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Optimum performance evaluations of three stages cascade vapour compression refrigeration systems for ultra-low temperature applications using new HFO ultra low GWP refrigerants

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Abstract

Now a day's GWP and ODP of the refrigerant is also considering due to environmental safety. Therefore, HFO refrigerants such as R1233zd (E) is increasing used in low temperature refrigeration system up to -75ºC. Similarly, another ecofriendly HFO-1336mzz(Z) and R-1225ye(Z) can be used up to -155ºC Numbers of researchers have evaluated the thermodynamic performance of the two stage cascade refrigeration systems for low temperature refrigeration system from -75ºC to -135ºC using R404a and hydrocarbons. Since all hydrocarbons are flammable in nature. In this paper, using thermal design method , the feasibility of HFO refrigerants (such as R-1234ze(Z), R-1224yd (Z), R-1234ze(E), R-1243zf, up to -10ºC high temperature circuit) in the three stages cascade vapour compression refrigeration systems have been compared by using R1233zd (E) , HFO-1336mzz(Z) and R-1225ye(Z) up to -75ºC in the low temperature evaporator temperature and it was found that up to temperature of -75ºC, R1233zd (E) gives better thermodynamic performances in the low temperature cycle as compared to other HFO(R1225ye(Z) and HFO -1336mzz(Z) refrigerants .Similarly for low temperature applications from -135ºC to -155ºC in the low temperature evaporator temperature, using HFO-1336mzz(Z) and R-1225ye(Z) in the low temperature cycle and R-1234ze(E), R-1243zf, R1233zd (E) up to -10ºC in the high temperature circuit have also been compared an improvements in the second aw exergetic performance by using three stages cascading is justified.

Keywords: HFO refrigerants, Energy -Exergy analysis, Three stages Cascade, Thermodynamic performances

1. Introduction

Vapour compression refrigeration or vapor-compression refrigeration system (VCRS) in which the refrigerant undergoes phase changes, is one of the many refrigeration cycles and is the most widely used method for air-conditioning of buildings and automobiles. It is not possible to achieve very low temperatures below -40ºC by using simple VCRS. In this system, we are cascading two VCRS thermally for achieving low temperatures and the system is known as cascade refrigeration system. Low temperature three stage cascade refrigeration systems are suitable for very low temperature industrial applications, like manufacturing of dry ice, storage of frozen food, bio medical applications etc. Low GWP- HFC refrigerants, ultra-low GWP-HFO refrigerants, Ammonia, carbon dioxide, propane and other natural refrigerants have drawn increased attention as working fluids to protect the environment. An appropriate selection of refrigerants to operate the low temperature cycle. Low temperature and high temperature cycles should be made in order to obtain high coefficient of performance (COP). The temperature difference between in low temperature condenser and high temperature evaporator cycle is temperature over-lapping also known as approach is an important parameter to decide best thermodynamic performances of working fluids along with other important characteristics such as toxicity, flammability, ODP, GWP etc. A direct expansion in low temperature refrigeration cycle [1] involves a large pressure lift between evaporating and condensing temperatures resulting in an increase in the compression ratio and reduction of volumetric efficiency of the compressors. Cascade system is similar to the binary vapor cycle used for the power plants. In the binary vapor cycle, a condenser for mercury works as a boiler for water. However, the condenser for low temperature cycle works as an evaporator for the high temperature cycle in the cascade vapour compression

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refrigeration system.

The exergy analysis is a powerful tool for finding irreversibilities (loss work i.e. exergy destruction) occurred in the components as well as complete cascade vapour compression refrigeration system. Global warming and ozone depletion is a big issue for saving our environment. Therefore, ultra-low GWP refrigerants are used in the vapor compression systems. G.Nicola et al [2] carried out comparison analysis using R23 in the low-temperature circuit and then replacing this fluid with the refrigerant binary system (R744-R744) an conclude that, it is possible to use the binary system R744-R744A to solve problems of the pure R744 because the cascade cycle stability with blends of R744 would appeared an attractive option for the future tests in different operating temperature and pressure conditions. . Alhamid et al [3] carried out the thermodynamic analysis (i.e. energy and exergy computation) by using propane in the high temperature circuit refrigerant and as ethane mixture as refrigerant in the low temperature circuit by using a multi liner regression analysis to optimize various performance parameters such as COP, Optimum evaporating and condensing temperatures.

Getu and Bansal [4] Analyzed a carbon dioxide–ammonia (R744–R717) cascade system thermodynamically to determine the optimum condensing temperature of R744 in the low temperature circuit and mass flow ratio, and to find out the system maximum COP in terms of sub cooling, superheating, evaporating temperature, condensing temperature and temperature difference in the system's cascade condenser and concluded the increase of superheat increases mass flow rate and reduces the COP of system. also an increase in sub cooling increased both COP and mass flow ratio in the system.

