass flow Rate (Kg/sec)	1.38	1.425	1.492	1.593
MTC Mass flow Rate (Kg/sec)	0.7365	0.8298	0.909	1.045
LTC Mass flow Rate (Kg/sec)	0.4454	0.4454	0.4454	0.4454
Q_Cond_HTC"kW"	477.2	480.4	492	515.4
Q_Cond_MTC"kW"	335.6	361.2	392.9	434.6
Q_Cond_LTC"kW"	243.2	243.2	243.2	243.2
Q_EVA_LTC"kW"	175.835	175.835	175.835	175.835
HTC compressor Work"kW"	141.6	119.2	99.11	80.78
MTC compressor Work"kW"	92.4	118	149.7	191.4
LTC compressor Work"kW"	67.38	67.38	67.38	67.38
System compressor Work"kW"	301.4	304.6	316.2	339.6
COP_{HTC}	2.37	3.03	3.965	5.38
HTC Exergy Destruction Ratio (EDR)	0.8652	0.8566	0.8964	1.031
HTC Exergetic Efficiency	0.5361	0.5386	0.5273	0.4924
HTC Exergy of Fuel "kW"	141.6	119.2	99.11	80.78
HTC Exergy of Product "kW"	75.92	64.21	52.26	39.78

2.6 Effect of different HFO and HCFO refrigerants in the HTC, MTC and LTC cycles on the maximum thermodynamic performances of three staged cascaded vapour compression refrigeration system

Effect of different HFO and HCFO refrigerants on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-4(*a*) respectively and it was found that system-5 (using R1233zd(E) in HTC, R1336mzz(Z) in MTC, R1225ye(Z) in LTC) gives best thermodynamic performances and system-28 using R1234yf in HTC, R1225ye(Z) in MTC, R1336mzz(Z) in LTC gives lowest thermodynamic performances. Thermodynamic performances of three staged vapour compression refrigeration systems were also compared with other systems using HFCs & HC in HTC, MTC & LTC cycles and it was found that the use of HFO & HCFO refrigerants re more suitable than using HFC refrigerants

Table-4(a): Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -90ºC , $T_{\_Eva\ LTC}$= -140ºC, $Temp\_Overlaping_{\_MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=5ºC, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%, Compressor $efficiency_{\_LTC}$=100%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
Refrigerant in HTC	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1234 zf	R1233 zd€	R1233 zd€	R1234yf	R1234yf
Refrigerant in MTC	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	2.319	2.319	2.295	2.295	2.561	2.561	2.148	2.148
COP_MTC	2.128	2.178	2.295	2.178	2.128	2.118	2.128	2.178
COP_LTC	1.766	1.7	1.766	1.7	1.766	1.7	1.766	1.7
Three Stage COP_Cascade	0.4358	0.4317	0.4338	0.4297	0.4543	0.45	0.4213	0.4173
($EDR_{\_\ Three\ Stage}$)	0.8518	0.8694	0.8601	0.8778	0.7762	0.7934	0.9157	0.9337
Three Stage Exergetic Efficiency	0.54	0.5349	0.5376	0.5325	0.563	0.5576	0.522	0.5171
Three Stage Exergy of Fuel "kW"	22.95	23.17	23.05	23.27	22	22.22	23.74	23.96
Two Stage COP_Cascade	0.906	0.919	0.9007	0.9135	0.9579	0.972	0.8664	0.8785
Two Stage EDR	0.7578	0.733	0.7683	0.7434	0.6626	0.6384	0.8382	0.8128
Two Stage Exergetic Efficiency	0.5689	0.577	0.5655	0.5736	0.6015	0.6103	0.544	0.5516
Two Stage Exergy of Fuel "kW"	17.29	17.28	17.39	17.39	16.35	16.34	18.08	18.08
$COP_{\_HTC}$	2.319	2.319	2.295	2.295	2.561	2.561	2.148	2.148
HTC_EDR	0.9062	0.9062	0.9259	0.9062	0.7263	0.7263	1.058	1.058
HTC Exergetic Efficiency	0.5246	0.5246	0.5192	0.5192	0.5793	0.5793	0.4859	0.4859
HTC Exergy of Fuel "kW"	9.926	9.926	10.3	10.1	8.99	9.049	10.72	10.79

Effect of different HFO and HCFO refrigerants on the thermodynamic performances of twenty five cascaded vapour compression refrigeration systems (three staged VCRS) at 0ºC of HTC evaporator temperature , -75ºC of MTC evaporator temperature, & -130ºC of LTC evaporator temperature have been computed & shown in table-*5(a)* to table-5(c) and it was found that system-1 (using R1234 ze(Z) in HTC, R1233zd(E) in MTC& R1225ye(Z) in LTC) gives best thermodynamic performances and cascaded system-25 using R1234yf in HTC, R1225ye(Z) in MTC, R1336mzz(Z) in LTC gives lowest thermodynamic performances .

Table-5(a) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=50ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -75ºC , $T_{\_Eva\ LTC}$= -130ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=10ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
Refrigerant in HTC	R1234 ze(Z)	R1234 ze(Z)	R1234 ze(Z)	R1234 ze(Z)	R1224 yd(Z)	R1224 yd(Z)	R1224 yd(Z)	R1224 yd(Z)
Refrigerant in MTC	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1336mzz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	3.669	3.669	3.669	3.669	3.448	1.418	1.418	1.36
COP_MTC	1.418	1.418	1.36	1.37	1.418	1.418	1.36	1.37
COP_LTC	1.288	1.232	1.288	1.232	1.288	1.232	1.288	1.232
Three Stage COP_Cascade	0.3503	0.3411	0.3422	0.3346	0.3439	0.335	0.336	0.3286
(EDR$_{_\ Three\ Stage}$)	1.636	1.707	1.699	1.76	1.685	1.757	1.749	1.811
Three Stage Exergetic Efficiency	0.3793	0.3691	0.3705	0.3623	0.3724	0.3627	0.3638	0.3558
Three Stage Exergy of Fuel “kW”	28.55	29.32	29.22	29.88	29.08	29.86	29.76	30.43
Three Stage Exergy of Product “kW”	10.83	10.83	10.83	10.83	10.83	10.83	10.83	10.83
Two Stage COP_Cascade	0.8545	0.8545	0.8545	0.8322	0.8333	0.8333	0.8073	0.8118
Two Stage_EDR	1.319	1.319	1.319	1.381	1.381	1.381	1.455	1.41
Two Stage Exergetic Efficiency	0.4312	0.4312	0.4312	0.42	0.4205	0.4205	0.4074	0.4097
Two Stage Exergy of Fuel “kW”	20.79	21.2	21.46	2177	21.31	21.74	22	22.42
Two Stage Exergy of Product “kW”	8.964	9.142	8.964	9.142	8.964	9.142	8.964	9.142
HTC Mass flow Rate (Kg/sec)	0.1884	0.1922	0.1917	0.1917	0.2557	0.2608	0.2602	0.2646
MTC Mass flow Rate (Kg/sec)	0.1215	0.124	0.1467	0.1669	0.1215	0.124	0.1467	0.1669
LTC Mass flow Rate (Kg/sec)	0.0653	0.0578	0.06525	0.0578	0.0653	0.0578	0.06525	0.0578
Q_Cond_HTC“kW”	38.55	39.32	39.22	39.32	39.08	39.86	39.76	40.43
Q_Cond_MTC“kW”	30.29	30.89	30.82	31.34	30.29	30.89	30.82	31.34
Q_Cond_LTC“kW”	17.76	18.12	17.76	18.12	17.76	18.12	17.76	18.12
Q_EVA_LTC“kW”	10	10	10	10	10	10	10	10
HTC compressor Work“kW”	8.257	8.421	8.402	8.543	8.786	8.961	8.941	9.091
MTC compressor Work“kW”	12.53	12.78	13.06	13.23	13.06	13.23	13.06	13.23
LTC compressor Work“kW”	7.761	8.115	7.761	8.115	7.761	8.115	7.761	8.115
System compressor Work“kW”	28.55	29.32	29.22	29.88	29.08	29.86	29.76	30.43
COP$_{_HTC}$	3.669	3.669	3.669	3.669	3.448	3.448	3.448	3.448
HTC Exergy Destruction Ratio (EDR)	1.978	1.978	1.978	1.978	2.169	2.169	2.169	2.169
HTC Exergetic Efficiency	0.3358	0.3358	0.3358	0.3358	0.3155	0.3155	0.3155	0.3155
HTC Exergy of Fuel “kW”	8.257	8.421	8.402	8.543	8.786	8.961	8.941	9.091
HTC Exergy of Product “kW”	2.772	2.828	2.821	2.868	2.772	2.828	2.821	2.868