A. D. Parekh et al [5] carried out the thermodynamic analysis of cascade refrigeration system by using two HFC refrigerant pairs R404A-R508B and R410-AR23 A. D. Parekh et al [6] carried out thermodynamic analysis of cascade refrigeration system by using ozone friendly refrigerants pair R507A and R23 to optimize the design and operating parameters of the system and concluded that COP of the system increased from 0.7851 to 1.232 as low temperature circuit due to evaporator temperature variation from - 80ºC to -50ºC. Souvik Bhattacharyya, et al. [7] performed thermodynamic analysis of two-stage cascade cycle for finding optimum intermediate temperature for maximum exergy and found unexpectedly high exergy rate is obtained due to drastic variation in supercritical CO_2 properties.

The cascade systems consist of HTC condenser, cascade condenser and LTC evaporator, and found that that the required heat transfer area of condenser and cascade condenser for R410A-R23 cascade system is lower than by using R404A-R508B cascade system but heat transfer area of evaporator is similar for both the system.

Dopazo et al [8]. carried out theoretically both exergy analysis and energy optimization, to determine the optimum condensing temperature of (R744) in the low-temperature circuit and found that the COP increases 70% when the temperature (Teva) R744 varies from (-55 C to -30 C). increases, the effect of other parameters on the COP also increases. COP diminishes 45% when the T_{Cond} of NH3 increases from (25ºC to 50ºC) the exergetic efficiency decreases around 45% and 9% with the increases in condenser temperature (T_{cond}) of NH_3 respectively.

The utility of exergy analysis (i.e. second law analysis) on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in the existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system

Mishra [9] carried out energy-exergy analysis of cascade refrigeration system with huge refrigerants including CFC, HCFC, HFC, HFC an HFO refrigerants etc., and optimizations conducted for such refrigerants. Huge number of refrigerants has been examined in cascade system for determining the appropriate combination of refrigerants in high temperature and low temperature cycle cycle both circuits of refrigerants however the trends shows that the HFO refrigerants an natural refrigerants are gaining more importance due to environmental conditions few natural refrigerants such as ammonia(R-717), CO_2 (R-744) are analyzed by but there is still shortcomings of ecofriendly refrigerants due to that R744 can be use up to a temperature of -40ºC. Although low GWP HFC refrigerants such as (R-152a, R245a , R32) can be more widely adopted to fill this gap also the analysis process can involve more design and operating parameters such as effect of sub cooling and superheating should also be taken in account. Refrigerants including blends of natural refrigerants can also be used [10].

Currently the highest energy utilized in cooling and air conditioning in industrial as well as for domestic applications. In addition to energy consumption by using refrigerants in cooling and air conditioning have high GWP and ODP, which are accountable for increasing global warming and ozone depletion. The main requirements of ideal refrigerants are having good physical and chemical properties. Due to excellent good physical and chemical properties such as non-corrosiveness, non-toxicity, non- flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades, but hydro chloro fluoro carbons (HCFCs) and Chlorofluorocarbons (CFCs) having large amount of chlorine content as well as high global warming potential and ozone depletion potential, so after 90s refrigerants under these categories these kinds of refrigerants are almost prohibited. Now a day's GWP and ODP of the refrigerant is also considering due to environmental safety. Therefore, R13 an R404a refrigerants are increasing used in ultra-low temperature refrigeration system causes high level of global warming. Numbers of researchers have evaluated the thermodynamic performance of the two stage cascade refrigeration systems using R717, R134a in the high temperature circuit and R404a, R125, R123, R407c, R236fa and R227ea, R507a in the low temperature cycle which produce high global warming. Therefore, the use of HFO refrigerants in the low temperature cycle is justified. In this paper, thermodynamic performances of HFO refrigerants on three stages cascade refrigeration systems have been presented.

2. Results and Discussion

Numerical computations have been carried out by using two methods entropy generation and energy exergy principles and for finding exergetic efficiency an rational efficiency of the cascade systems. It is found that maximum exergetic efficiency was found by using energy exergy principles an R1233yd (Z) in HTC an R1225ye(Z) in LTC. By designing the cascade refrigeration system using HFO refrigerants in high temperature cycle side and using HFO-1336mzz(Z) and R1225ye(Z) refrigerants in low temperature cycle side. The following cascade systems of Vapour compression refrigeration system using ecofriendly refrigerants for ultra-low temperature applications have been chosen or numerical computations are

System-1

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1234ze(Z) in high temperature cycle R1233zd (E) in medium/ intermediate temperature cycle (MTC), and HFO 1336mzz(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC, $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =10ºC.

System-2

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1234ze(Z) in high temperature cycle R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =10ºC,

System-3

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1234ze(E) in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (HTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-4

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1234ze(E) in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-5

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1243zf in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (HTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC.

System-6

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1243zf in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-7

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1224yd (Z) in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (HTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-8

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1224yd (Z) in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-9

Three cascade vapour compression refrigeration system using ecofriendly R1225ye(Z) in high temperature cycle (HTC), using ecofriendly R1233zd (E) in medium/ intermediate temperature cycle (MTC), and HFO 1336mzz(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 35. kW cooling load using $T_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_\ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC.

System-10

Three cascade vapour compression refrigeration system using ecofriendly HFO 1336mzz(Z) in high temperature cycle (HTC), using ecofriendly R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 35. kW cooling load using $T_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_\ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-11

Three cascade vapour compression refrigeration system using ecofriendly R1233zd (E) in high temperature cycle (HTC), ecofriendly R1225ye(Z) in medium/ intermediate temperature cycle (MTC), and HFO 1336mzz(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $T_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_\ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-12

Three cascade vapour compression refrigeration system using ecofriendly R1233zd (E) in high temperature cycle (HTC), ecofriendly HFO 1336mzz(Z) in medium/intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $T_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC, $T_{\_Eva\_\ HTC}$ = -10ºC, $T_{\_Eva\ \_LTC}$ = -70ºC, Temperature overlapping in LTC compressor =5ºC,

System-13

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1234yf in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (HTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_\ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

System-14

Three cascade vapour compression refrigeration system using ecofriendly using ecofriendly R1243yf in high temperature cycle (HTC), R1233zd (E) in medium/ intermediate temperature cycle (MTC), and R1225ye(Z) in low temperature cycle (LTC) for compressors efficiency= 80% for 70.334. kW cooling load using $_{\_Cond}$= 50ºC, $T_{_cond_}$sub-cooling = 45ºC , $T_{\_Eva\_\ HTC}$ = -10ºC , $T_{\_Eva\ \_LTC}$ = -70ºC , Temperature overlapping in LTC compressor =5ºC,

2.1 Effect of ecofriendly refrigerants on thermodynamic performances of three Stages Cascade VCRS

Table-1(a) The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the low temperature cycle (LTC) and computed results are shown in Table-1(a) to tables-2(b) respectively. The optimum results were observed by using optimum combination of cascade system is R1234ze(Z) high temperature cycle at HTC evaporator temperature of -10ºC using HTC condenser temperature of 50ºC & R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and ecofriendly HFO -1336mzz(Z) refrigerant in low temperature cycle (LTC) at LTC evaporator temperature of -135ºC.

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the low temperature cycle (MTC) and computed results are shown in Table-3(a) to table-5(b) respectively. The optimum results were observed by using optimum combination of cascade system is R1234ze(Z) high temperature cycle at HTC evaporator temperature of -10ºC using HTC condenser temperature of 50ºC & R1225ye(Z) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and ecofriendly HFO -1336mzz(Z) refrigerant in low temperature cycle (LTC) at LTC evaporator temperature of -135ºC

Table-1(a): Effect of LTC refrigerants at LTC evaporator temperature of -135ºC on thermodynamic performances of Three stages Cascade VCRS using R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and R1234ze(Z) high temperature cycle at HTC evaporator temperature of -10ºC an HTC condenser temperature of 50ºC

Ecofriendly refrigerants in low temperature cycle (LTC)	$COP_{\_Cascade\ \_LTC}$	Exergetic Efficiency $_{\_LTC}$	% Improvement	Exergy $EDR_{\_\ LTC}$	COP_{HTC}	$COP_{\_LTC}$	Exergetic Efficiency $_{\_\ HTC}$	Cascade $EDR_{\_\ HTC}$
R1225ye(Z)	0.4907	0.4883	24.07	1.048	2.972	1.683	0.3955	1.528
HFO -1336mzz(Z)	0.5372	0.5206	35.828	0.9209	2.755	1.907	0.3955	1.528
R404a	0.5597	0.5356	35.42	0.8670	2.750	2.02	0.3955	1.528

Table-1(b): Effect of LTC refrigerants at LTC evaporator temperature of -135°C on thermodynamic performances of two stages cascade VCRS using R-1233zd (E) in intermediate /medium temperature cycle at evaporator temperature of -75°C and R1234ze(Z) high temperature cycle at HTC evaporator temperature of -10°C an HTC condenser temperature of 50°C