Table-5(b) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=50ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva-MTC}$= -75ºC , $T_{\_Eva\ LTC}$= -130ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=10ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three staged cascade system	System 9	System 10	System 11	System 12	System 14	System 15	System 16	System 17
Refrigerant in HTC	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1234 zf	R1243 zf	R1234 zf
Refrigerant in MTC	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1336mzz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	3.215	3.215	3.215	3.215	3.169	3.169	3.169	3.169
COP_MTC	1.418	1.418	1.36	1.37	1.418	1.418	1.36	1.37
COP_LTC	1.288	1.232	1.288	1.232	1.288	1.232	1.288	1.232
Three Stage COP_Cascade	0.3366	0.3278	0.3288	0.3217	0.335	0.3263	0.3273	0.3202
(EDR_ $_{\text{Three Stage}}$)	1.744	1.817	1.808	1.871	1.757	1.83	1.821	1.884
Three Stage Exergetic Efficiency	0.3644	0.355	0.3561	0.3483	0.3624	0.3534	0.3544	0.3467
Three Stage Exergy of Fuel “kW”	29.71	30.5	30.41	31.09	29.85	30.64	30.55	31.23
Three Stage Exergy of Product “kW”	10.83	10.83	10.83	10.83	10.83	10.83	10.83	10.83
Two Stage COP_Cascade	0.8092	0.8092	0.7842	0.7885	0.8041	0.8041	0.7794	0.7837
Two Stage_EDR	1.449	1.449	1.527	1.513	1.464	1.464	1.542	1.528
Two Stage Exergetic Efficiency	0.4084	0.4084	0.3958	0.398	0.4058	0.4058	0.3933	0.3955
Two Stage Exergy of Fuel “kW”	21.95	22.39	22.65	22.97	22.09	22.09	22.79	23.12
Two Stage Exergy of Product “kW”	8.964	9.142	8.964	9.142	8.964	9.142	8.964	9.142
HTC Mass flow Rate (Kg/sec)	0.2664	0.2717	0.2711	0.2757	0.2389	0.2436	0.2431	0.2472
MTC Mass flow Rate (Kg/sec)	0.1215	0.124	0.1467	0.1669	0.1215	0.124	0.1467	0.1669
LTC Mass flow Rate (Kg/sec)	0.0653	0.0578	0.06525	0.0578	0.06525	0.05782	0.06525	0.05782
Q_Cond_HTC“kW”	39.71	40.5	40.41	41.09	39.85	40.64	40.55	41.23
Q_Cond_MTC“kW”	30.29	30.89	30.82	31.34	30.29	30.89	30.82	31.34
Q_Cond_LTC“kW”	17.76	18.12	17.76	18.12	17.76	18.12	17.76	18.12
Q_EVA_LTC“kW”	10	10	10	10	10	10	10	10
HTC compressor Work“kW”	9.421	9.609	9.587	9.748	9.559	9.749	9.727	9.89
MTC compressor Work“kW”	12.53	12.78	13.06	13.23	13.06	13.23	13.06	13.23
LTC compressor Work“kW”	7.761	8.115	7.761	8.115	7.761	8.115	7.761	8.115
System compressor Work“kW”	29.71	30.5	30.41	31.09	29.85	30.64	30.55	31.23
COP$_{_HTC}$	3.215	29.71	30.5	30.41	3.169	3.169	3.169	3.169
HTC Exergy Destruction Ratio (EDR)	2.398	29.71	30.5	30.41	2.448	2.448	2.448	2.448
HTC Exergetic Efficiency	0.2943	29.71	30.5	30.41	0.29	0.29	0.29	0.29
HTC Exergy of Fuel “kW”	9.421	9.609	9.587	9.748	9.559	9.749	9.727	9.89
HTC Exergy of Product “kW”	2.772	2.828	2.821	2.868	2.772	2.828	2.821	2.868