Ecofriendly refrigerants in low temperature cycle (LTC)	$COP\_{Cascade\_MTC}$	Exergetic Efficiency $_{MTC}$	% improvement	Cascade EDR $_{MTC}$	COP_{HTC}	$COP\_\_{MTC}$	Exergetic Efficiency $_{\_HTC}$	Cascade EDR$_{_HTC}$
R1225ye(Z)	0.8954	0.4522	14.3	1.211	2.972	1.713	0.3955	1.528
HFO -1336mzz(Z)	0.8954	0.4522	14.3	1.211	2.755	1.713	0.3955	1.528
R404a	0.8954	0.4522	14.3	1.211	2.750	1.713	0.3955	1.528

Table-2(a): Effect of MTC refrigerants on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at evaporator temperature of -75°C and HFO -1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

Ecofriendly refrigerants in high temperature cycle (MTC)	$COP\_{Cascade\_LTC}$	Exergetic Efficiency$_{_LTC}$	Exergy EDR$_{_LTC}$	% improvement	COP_{HTC}	Exergetic Efficiency $_{\_HTC}$	Cascade EDR$_{_HTC}$
R-1233zd (E)	0.4907	0.5206	0.9209	31.631	2.972	0.3955	1.528
R1225ye(Z)	0.6406	0.5819	0.7184	47.1	2.972	0.3955	1.528

Table-2(b): Effect of MTC refrigerants on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at evaporator temperature of -75°C and HFO -1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

Ecofriendly refrigerants in high temperature cycle (MTC)	$COP\_{Cascade\_MTC}$	Exergetic Efficiency $_{\_MTC}$	Cascade EDR $_{MTC}$	% improvement	COP_{HTC}	COP_{MTC}	Exergetic Efficiency $_{\_HTC}$	Cascade EDR$_{_HTC}$
R-1233zd (E)	0.8954	0.4522	1.211	14.33	2.972	1.713	0.3955	1.528
R1225ye(Z)	0.8838	0.4464	1.24	12.87	2.972	1.681	0.3955	1.528

Table-3(a): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using HFO -1336mzz(Z) in Intermediate /medium temperature cycle at evaporator temperature of -75°C and R1225ye(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

Ecofriendly refrigerants in high temperature cycle (HTC)	$COP\_{Cascade\_LTC}$	Exergetic Efficiency $_{\_LTC}$	Exergy EDR$_{_LTC}$	$COP\_\_{HTC}$	% improvement	$COP\_\_{LTC}$	Exergetic Efficiency $_{\_HTC}$	Cascade EDR$_{_HTC}$
R1234ze(Z)	0.5416	0.5169	0.9345	2.972	30.695	1.942	0.3955	1.528
R1234ze(E)	0.5233	0.5025	0.990	2.755	32.313	1.942	0.3666	1.728
R1243zf	0.5229	0.5022	0.9913	2.750	32.21	1.942	0.3660	1.732
R1224yd (Z)	0.5356	0.5123	0.9522	2.899	35.424	1.942	0.3858	1.592
R1233zd (E)	0.5392	0.5151	0.9414	2.942	36.334	1.942	0.3917	1.553
R1234yf	0.510	0.4918	1.033	2.607	28.951	1.942	0.3469	1.883

Table-3(b): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using HFO -1336mzz(Z) in Intermediate /medium temperature cycle at evaporator temperature of -75°C and R1225ye(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

Ecofriendly refrigerants in high temperature cycle (HTC)	$COP\_{Cascade\_MTC}$	Exergetic Efficiency $_{\_MTC}$	Cascade EDR $_{MTC}$	COP_{HTC}	% improvement	COP_{MTC}	Exergetic Efficiency $_{\_HTC}$	Cascade EDR$_{_HTC}$
R1234ze(Z)	0.8768	0.4428	1.258	2.972	11.96	1.662	0.3955	1.528
R1234ze(E)	0.8453	0.4269	1.328	2.755	07.94	1.662	0.3666	1.728
R1243zf	0.8446	0.4266	1.344	2.750	07.86	1.662	0.3660	1.732
R1224yd (Z)	0.8665	0.4376	1.285	2.899	10.644	1.662	0.3858	1.592
R1233zd (E)	0.8728	0.4408	1.269	2.942	11.454	1.662	0.3917	1.553
R1234yf	0.8224	0.4153	1.408	2.607	5.0	1.662	0.3469	1.883

Table-4(a): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75°C and HFO-1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