Table-5(c) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=50ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva-MTC}$= -75ºC , $T_{\_Eva\ LTC}$= -130ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=10ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three staged cascade system	System 18	System 19	System 20	System 21	System 22	System 23	System 24	System 25
Refrigerant in HTC	R1233 zd(E)	R1233 zd(E)	R1336 mzz(Z)	R1225 ye(Z)	R1234 yf	R1234yf	R1234yf	R1234yf
Refrigerant in MTC	R1336 mzz(Z)	R1225 ye(Z)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1336m zz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	3.523	3.523	3.402	3.160	2.986	2.986	2.986	2.986
COP_MTC	1.36	1.37	1.418	1.418	1.418	1.418	1.36	1.37
COP_LTC	1.288	1.232	1.288	1.232	1.288	1.232	1.288	1.232
Three Stage COP_Cascade	0.3382	0.3382	0.3425	0.3260	0.3286	0.3201	0.3211	0.3141
Exergy Destruction Ratio (EDR_ Three Stage)	1.731	1.793	1.696	1.833	1.811	1.885	1.876	1.940
Three Stage Exergetic Efficiency	0.3661	0.3581	0.3709	0.3530	0.3558	0.3466	0.3477	0.3401
Three Stage Exergy of Fuel "kW"	29.57	30.24	29.19	30.24	30.43	31.24	31.14	31.84
Three Stage Exergy of Product "kW"	10.83	10.83	10.83	10.83	10.83	10.83	10.83	10.83
Two Stage COP_Cascade	0.8143	0.8189	0.8287	0.8092	0.7834	0.7838	0.7596	0.7637
Two Stage Exergy Destruction Ratio (EDR)	1.433	1.420	1.391	1.467	1.529	1.529	1.609	1.595
Two Stage Exergetic Efficiency	0.4110	0.4133	0.4182	0.4053	0.3954	0.3954	0.3833	0.3854
Two Stage Exergy of Fuel "kW"	21.81	22.12	21.43	22.56	22.67	23.12	23.38	23.72
Two Stage Exergy of Product "kW"	8.964	9.142	8.964	9.142	8.964	9.142	8.964	9.142
HTC Mass flow Rate (Kg/sec)	0.2163	0.2199	0.2545	0.3220	0.3245	0.3310	0.3302	0.3358
MTC Mass flow Rate (Kg/sec)	0.1467	0.1669	0.1215	0.1240	0.1215	0.1240	0.1467	0.1669
LTC Mass flow Rate (Kg/sec)	0.06525	0.05782	0.06525	0.05782	0.06525	0.05782	0.06525	0.05782
Q_Cond_HTC"kW"	39.57	40.24	39.19	40.67	40.43	41.24	41.14	41.84
Q_Cond_MTC"kW"	30.82	31.34	30.29	30.89	30.29	30.89	30.29	30.89
Q_Cond_LTC"kW"	17.76	18.12	17.76	18.12	17.76	18.12	17.76	18.12
Q_EVA_LTC"kW"	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work"kW"	8.75	8.897	8.903	9.777	10.14	10.35	10.32	10.50
MTC compressor Work"kW"	13.06	13.23	12.53	12.78	12.53	12.78	13.06	13.23
LTC compressor Work"kW"	7.761	8.115	7.761	8.115	7.761	8.115	7.761	8.115
System compressor Work"kW"	29.57	30.24	29.19	30.24	30.43	31.24	31.14	31.84
COP_HTC	3.523	3.523	3.402	3.16	2.986	2.986	2.986	2.986
HTC Exergy Destruction Ratio (EDR)	2.102	2.102	2.212	2.458	2.659	2.659	2.659	2.659
HTC Exergetic Efficiency	0.3224	0.3224	0.3114	0.2892	2.733	2.733	2.733	2.733
HTC Exergy of Fuel "kW"	8.75	8.897	8.903	9.777	10.14	10.35	10.32	10.50
HTC Exergy of Product "kW"	2.821	2.868	2.772	2.828	2.772	2.828	2.821	2.868

2.7 Effect of temperature overlapping in the HTC, MTC and LTC cycles on actual thermodynamic performances of three staged cascaded vapour compression refrigeration system using HFO and HCFO refrigerants for ultra-low temperature applications

Effect of different HFO and HCFO refrigerants on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems (three staged VCRS) at -30ºC of HTC evaporator temperature , -90ºC of MTC evaporator temperature, & -140ºC of LTC evaporator temperature have been computed & shown in tables(three staged VCRS) at 0ºC of HTC evaporator temperature , -75ºC of MTC evaporator temperature, & -130ºC of LTC evaporator temperature have been computed & shown in table-6*(a) to* table-6*(c)* respectively and it was found that system-5 (using R1233zd(E) in HTC, R1336mzz(Z) in MTC, R1225ye(Z) in LTC) gives best thermodynamic performances and system-28 using R1234yf in HTC, R1225ye(Z) in MTC, R1336mzz(Z) in LTC gives lowest thermodynamic performances . it is concluded that R1336mzz(Z) and R1225ye(Z) are suitable for replacing R23 in MTC and R1336mzz(Z) and R1225ye(Z) are suitable for replacing R14 in LTC cycle. It was also observed that when temperature overlapping increasing the thermodynamic performances were decreasing .The maximum thermodynamic performances were found with zero approach temperature overlapping)

Table-6(a) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -90ºC , $T_{\_Eva\ LTC}$= -140ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=10ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
Refrigerant in HTC	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1234 zf	R1233 zd(E)	R1233 zd(E)	R1234yf	R1234yf
Refrigerant in MTC	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336m zz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
COP_MTC	1.537	1.574	1.537	1.574	1.537	1.574	1.537	1.574
COP_LTC	1.271	1.217	1.271	1.217	1.271	1.217	1.271	1.217
Three Stage COP_Cascade	0.2825	0.2790	0.2812	0.2777	0.2951	0.2913	0.2728	0.2693
Exergy Destruction Ratio (EDR_ Three Stage)	1.856	1.893	1.869	1.906	1.735	1.771	1.958	1.996
Three Stage Exergetic Efficiency	0.3501	0.3457	0.3485	0.3441	0.3656	0.3609	0.3380	0.3338
Three Stage Exergy of Fuel "kW"	35.69	35.85	35.56	36.01	33.89	34.33	36.66	37.13
Three Stage Exergy of Product "kW"	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6493	0.6594	0.6454	0.6554	0.6867	0.6976	0.6207	0.6302
Two Stage Exergy Destruction Ratio (EDR)	1.453	1.415	1.468	1.430	1.319	1.283	1.566	1.527
Two Stage Exergetic Efficiency	0.4077	0.4140	0.4053	0.4115	0.4312	0.4380	0.3898	0.3957
Two Stage Exergy of Fuel "kW"	27.52	27.63	27.69	27.80	26.02	26.11	28.79	28.91
Two Stage Exergy of Product "kW"	11.22	11.44	11.22	11.44	11.22	11.44	11.44	11.44
HTC Mass flow Rate (Kg/sec)	0.2749	0.2776	0.2407	0.2431	0.2205	0.2227	0.3334	0.3367
MTC Mass flow Rate (Kg/sec)	0.1260	0.1423	0.1260	0.1423	0.1260	0.1423	0.1260	0.1423
LTC Mass flow Rate (Kg/sec)	0.0615	0.0537	0.0615	0.0537	0.0615	0.0537	0.0615	0.0537
Q_Cond_HTC"kW"	45.39	45.85	45.56	46.01	43.89	44.33	46.66	47.13
Q_Cond_MTC"kW"	29.5	29.79	29.5	29.79	29.5	29.79	29.5	29.79
Q_Cond_LTC"kW"	17.87	18.22	17.87	18.22	17.87	18.22	17.87	18.22
Q_EVA_LTC"kW"	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work"kW"	15.90	16.06	16.06	16.22	14.4	14.54	17.16	17.34
MTC compressor Work"kW"	11.63	11.57	11.63	11.57	11.63	11.57	11.63	11.57
LTC compressor Work"kW"	7.87	8.219	7.87	8.219	7.87	8.219	7.87	8.219
System compressor Work"kW"	35.69	35.85	35.56	36.01	33.89	34.33	36.66	37.13
COP_{HTC}	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
HTC Exergy Destruction Ratio (EDR)	1.383	1.383	1.407	1.407	1.158	1.158	1.537	1.537
HTC Exergetic Efficiency	0.4197	0.4197	0.4154	0.4154	0.4634	0.4634	0.3887	0.3887
HTC Exergy of Fuel "kW"	15.90	16.06	16.06	16.22	14.4	14.54	17.16	17.34
HTC Exergy of Product "kW"	6.672	6.739	6.672	6.739	6.672	6.739	6.672	6.739

Table-6(b) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40^{o}C, T_ambient=25^{o}C, $T_{\_Eva\ HTC}$ =-30^{o}C, $T_{\_Eva\text{-}MTC}$= -90^{o}C , $T_{\_Eva\ LTC}$= -140^{o}C, $Temp\_Overlaping_{\_MTC}$=5^{o}C, $Temp\_Overlaping_{\_LTC}$=10^{o}C, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
Refrigerant in HTC	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1234 zf	R1233 zd(E)	R1233 zd(E)	R1234yf	R1234yf
Refrigerant in MTC	R1336 mzz(Z)	R1225 ye(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336m zz(Z)	R1225 ye(Z)
Refrigerants in LTC	R1225 ye(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)
COP_HTC	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
COP_MTC	1.702	1.265	1.743	1.702	1.702	1.743	1.702	1.743
COP_LTC	1.413	1.360	1.360	1.413	1.413	1.360	1.413	1.360
Three Stage COP_Cascade	0.3153	0.3122	0.3107	0.3138	0.3296	0.3263	0.3041	0.3012
Exergy Destruction Ratio (EDR_ Three Stage)	1.56	1.265	1.579	1.572	1.448	1.473	1.654	1.680
Three Stage Exergetic Efficiency	0.3907	0.3869	0.3850	0.3888	0.4084	0.4044	0.3769	0.3732
Three Stage Exergy of Fuel "kW"	31.72	32.03	32.18	31.87	30.34	30.64	32.88	33.20
Three Stage Exergy of Product "kW"	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.693	0.7032	0.6989	0.6888	0.7341	0.7452	0.6617	0.6713
Two Stage Exergy Destruction Ratio (EDR)	1.298	1.265	1.279	1.312	1.17	1.137	1.407	1.372
Two Stage Exergetic Efficiency	0.4351	0.4416	0.4388	0.4325	0.4609	0.4679	0.4155	0.4215
Two Stage Exergy of Fuel "kW"	24.64	24.64	24.83	24.79	23.26	23.29	25.81	25.85
Two Stage Exergy of Product "kW"	10.72	10.90	10.90	10.72	10.72	10.90	10.72	10.90
HTC Mass flow Rate (Kg/sec)	0.2526	0.2545	0.2227	0.2205	0.2027	0.2042	0.3334	0.3367
MTC Mass flow Rate (Kg/sec)	0.1154	0.1303	0.1303	0.1154	0.1154	0.1303	0.1154	0.1303
LTC Mass flow Rate (Kg/sec)	0.06001	0.05209	0.05209	0.06001	0.06001	0.05209	0.06001	0.05209
Q_Cond_HTC"kW"	41.72	42.03	42.18	41.87	40.34	40.64	42.88	43.20

Q_Cond_MTC"kW"	27.11	27.31	27.31	27.11	27.11	27.31	27.11	27.31
Q_Cond_LTC"kW"	17.08	17.35	17.35	17.08	17.08	17.35	17.08	17.35
Q_EVA_LTC"kW"	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work"kW"	14.61	14.72	14.87	14.76	13.23	13.33	15.77	15.89
MTC compressor Work"kW"	10.03	11.57	9.958	10.03	10.03	9.958	10.03	9.958
LTC compressor Work"kW"	7.077	7.354	7.354	7.077	7.077	7.354	7.077	7.354
System compressor Work"kW"	31.72	32.03	32.18	31.87	30.34	30.64	32.88	33.20
COP_{HTC}	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
HTC Exergy Destruction Ratio (EDR)	1.383	1.383	1.407	1.407	1.158	1.158	1.573	1.573
HTC Exergetic Efficiency	0.4197	0.4197	0.4154	0.4154	0.4634	0.4634	0.3887	0.3887
HTC Exergy of Fuel "kW"	14.61	14.72	14.87	14.76	13.23	13.33	15.77	15.89
HTC Exergy of Product "kW"	6.132	6.178	6.178	6.132	6.132	6.178	6.132	6.178

Table-6 (c) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -90ºC , $T_{\_Eva\ LTC}$= -120ºC, $Temp\_Overlaping_{\_MTC}$=5ºC, $Temp\_Overlaping_{\_LTC}$=10ºC, Compressor $efficiency_{\_HTC}$=80%, Compressor $efficiency_{\_MTC}$=80%, Compressor $efficiency_{\_LTC}$=80%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8
Refrigerant in HTC	R1234 ze(E)	R1234 ze(E)	R1243 zf	R1234 zf	R1233 zd(E)	R1233 zd(E)	R1234yf	R1234yf
Refrigerant in MTC	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336 mzz(Z)	R1225 ye(Z)	R1336m zz(Z)	R1225 ye(Z)
Refrigerants in LTC	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_HTC	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
COP_MTC	1.537	1.574	1.537	1.574	1.537	1.574	1.537	1.574
COP_LTC	1.271	1.217	1.271	1.217	1.271	1.217	1.271	1.217
Three Stage COP_Cascade	0.2825	0.2790	0.2812	0.2777	0.2951	0.2913	0.2728	0.2693
Exergy Destruction Ratio ($EDR_{\_Three\ Stage}$)	1.856	1.893	1.869	1.906	1.735	1.771	1.958	1.996
Three Stage Exergetic Efficiency	0.3501	0.3457	0.3485	0.3441	0.3656	0.3609	0.3380	0.3338
Three Stage Exergy of Fuel "kW"	35.69	35.85	35.56	36.01	33.89	34.33	36.66	37.13
Three Stage Exergy of Product "kW"	12.39	12.39	12.39	12.39	12.39	12.39	12.39	12.39
Two Stage COP_Cascade	0.6493	0.6594	0.6454	0.6554	0.6867	0.6976	0.6207	0.6302
Two Stage Exergy Destruction Ratio (EDR)	1.453	1.415	1.468	1.430	1.319	1.283	1.566	1.527
Two Stage Exergetic Efficiency	0.4077	0.4140	0.4053	0.4115	0.4312	0.4380	0.3898	0.3957
Two Stage Exergy of Fuel "kW"	27.52	27.63	27.69	27.80	26.02	26.11	28.79	28.91
Two Stage Exergy of Product "kW"	11.22	11.44	11.22	11.44	11.22	11.44	11.44	11.44
HTC Mass flow Rate (Kg/sec)	0.2749	0.2776	0.2407	0.2431	0.2205	0.2227	0.3334	0.3367
MTC Mass flow Rate (Kg/sec)	0.1260	0.1423	0.1260	0.1423	0.1260	0.1423	0.1260	0.1423
LTC Mass flow Rate (Kg/sec)	0.06157	0.05379	0.06157	0.05379	0.06157	0.05379	0.06157	0.05379
Q_Cond_HTC"kW"	45.39	45.85	45.56	46.01	43.89	44.33	46.66	47.13
Q_Cond_MTC"kW"	29.5	29.79	29.5	29.79	29.5	29.79	29.5	29.79
Q_Cond_LTC"kW"	17.87	18.22	17.87	18.22	17.87	18.22	17.87	18.22
Q_EVA_LTC"kW"	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work"kW"	15.90	16.06	16.06	16.22	14.4	14.54	17.16	17.34
MTC compressor Work"kW"	11.63	11.57	11.63	11.57	11.63	11.57	11.63	11.57
LTC compressor Work"kW"	7.87	8.219	7.87	8.219	7.87	8.219	7.87	8.219
System compressor Work"kW"	35.69	35.85	35.56	36.01	33.89	34.33	36.66	37.13
COP_{HTC}	1.855	1.855	1.836	1.836	2.049	2.049	1.718	1.718
HTC Exergy Destruction Ratio (EDR)	1.383	1.383	1.407	1.407	1.158	1.158	1.537	1.537
HTC Exergetic Efficiency	0.4197	0.4197	0.4154	0.4154	0.4634	0.4634	0.3887	0.3887
HTC Exergy of Fuel "kW"	15.90	16.06	16.06	16.22	14.4	14.54	17.16	17.34
HTC Exergy of Product "kW"	6.672	6.739	6.672	6.739	6.672	6.739	6.672	6.739