Ecofriendly refrigerants in high temp cycle (HTC)	First law Efficiency of three stages $COP\_{Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy EDR$_{_LTC}$	% improvement	First law Efficiency of HT Cycle $COP\_\_{HTC}$	First law Efficiency of LT Cycle COP_{LTC}	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle EDR_{HTC}
R1234ze(Z)	0.5372	0.5206	0.9209	31.63	2.972	1.942	0.3956	1.528
R1234ze(E)	0.5193	0.506	0.9762	27.94	2.755	1.942	0.3666	1.728
R1243zf	0.5189	0.5057	0.9774	27.863	2.750	1.942	0.3660	1.732
R1224yd (Z)	0.5314	0.5159	0.9385	30.442	2.899	1.942	0.3858	1.592
R1233zd (E)	0.5165	0.5037	0.9854	27.358	2.722	1.942	0.3622	1.761
R1234yf	0.5063	0.4453	1.019	12.59	2.607	1.942	0.3469	1.883

Table-4(b): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

Ecofriendly refrigerants in high temperature cycle (HTC)	First law Efficiency of two stage $COP_{Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	% improve ment	First law Efficiency of HT Cycle COP_{HTC}	First law Efficiency of MT Cycle COP_{MTC}	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR_{HTC}
R1234ze(Z)	0.8954	0.4522	1.211	14.34	2.972	1.662	0.3956	1.528
R1234ze(E)	0.8629	0.4358	1.295	10.19	2.755	1.662	0.3666	1.728
R1243zf	0.8622	0.4359	1.296	10.215	2.750	1.662	0.3660	1.732
R1224yd (Z)	0.8848	0.4469	1.238	12.99	2.899	1.662	0.3858	1.592
R1233zd (E)	0.8577	0.4332	1.308	09.53	2.722	1.662	0.3622	1.761
R1234yf	0.8393	0.4239	1.359	07.18	2.607	1.662	0.3469	1.883

Table-5(a): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and R-1225ye(Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

Ecofriendly refrigerants in high temperature cycle (HTC)	First law Efficiency of three stages $COP_{Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{LTC}$	Exergy destruction Ratio of three stage Exergy EDR_{LTC}	% improvement	First law Efficiency of HT Cycle COP_{HTC}	First law Efficiency of LT Cycle COP_{LTC}	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR_{HTC}
R1234ze(Z)	0.4907	0.488	1.048	23.39	2.972	1.683	0.3955	1.528
R1234ze(E)	0.4751	0.4749	1.106	20.13	2.755	1.683	0.3666	1.728
R1243zf	0.4748	0.4746	1.107	20.0	2.750	1.683	0.3660	1.732
R1224yd (Z)	0.4857	0.4839	1.066	22.35	2.899	1.683	0.3858	1.592
HFO1336mzz(Z)	0.483	0.4816	1.076	21.77	2.862	1.683	0.3808	1.626
R1234yf	0.4637	0.4650	1.151	17.57	2.607	1.683	0.3469	1.883

Table-5(b): Effect of HTC refrigerants on thermodynamic performances of three stages cascade VCRS using R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and R-1225ye(Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

Ecofriendly refrigerants in high temperature cycle (HTC)	First law Efficiency of two stage $COP_{Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	% improve ment	First law Efficiency of HT Cycle COP_{HTC}	First law Efficiency of MT Cycle COP_{MTC}	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR_{HTC}
R1234ze(Z)	0.8954	0.4522	1.211	14.34	2.972	1.713	0.3955	1.528
R1234ze(E)	0.8629	0.4358	1.295	10.19	2.755	1.713	0.3666	1.728
R1243zf	0.8622	0.4355	1.296	10.113	2.750	1.713	0.3660	1.732
R1224yd (Z)	0.8848	0.4469	1.238	12.996	2.899	1.713	0.3858	1.592
HFO1336mzz(Z)	0.8792	0.4440	1.252	12.263	2.862	1.713	0.3808	1.626
R1234yf	0.8393	0.4239	1.359	7.18	2.607	1.713	0.3469	1.883

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the low temperature cycle (MTC) and computed results are shown in Table-3(a) to table-5(b) respectively. The optimum results were observed by using optimum combination of cascade system is R1234ze(Z) high temperature cycle at HTC evaporator temperature of -10ºC using HTC condenser temperature of 50ºC & R1225ye(Z) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and ecofriendly HFO -1336mzz(Z) refrigerant in low temperature cycle (LTC) at LTC evaporator temperature of -135ºC.

2.2 Effect of HTC Condenser temperature on thermodynamic performances of three stages cascade VCRS

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the high temperature cycle (HTC) and computed results are shown in Table-6(a) to table-7(b) respectively.