2.8 Options for alternative refrigerants for replacing R404 in HTC, R23 in MTC and R14 in LTC in the three staged cascaded vapour compression refrigeration system for low temperature applications

In this section, the several options are available for replacing high GWP ecofriendly R404 in HTC by the HFOs, hydrocarbons and low GWP ecofriendly HFC refrigerants in the high temperature cycle. Also R170 & R41 for replacing R23 in medium temperature cycle (MTC) and R1150 for replacing R14 in the low temperature cycle(LTC) . The performance evaluation was carried out for maximum and actual thermodynamic performances in the following sections

2.9 Effect of different ecofriendly refrigerants in the HTC, MTC and LTC cycles on the maximum thermodynamic performances of three staged cascaded vapour compression refrigeration system

Effect of different HFOs HC and HFCs refrigerants in high temperature cycle, HTC for replacing R404a and HFCs refrigerants in medium temperature cycle for replacing R23and HC refrigerant in low temperature cycle(LTC) for replacing R14 on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-7(a*)* respectively and it was found that system-2 (using R152a in HTC, R170 in MTC, R1150in LTC) gives best thermodynamic performances & System-10 gives lowest thermodynamic performances

Comparing thermodynamic performances between two cascaded vapour compression refrigeration systems system-15, using R1150 in LTC were compared with the thermodynamic performances of system-17 using R14 in the low temperature cycle(LTC) s shown in table-7(*b) to* table-7(*d)* it was found that cascade systems using R1150 in LTC gives better thermodynamic performances as compared with cascade systems using R14 in low temperature cycle

Similarly system-19 using R41 in MTC & system-15& system-16 using R170 in MTC were compared with system-17 & system-18 using R23 in MTC it was found that it is concluded that using R41 & R170 used in MTC are suitable for replacing R23 in MTC therefore, it is concluded that R41 & R170 are suitable for replacing R23 in MTC and R1150 are suitable for replacing R14 in LTC cycle.

Since the thermodynamic performances using HFO refrigerants with using R41 & R170 in MTC for replacing R-23 and R1150 in LTC for replcing R14 were compared with HFO refrigerants it was found that the R1336mzz(Z) and R1225ye(Z) are suitable for replacingR23 in MTC and R1336mzz(Z) and R1225ye(Z) are suitable for replacing R14 in LTC cycle**.** The actual thermodynamic performances of three stage cascade vapour compression refrigeration system-12& system-13 have been compared and it was found that system-12 using R1234ze in HTC, R170in MTC & R1150 in LTC gives better thermodynamic performances thn system-13 using R404a in HTC, R23n MTC & R14 in LTC

Table-7(a) Maximum thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva-MTC}$= -90°C , $T_{\_Eva\ LTC}$= -140°C, $Temp\_Overlaping_{\_MTC}$=5°C, $Temp\_Overlaping_{\_LTC}$=5°C, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%, Compressor $efficiency_{\_LTC}$=100%)

Three staged cascade system	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8	System 9	System 10
Refrigerant in HTC	R245 fa	R152a	R32	R161	R1270	R290	R600a	R1234yf	R1234ze(E)	R404a
Refrigerant in MTC	R170	R170	R170	R170	R170	R170	R170	R170	R170	R23
Refrigerants in LTC	R1150	R1150	R1150	R1150	R1150	R1150	R1150	R1150	R1150	R14
COP_HTC	2.513	2.561	2.381	2.515	2.370	2.348	2.368	2.177.	2.319	2.026
COP_MTC	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.999	1.581
COP_LTC	1.666	1.666	1.666	1.666	1.666	1.666	1.666	1.666	1.666	1.171
Three Stage COP_Cascade	0.4237	0.4269	0.4143	0.4238	0.4136	0.4119	0.4134	0.3987	0.4098	0.3717
Three Stage Exergetic Effi	0.525	0.529	0.5134	0.5252	0.5125	0.5105	0.5123	0.4941	0.5078	0.4607
Two Stage COP_Cascade	0.9114	0.9207	0.8845	0.9117	0.8824	0.8777	0.8819	0.8407	0.8717	0.7933
Two Stage Exergetic Effi	0.5722	0.5781	0.5554	0.5725	0.5540	0.5511	0.5537	0.5279	0.5473	0.4981
$COP_{\_HTC}$	2.513	2.561	2.381	2.515	2.370	2.348	2.368	2.177	2.319	2.026
HTC Exergetic Efficiency	0.5685	0.5793	0.5385	0.5689	0.5361	0.5310	0.5356	0.4924	0.5246	0.4981

Table-7(b) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva-MTC}$= -90°C , $T_{\_Eva\ LTC}$= -120°C, $Temp\_Overlaping_{\_MTC}$=5°C, $Temp\_Overlaping_{\_LTC}$=5°C, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100%.

Three staged cascade system	System 11	System 12	System 13	System 14	System 15	System 16	System 17	System 18
Refrigerant in HTC	R1234 ze	R1234ze	R1270	R1270	R600a	R600a	R290	R290
Refrigerant in MTC	R41	R170	R41	R170	R41	R170	R41	R170
Refrigerants in LTC	R1150	R1150	R1150	R1150	R1150	R1150	R1150	R1150
COP_HTC	2.319	2.319	2.370	2.37	2.368	2.368	2.348	2.348
COP_MTC	1.985	1.999	1.985	1.999	1.985	1.999	1.985	1.999
COP_LTC	3.555	3.555	3.555	3.555	3.555	3.555	3.555	3.555
Three Stage COP_Cascade	0.5690	0.5711	0.5749	0.5769	0.5746	0.5767	0.5723	0.5744
($EDR_{\_\ Three\ Stage}$)	0.8561	0.8495	0.8373	0.8307	0.8381	0.8316	0.8455	0.8389
Three Stage Exergetic Efficiency	0.5388	0.5407	0.5443	0.5462	0.5440	0.5460	0.5419	0.5438
Three Stage Exergy of Fuel “kW”	17.57	17.51	17.39	17.33	17.40	17.34	17.47	17.41
Three Stage Exergy of Product “kW”	9.468	9.468	9.468	9.468	9.468	9.468	9.468	9.468
Two Stage COP_Cascade	0.8680	0.8717	0.8786	0.8824	0.8782	0.8819	0.874	0.8777
Two Stage_EDR	0.8348	0.8270	0.8126	0.8049	0.8136	0.8059	0.8222	0.8146
Two Stage Exergetic Efficiency	0.5450	0.5473	0.5517	0.554	0.5514	0.5537	0.5419	0.5511
Two Stage Exergy of Fuel “kW”	14.76	14.70	14.58	14.52	14.59	14.53	14.66	14.60
Two Stage Exergy of Product “kW”	8.045	8.045	8.045	8.045	8.045	8.045	8.045	8.045
HTC Mass flow Rate (Kg/sec)	0.1796	0.1792	0.07923	0.07906	0.09126	0.09106	0.0829	0.08272
MTC Mass flow Rate (Kg/sec)	0.03521	0.04015	0.03521	0.04015	0.03521	0.04015	0.03521	0.04015
LTC Mass flow Rate (Kg/sec)	0.02382	0.02382	0.02382	0.02382	0.02382	0.02382	0.02382	0.02382
Q_Cond_HTC“kW”	27.57	27.51	27.39	27.33	27.40	27.34	27.51	27.51
Q_Cond_MTC“kW”	19.27	19.22	19.27	19.27	19.27	19.22	19.27	19.27
Q_Cond_LTC“kW”	12.81	12.81	12.81	12.81	12.81	12.81	12.81	12.81
Q_EVA_LTC“kW”	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work“kW”	8.307	8.288	8.129	8.110	8.137	8.113	8.207	8.188
MTC compressor Work“kW”	6.454	6.410	6.454	6.410	6.454	6.410	6.454	6.410
LTC compressor Work“kW”	2.183	2.183	2.183	2.183	2.183	2.183	2.183	2.183
System compressor Work“kW”	17.57	17.51	17.39	17.33	17.40	17.34	17.47	17.41
$COP_{\_HTC}$	2.319	2.319	2.370	2.37	2.368	2.368	2.348	2.348
HTC Exergy Destruction Ratio (EDR)	0.9062	0.9062	0.8652	0.8652	0.8671	0.8671	0.8831	0.8831
HTC Exergetic Efficiency	0.5246	0.5246	0.5361	0.5361	0.5356	0.5356	0.5310	0.5310
HTC Exergy of Fuel “kW”	8.307	8.288	8.129	8.110	8.137	8.118	8.207	8.188
HTC Exergy of Product “kW”	4.358	4.348	4.358	4.348	4.358	4.348	4.358	4.348

Table-7(c) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40°C, T_ambient=25°C, $T_{\_Eva\ HTC}$ =-30°C, $T_{\_Eva-MTC}$= -90°C , $T_{\_Eva\ LTC}$= -140°C, $Temp\_Overlaping_{\_MTC}$=5°C, $Temp\_Overlaping_{\_LTC}$=10°C, Compressor $efficiency_{\_HTC}$=100%, Compressor $efficiency_{\_MTC}$=100.

Three staged cascade system	System 19	System 20	System 21	System 22	System 23	System 24	System 25	System 26
Refrigerant in HTC	R1234 yf	R1234 yf	R245fa	R245fa	R717	R717	R717	R717
Refrigerant in MTC	R41	R170	R170	R41	R41	R170	R41	R23
Refrigerants in LTC	R1150	R1150	R1150	R1150	R1150	R1150	R14	R14
COP_HTC	2.177	2.177	2.513	2.513	2.571	2.571	2.571	2.571
COP_MTC	1.985	1.999	1.985	1.985	1.985	1.999	1.985	1.947
COP_LTC	3.555	3.555	3.555	3.555	3.346	3.346	3.346	3.346
Three Stage COP_Cascade	0.5520	0.5539	0.5927	0.5906	0.5967	0.5989	0.5839	0.5779
($EDR_{\_\ Three\ Stage}$)	0.9135	0.9068	0.782	0.7884	0.770	0.7637	0.8088	0.8276
Three Stage Exergetic Efficiency	0.5226	0.5244	0.5612	0.5592	0.5650	0.5670	0.5528	0.5472
Three Stage Exergy of Fuel “kW”	18.12	18.053	16.87	16.93	16.76	17.70	17.13	17.30
Three Stage Exergy of Product “kW”	9.468	9.468	9.468	9.468	9.468	9.468	9.468	9.468
Two Stage COP_Cascade	0.8372	0.8407	0.9114	0.9014	0.9187	0.9227	0.9187	0.9073
Two Stage_EDR	0.9023	0.8945	0.7475	0.755	0.7335	0.7260	0.7375	0.7553
Two Stage Exergetic Efficiency	0.5257	0.5279	0.5722	0.5698	0.5769	0.5794	0.5769	0.5472
Two Stage Exergy of Fuel “kW”	15.30	15.24	14.06	14.12	13.95	13.89	14.14	14.32
Two Stage Exergy of Product “kW”	8.045	8.045	8.045	8.045	8.045	8.045	8.045	8.155

HTC Mass flow Rate (Kg/sec)	0.215	0.02145	0.1477	0.1480	0.01866	0.01861	0.01891	0.01904
MTC Mass flow Rate (Kg/sec)	0.03521	0.04015	0.04015	0.03521	0.03521	0.04015	0.03569	0.08112
LTC Mass flow Rate (Kg/sec)	0.02381	0.02382	0.02382	0.02382	0.02382	0.02382	0.1085	0.1085
Q_Cond_HTC“kW”	28.12	28.05	26.87	26.93	26.76	26.7	27.13	27.30
Q_Cond_MTC“kW”	19.27	19.22	19.22	19.27	19.22	19.27	19.53	19.66
Q_Cond_LTC“kW”	12.81	12.81	12.81	12.81	12.81	12.81	12.99	12.99
Q_EVA_LTC“kW”	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work“kW”	8.851	8.831	7.649	7.666	7.492	7.475	7.595	7.645
MTC compressor Work“kW”	6.454	6.410	6.410	6.454	6.454	6.410	6.542	6.670
LTC compressor Work“kW”	2.813	2.813	2.813	2.813	2.813	2.813	2.989	2.989
System compressor Work“kW”	18.12	18.053	16.87	16.93	16.76	17.70	17.13	17.30
COP_HTC	2.177	2.177	2.513	2.513	2.571	2.571	2.571	2.571
HTC_ EDR	1.031	1.031	0.759	0.759	0.7192	0.7192	0.7192	0.7192
HTC Exergetic Efficiency	0.4924	0.4924	0.5685	0.5685	0.5817	0.5817	0.5817	0.5817
HTC Exergy of Fuel “kW”	8.851	8.831	7.649	7.666	7.492	7.475	7.595	7.645
HTC Exergy of Product “kW”	4.348	4.348	4.348	4.358	4.358	4.348	4.418	4.447

Table-7(d) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40°C, T_ambient=25°C, $T_{Eva\ HTC}$ =-30°C, $T_{Eva\text{-}MTC}$= -90°C , $T_{Eva\ LTC}$= -140°C, Temp_Overlaping$_{MTC}$=5°C, Temp_Overlaping$_{LTC}$=10°C, Compressor efficiency$_{HTC}$=80%, Compressor efficiency$_{MTC}$=80