Table -6(a): Effect of HTC condenser temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

HTC Condenser temperature (ºC)	First law Efficiency of three stages COP_Cascade_LTC	Second law Exergetic Efficiency of three stage _LTC	Exergy destruction Ratio of three stage Exergy EDR_ LTC	First law Efficiency of LT Cycle COP__LTC	First law Efficiency of LT Cycle COP__LTC	First law Efficiency of HT Cycle COP__HTC	Second law Exergetic Efficiency of HT Cycle _ HTC	Second law Exergetic Efficiency of two stage _MTC	Exergy destruction Ratio of HT Cycle EDR_HTC
60	0.4871	0.4794	1.086	1.907	1.907	2.406	0.3201	0.4065	2.124
55	0.5118	0.4999	1.0	1.907	1.907	2.669	0.3552	0.4290	1.815
50	0.5372	0.5206	0.9209	1.907	1.907	2.972	0.3955	0.4522	1.528
45	0.5634	0.5416	0.8464	1.907	1.907	3.326	0.4426	0.4764	1.259
40	0.5905	0.5630	0.776	1.907	1.907	3.746	0.4985	0.5017	1.006
35	0.6186	0.5849	0.7097	1.907	1.907	4.256	0.5662	0.5282	0.7661

Table -6(b): Effect of HTC Condenser temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

HTC Condenser temperature (ºC)	First law Efficiency of two stage COP_Cascade_MTC	Second law Exergetic Efficiency of two stage _MTC	Exergy destruction Ratio of two stage Cascade EDR MTC	First law Efficiency of MT Cycle COP__MTC	First law Efficiency of HT Cycle COP__HTC	Second law Exergetic Efficiency of HT Cycle _ HTC	Exergy destruction Ratio of HT Cycle EDR_HTC
60	0.8049	0.4065	1.48	1.713	2.406	0.3201	2.124
55	0.8494	0.4290	1.331	1.713	2.669	0.3552	1.815
50	0.8954	0.4522	1.211	1.713	2.972	0.3955	1.528
45	0.9433	0.4764	1.099	1.713	3.326	0.4426	1.259
40	0.9933	0.5017	0.9933	1.713	3.746	0.4985	1.006
35	1.046	0.5282	0.8932	1.713	4.256	0.5662	0.7661

Table-7 (a): Effect of HTC Condenser temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

HTC Condenser temperature (ºC)	First law Efficiency of three stages COP_Cascade_LTC	Second law Exergetic Efficiency of three stage _LTC	Exergy destruction Ratio of three stage Exergy EDR_ LTC	First law Efficiency of LT Cycle COP__LTC	First law Efficiency of HT Cycle COP__HTC	Second law Exergetic Efficiency of HT Cycle _ HTC	Exergy destruction Ratio of HT Cycle EDR_HTC
60	0.4469	0.4504	1.22	1.683	2.406	0.3201	2.124
55	0.4686	0.4692	1.131	1.683	2.669	0.3552	1.815
50	0.4907	0.4883	1.048	1.683	2.972	0.3955	1.528
45	0.5135	0.5076	0.970	1.683	3.326	0.4426	1.259
40	0.5370	0.527	0.8966	1.683	3.746	0.4985	1.006
35	0.5613	0.5473	0.8271	1.683	4.256	0.5662	0.7661

Table-7(b): Effect of HTC Condenser temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle at LTC evaporator temperature of -135ºC

HTC Condenser temperature (ºC)	First law Efficiency of two stage COP_Cascade_MTC	Second law Exergetic Efficiency of two stage _MTC	Exergy destruction Ratio of two stage Cascade EDR MTC	First law Efficiency of MT Cycle COP__MTC	First law Efficiency of HT Cycle COP__HTC	Second law Exergetic Efficiency of HT Cycle _ HTC	Exergy destruction Ratio of HT Cycle EDR_HTC
60	0.8049	0.4065	1.48	1.713	2.406	0.3201	2.124
55	0.8494	0.4292	1.331	1.713	2.669	0.3552	1.815
50	0.8954	0.4522	1.211	1.713	2.972	0.3955	1.528
45	0.9433	0.4764	1.099	1.713	3.326	0.4426	1.259
40	0.9933	0.5017	0.9933	1.713	3.746	0.4985	1.006
35	1.046	0.5282	0.8932	1.713	4.256	0.5662	0.7661

It was observing that when HTC Condenser temperature (ºC) increasing, the thermodynamic first and second law performances are decreasing however exergy destruction ratio of cascade system is increasing. Similarly cycle thermodynamic performances is also being decreasing

2.3 Effect of HTC evaporator temperature on thermodynamic performances of three stages Cascade VCRS

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants such as R1234ze(Z) and R1234ze(E) R1234ze(Z) in the high temperature cycle (HTC) and computed results are shown in Table-8(a) to table-8(h) respectively. It was observed that when HTC evaporator temperature (°C) increasing, the thermodynamic first and second law performances are decreasing however exergy destruction ratio of cascade system is increasing. Similarly cycle thermodynamic performances is also decreasing. It was found that HFO 1234ze(Z) refrigerants used in the HTC gives better (2.59% higher) thermodynamic performances than using HFO 1234ze(E) refrigerants used in the HTC up to HTC evaporator temperature of -10°C with temperature overlapping between MTC condenser temperature and HTC evaporator temperature