Three staged cascade system	System 27	System 28	System 29	System 30	System 31	System 32	System 33	System 34	System 35
Refrigerant in HTC	R161	R161	R152a	R152a	R152a	R32	R32	R32	R404a
Refrigerant in MTC	R41	R170	R41	R170	R170	R23	R170	R41	R23
Refrigerants in LTC	R1150	R1150	R1150	R1150	R14	R1150	R1150	R1150	R14
COP_HTC	2.515	2.515	2.561	2.561	2.561	2.381	2.381	2.381	2.026
COP_MTC	1.985	1.999	1.985	1.999	1.947	1.947	1.999	1.985	1.947
COP_LTC	3.555	3.555	3.555	3.555	3.346	3.555	3.555	3.555	3.346
Three Stage COP_Cascade	0.5908	0.5929	0.5956	0.5978	0.5769	0.5702	0.5781	0.5761	0.5165
Exergy Destruction Ratio (EDR_ Three Stage)	0.7878	0.7814	0.7733	0.7669	0.8309	0.8525	0.827	0.8335	1.045
Three Stage Exergetic Efficiency	0.5593	0.5614	0.5639	0.5660	0.5462	0.5398	0.5473	0.5454	0.489
Three Stage Exergy of Fuel “kW”	16.93	16.87	16.79	16.73	17.10	17.54	17.30	17.36	19.36
Three Stage Exergy of Product “kW”	9.468	9.468	9.468	9.468	9.468	9.468	9.468	9.468	9.468
Two Stage COP_Cascade	0.9078	0.9117	0.9167	0.9207	0.9053	0.8701	0.8845	0.8808	0.7933
Two Stage Exergy Destruction Ratio (EDR)	0.7544	0.7469	0.7373	0.7298	0.7591	0.8305	0.8005	0.8571	1.007
Two Stage Exergetic Efficiency	0.570	0.5725	0.5756	0.5781	0.5462	0.5462	0.5554	0.5530	0.4981
Two Stage Exergy of Fuel “kW”	14.11	14.05	13.98	13.92	14.35	14.73	14.49	14.55	16.37
Two Stage Exergy of Product “kW”	8.045	8.045	8.045	8.045	8.155	8.045	8.045	8.045	8.155
HTC Mass flow Rate (Kg/sec)	0.07288	0.07272	0.09026	0.09005	0.0921	0.08407	0.08334	0.08353	0.2193
MTC Mass flow Rate (Kg/sec)	0.03521	0.4015	0.03521	0.04015	0.0811	0.08002	0.04015	0.03521	0.08112
LTC Mass flow Rate (Kg/sec)	0.2832	0.2832	0.2382	0.2382	0.1085	0.2382	0.2382	0.2382	0.1085
Q_Cond_HTC“kW”	26.93	26.87	26.79	26.73	27.34	27.54	27.30	27.36	29.36
Q_Cond_MTC“kW”	19.27	19.22	19.27	19.22	19.66	19.39	19.22	19.27	19.66
Q_Cond_LTC“kW”	12.81	12.81	12.81	12.81	12.99	12.81	12.81	12.81	12.99
Q_EVA_LTC“kW”	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
HTC compressor Work“kW”	7.661	7.643	7.523	7.506	7.676	8.146	8.075	8.093	8.702
MTC compressor Work“kW”	6.454	6.41	6.454	6.41	6.67	6.580	6.410	6.454	6.67
LTC compressor Work“kW”	2.813	2.813	2.813	2.813	2.989	2.813	2.813	2.813	2.989
System compressor Work“kW”	16.93	16.87	16.79	16.73	17.10	17.54	17.30	17.36	19.36
COP_HTC	2.515	2.515	2.561	2.561	2.561	2.381	2.381	2.381	2.026
HTC Exergy Destruction Ratio (EDR)	0.7579	0.7579	0.7263	0.7263	0.7263	0.8571	0.8571	0.8571	1.182
HTC Exergetic Efficiency	0.5689	0.5689	0.5793	0.5793	0.5793	0.5385	0.5385	0.5385	0.4583
HTC Exergy of Fuel “kW”	7.661	7.643	7.523	7.506	7.676	8.146	8.075	8.093	8.702
HTC Exergy of Product “kW”	4.348	4.348	4.358	4.346	4.447	4.387	4.348	4.358	4.447

2.10 Effect of different HC refrigerants in the HTC, on the actual thermodynamic performances of three stage cascade vapour compression refrigeration system

The effect of different HC refrigerants(R600a, R290, R1270) in high temperature cycle on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-8(a) respectively and it was found that system-3 using R600a in HTC, R170in MTC, R1150in LTC gives best thermodynamic performances and system-1 using R1250 in HTC, R170in MTC, R1150in LTC gives slightly lower thermodynamic performances than system-3 but higher than system-2 using R290 in HTC, R170 in MTC & R1150 in LTC . it is concluded that R170are suitable for replacing R23 in MTC and R1150 are suitable for replacing R14 in LTC cycle.

Table-8(a) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerant(R-1270) in HTC, R-170, R23 &R41 in MTC & R-1150 & R14 in LTC (Q_Eva=10.0kW, T_Cond=40°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%.

Three staged cascade system	System 1	System 2	System 3
Refrigerant in HTC	R1270	R290	R600a
Refrigerant in MTC	R170	R170	R170
Refrigerants in LTC	R1150	R1150	R1150
COP_HTC	1.896	1.878	1.940
COP_MTC	1.428	1.428	1.428
COP_LTC	1.182	1.182	1.182
Three Stage COP_Cascade	0.2635	0.2624	0.2662
Three Stage_EDR	2.062	2.075	2.032
Three Stage Exergetic Efficiency	0.3266	0.3252	0.3298
Three Stage Exergy of Fuel "kW"	37.95	38.11	37.57
Three Stage Exergy "kW"	12.39	11.59	11.59
Two Stage COP_Cascade	0.6262	0.6229	0.6343
Two Stage_EDR	1.543	1.557	1.511
Two Stage Exergetic Efficiency	0.3932	0.3911	0.3983
Two Stage Exergy of Fuel "kW"	29.48	29.64	29.11
Two Stage Exergy "kW"	11.59	11.59	11.59
HTC Mass flow Rate (Kg/sec)	0.1259	0.1351	0.1439
MTC Mass flow Rate (Kg/sec)	0.06071	0.06071	0.06071
LTC Mass flow Rate (Kg/sec)	0.02597	0.02597	0.02597
Q_Cond_HTC"kW"	47.95	48.11	47.57
Q_Cond_MTC"kW"	31.39	31.39	31.39
Q_Cond_LTC"kW"	18.46	18.46	18.46
Q_EVA_LTC"kW"	10.0	10.0	10.0
HTC compressor Work"kW"	16.27	16.71	16.16
MTC compressor Work"kW"	12.93	12.93	12.93
LTC compressor Work"kW"	8.463	8.463	8.463
System compressor Work"kW"	37.95	38.11	37.57
COP$_{HTC}$	1.896	1.896	1.896
(EDR_ $_{HTC}$)	1.332	1.332	1.332
HTC Exergetic Efficiency	0.4289	0.4289	0.4289
HTC Exergy of Fuel "kW"	16.27	16.71	16.16
HTC Exergy of Product "kW"	7.10	7.10	6.931

2.11 Effect of different HC, HFCs & HFOs refrigerants in the HTC, and hydrocarbons in MTC & LTC on the actual thermodynamic performances of three stage cascade vapour compression refrigeration system for replcing R23 in MTC& R4 in LTC

Effect of different HFOs HC and HFCs refrigerants in high temperature cycle, HTC for replacing R404a and HFCs refrigerants in medium temperature cycle for replacing R23and HC refrigerant in low temperature cycle(LTC) for replacing R14 on the thermodynamic performances of three staged cascaded vapour compression refrigeration systems have been computed & shown in table-8(*b) to* table-8(*c)* respectively and it was found that system-2 (using R152a in HTC, R170 in MTC, R1150in LTC) gives best thermodynamic performances
The actual thermodynamic performances of three stage cascade vapour compression refrigeration system-12& system-13 have been compired and it was found that system-12 using R1234ze in HTC, R170in MTC & R1150 in LTC gives better thermodynamic performances thn system-13 using R404a in HTC, R23in the MTC & R14 in LTC

3. Conclusions

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

- In the three staged cascaded vapour compression refrigeration systems R41 & R170 are suitable for replacing R23 in medium temperature cycle (MTC) up to -90°C
- In the three staged cascaded vapour compression refrigeration systems R717 & R152 are suitable for replacing R161 in high temperature cycle (HTC) up to -30°C
- In the three staged cascaded vapour compression refrigeration systems R1150 are suitable for replacing R14 in lower temperature cycle (LTC) cycle up to -140°C.
- The cascaded VCRS using R1233zd(E) in the high temperature cycle at -30°C of evaporator temperature in the high temperature cycle -90°C of evaporator temperature in the medium temperature cycle using R1336mzz(Z) and -140°C of evaporator temperature in the low temperature cycle using R1225ye(Z) ecofriendly refrigerant gives best thermodynamic performances for ultra-low temperature applications
- The cascaded VCRS using R1234ze(Z) in the high temperature cycle at 0°C of evaporator temperature in the high temperature cycle & R1233d(E) in the medium temperature cycle at -75°C of evaporator temperature in the medium temperature cycle 130°C of evaporator temperature in the low temperature cycle using R1225ye(Z) ecofriendly refrigerant gives best thermodynamic performances for low temperature applications

- The cascaded VCRS using R1224yd(Z) in the high temperature cycle at 0ºC of evaporator temperature in the high temperature cycle & R1233d(E) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle 130ºC of evaporator temperature in the low temperature cycle using R1225ye(Z) ecofriendly refrigerant gives slightly low thermodynamic performances than the cascaded VCRS using R1234ze(Z) in the high temperature cycle at 0ºC of evaporator temperature in the high temperature cycle & R1233d(E) in the medium temperature cycle at -75ºC of evaporator temperature in the medium temperature cycle 130ºC of evaporator temperature in the low temperature cycle using R1225ye(Z) ecofriendly refrigerant for low temperature applications
- HFO, ecofriendly Low GWP HFCs & hydrocarbons (HC) refrigerants are more suitable for replacing high GWP refrigerants such as R404a, R134a and R125 in the high temperature cycle up to -30ºC, R170, R41 for replacing R23 medium temperature applications up to -90ºC and R1150 for replying R14 in the ultra-low temperature cycle up to -140ºC

Table-8(b) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -90ºC , $T_{\_Eva\ LTC}$= -140ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=5ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%, Compressor efficiency$_{_LTC}$=80%)

Three staged cascade system	System-1	System-2	System-3	System-4	System-5
Refrigerant in HTC	R245 fa	R152a	R32	R161	R1270
Refrigerant in MTC	R170	R170	R170	R170	R170
Refrigerants in LTC	R1150	R1150	R1150	R1150	R1150
COP_HTC	2.011	2.049	1.904	2.012	1.896
COP_MTC	1.599	1.599	1.599	1.599	1.599
COP_LTC	1.328	1.328	1.328	1.328	1.328
Three Stage COP_Cascade	0.3062	0.3087	0.2990	0.3063	0.2984
Exergy Destruction Ratio (EDR_ $_{\text{Three Stage}}$)	1.635	1.614	1.699	1.635	1.704
Three Stage Exergetic Efficiency	0.3795	0.3825	0.3705	0.3796	0.3698
Three Stage Exergy of Fuel “kW”	32.66	32.99	33.45	32.65	33.51
Two Stage COP_Cascade	0.6975	0.7049	0.6762	0.6977	0.6745
Two Stage Exergy Destruction Ratio (EDR)	1.283	1.259	1.355	1.282	1.361
Two Stage Exergetic Efficiency	0.4379	0.4426	0.4246	0.4381	0.4235
Two Stage Exergy of Fuel “kW”	25.13	24.87	25.92	25.12	25.99
COP$_{_HTC}$	2.011	2.049	1.904	2.012	1.896
HTC Exergy Destruction Ratio (EDR)	1.199	1.158	1.321	1.197	1.332
HTC Exergetic Efficiency	0.4548	0.4634	0.4308	0.4551	0.4289
HTC Exergy of Fuel “kW”	14.17	13.91	14.96	14.16	15.02

Table-8(c) Thermodynamic performances of three staged cascaded vapour compression refrigeration system using ecofriendly low GWP HFOs & HCFO refrigerants (Q_Eva=10.0 kW, T_Cond=40ºC, T_ambient=25ºC, $T_{\_Eva\ HTC}$ =-30ºC, $T_{\_Eva\text{-}MTC}$= -90ºC , $T_{\_Eva\ LTC}$= -140ºC, Temp_Overlaping$_{_MTC}$=5ºC, Temp_Overlaping$_{_LTC}$=5ºC, Compressor efficiency$_{_HTC}$=80%, Compressor efficiency$_{_MTC}$=80%

Three staged cascade system	System 9	System 10	System 11	System 12	System 13
Refrigerant in HTC	R290	R600a	R1234yf	R1234ze	R404a
Refrigerant in MTC	R170	R170	R170	R170	R23
Refrigerants in LTC	R1150	R1150	R1150	R1150	R14
COP_HTC	1.817	1.894	1.741	1.855	1.621
COP_MTC	1.599	1.599	1.599	1.599	1.558
COP_LTC	1.328	1.328	1.328	1.328	1.265
Three Stage COP_Cascade	0.2971	0.2983	0.287	0.2925	0.2664
Exergy Destruction Ratio (EDR_ $_{\text{Three Stage}}$)	1.716	1.599	1.812	1.731	2.029
Three Stage Exergetic Efficiency	0.3682	0.3696	0.3556	0.3662	0.3302
Three Stage Exergy of Fuel “kW”	33.66	33.53	34.85	33.84	37.53
Two Stage COP_Cascade	0.6708	0.6741	0.6415	0.666	0.6043
Two Stage Exergy Destruction Ratio (EDR)	1.374	1.363	1.482	1.391	1.636
Two Stage Exergetic Efficiency	0.4212	0.4233	0.4028	0.4182	0.3794
Two Stage Exergy of Fuel “kW”	26.13	26.0	27.32	26.32	29.63
COP$_{_HTC}$	1.817	1.894	1.741	1.855	1.621
HTC Exergy Destruction Ratio (EDR)	1.354	1.334	1.539	1.383	1.727
HTC Exergetic Efficiency	0.4248	0.4285	0.3939	0.4197	0.3667
HTC Exergy of Fuel “kW”	15.17	15.04	16.36	15.35	18.14

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