Table-8(a): Effect of HTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(E) in high temperature cycle at HTC evaporator temperature -10°C R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75°C and HFO-1336mzz(Z) in lowest temperature cycle at LTC evaporator temperature of -135°C

HTC evaporator temperature (°C)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of HT Cycle $COP_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.6545	0.4891	1.045	5.198	0.2755	2.63
5	0.6495	0.5137	0.9466	4.452	0.3203	2.122
0	0.6456	0.5374	0.8609	3.858	0.3533	1.830
-5	0.6427	0.5601	0.7854	3.374	0.3777	1.648
-10	0.6406	0.5819	0.7184	2.972	0.3955	1.528
-15	0.6392	0.6029	0.6587	2.634	0.4083	1.449
-20	0.6386	0.6230	0.6052	2.345	0.4172	1.397

Table-8(b): Effect of HTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(E) in high temperature cycle at HTC evaporator temperature -10°C R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75°C and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135°C

HTC evaporator temperature (°C)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP_{\_LTC}$	First law Efficiency of HT Cycle $COP_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.6436	0.4838	1.067	2.032	4.962	0.2630	2.802
5	0.6361	0.5064	0.9747	2.132	4.222	0.3037	2.292
0	0.6293	0.5275	0.8957	2.225	3.633	0.3327	2.006
-5	0.6230	0.5471	0.8279	2.342	3.153	0.3529	1.834
-10	0.6171	0.5651	0.7696	2.476	2.755	0.3666	1.728
-15	0.6115	0.5814	0.7199	2.632	2.420	0.3752	1.685
-20	0.6061	0.5961	0.677	2.814	2.136	0.3752	1.633

Table-8(c): Effect of HTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(E) in high temperature cycle at HTC evaporator temperature -10°C HFO-1336mzz(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75°C and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135°C

HTC evaporator temperature (°C)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP_{\_LTC}$	First law Efficiency of HT Cycle $COP_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.5346	0.4891	1.045	1.60	4.962	0.2630	2.802
5	0.5309	0.5137	0.9466	1.670	4.222	0.3037	2.292
0	0.5278	0.5374	0.8609	1.749	3.633	0.3327	2.006
-5	0.5253	0.5601	0.7854	1.839	3.153	0.3529	1.834
-10	0.5233	0.5819	0.7184	1.942	2.755	0.3666	1.728
-15	0.5218	0.6029	0.6587	2.061	2.420	0.3752	1.685
-20	0.5206	0.6230	0.6052	2.201	2.136	0.3799	1.633

Table-8(d): Effect of HTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC HFO-1336mzz(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

HTC evaporator temperature (ºC)	First law Efficiency of three stages cascade $COP_{\_Cascade\_LTC}$	cascade Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law cycle Efficiency of LT Cycle $COP_{\_\_LTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.5428	0.4341	1.304	1.60	5.198	0.2755	2.63
5	0.5411	0.4553	1.196	1.670	4.452	0.3203	2.122
0 (optimum)	0.5403	0.4762	1.10	1.749	3.858	0.3533	1.830
-5	0.5406	0.4967	1.013	1.839	3.374	0.3777	1.648
-10	0.5416	0.5169	0.9345	1.942	2.972	0.3955	1.528
-15	0.5435	0.5369	0.8627	2.061	2.634	0.4083	1.449
-20	0.5463	0.5565	0.7969	2.201	2.345	0.4172	1.397

Table-8(e): Effect of HTC evaporator temperature on thermodynamic performances of Two stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

HTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.7944	0.4012	1.493	1.118	5.198	0.2755	2.63
05	0.8238	0.4161	1.404	1.238	4.452	0.3203	2.122
0	0.8485	0.4286	1.333	1.370	3.858	0.3533	1.830
-5	0.8686	0.4387	1.28	1.516	3.374	0.3777	1.648
-10	0.8838	0.4464	1.24	1.681	2.972	0.3955	1.528
-15	0.8943	0.4516	1.214	1.868	2.634	0.4083	1.449
-20	0.90	0.4546	1.20	2.083	2.345	0.4172	1.397

Table-8(f): Effect of HTC evaporator temperature on thermodynamic performances of two stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC HFO-1336mzz(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

HTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.7944	0.4011	1.493	1.118	5.198	0.2755	2.63
5	0.821	0.4146	1.412	1.233	4.452	0.3203	2.122
0	0.8438	0.4261	1.347	1.360	3.858	0.3533	1.830
-5	0.8624	0.4356	1.296	1.502	3.374	0.3777	1.648
-10	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-15	0.8869	0.4480	1.232	1.845	2.634	0.4083	1.449
-20	0.8928	0.4509	1.218	2.056	2.345	0.4172	1.397

Table-8(g): Effect of HTC evaporator temperature on thermodynamic performances of two stages cascade VCRS using R1234ze(E) in high temperature cycle at HTC evaporator temperature -10ºC R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

HTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
10	0.7836	0.3957	1.527	1.118	4.962	0.2630	2.802
5	0.8090	0.4086	1.447	1.238	4.222	0.3037	2.292

0	0.8290	0.4187	1.389	1.370	3.633	0.3327	2.006
-5	0.8433	0.4259	1.348	1.516	3.153	0.3529	1.834
-10	0.8519	0.4303	1.324	1.681	2.755	0.3666	1.728
-15	0.8550	0.4318	1.316	1.868	2.420	0.3752	1.685
-20	0.8525	0.4306	1.323	2.083	2.136	0.3752	1.633

Table-8(h): Effect of HTC evaporator temperature on thermodynamic performances of Two stages Cascade VCRS using R1234ze(E) in high temperature cycle at HTC evaporator temperature -10°C HFO-1336mzz(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75°C and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135°C

HTC evaporator temperature (°C)	First law Efficiency of two stage COP$_{Cascade_MTC}$	Second law Exergetic Efficiency of two stage $_{MTC}$	Exergy destruction Ratio of two stage Cascade EDR $_{MTC}$	First law Efficiency of MT Cycle COP$_{MTC}$	First law Efficiency of HT Cycle COP$_{HTC}$	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR$_{HTC}$
10	0.7835	0.3957	1.527	1.118	4.962	0.2630	2.802
5	0.8063	0.4072	1.456	1.233	4.222	0.3037	2.292
0	0.8243	0.4163	1.402	1.360	3.633	0.3327	2.006
-5	0.8374	0.4229	1.365	1.502	3.153	0.3529	1.834
-10	0.8453	0.4269	1.342	1.662	2.755	0.3666	1.728
-15	0.8480	0.4283	1.335	1.845	2.420	0.3752	1.685
-20	0.8454	0.4272	1.341	2.056	2.136	0.3799	1.633

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the high temperature cycle (HTC) to intermediate an low temperature cycles and variation of thermodynamic performance parameters with varying MTC evaporator temperature are computed and results are shown in Table-9(a) to table-12(b) respectively. It was observe that when MTC evaporator temperature (°C) increasing, the thermodynamic first law performances (cascade COP) of whole system is decreasing and second law (exergetic) performances is also decreasing however exergy destruction ratio of cascade system is increasing. Similarly cycle thermodynamic performance is also decreasing.

Table-9(a): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10°C R-1233yd(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75°C and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135°C

MTC evaporator temperature (°C)	First law Efficiency of three stages COP$_{Cascade_LTC}$	Second law Exergetic Efficiency of three stage $_{LTC}$	Exergy destruction Ratio of three stage Exergy EDR$_{LTC}$	First law Efficiency of HT Cycle COP$_{HTC}$	First law Efficiency of LT Cycle COP$_{LTC}$	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR$_{HTC}$
-100	0.3710	0.2991	2.344	2.972	1.363	0.3955	1.528
-95	0.4017	0.3355	1.980	2.972	1.462	0.3955	1.528
-90	0.4339	0.3752	1.666	2.972	1.569	0.3955	1.528
-85	0.4677	0.4183	1.391	2.972	1.683	0.3955	1.528
-80	0.5035	0.4654	1.149	2.972	1.806	0.3955	1.528
-75	0.5416	0.5169	0.9345	2.972	1.941	0.3955	1.528
-70	0.5824	0.5735	0.7437	2.972	2.091	0.3955	1.528
-65	0.6264	0.6359	0.5726	2.972	2.259	0.3955	1.528
-60	0.6747	0.7051	0.4182	2.972	2.449	0.3955	1.528
-55	0.7278	0.7825	0.2779	2.972	2.669	0.3955	1.528
-50	0.7874	0.8698	0.1497	2.972	2.930	0.3955	1.528

Table-9(b): Effect of MTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10°C R-1233yd(Z)) *in Intermediate / medium temperature cycle at evaporator temperature of -75°C and HFO-1336mzz(Z) in lowest temperature cycle (LTC)* at evaporator temperature of -135°C

MTC evaporator temperature (°C)	First law Efficiency of two stage COP$_{Cascade_MTC}$	Second law Exergetic Efficiency of two stage $_{MTC}$	Exergy destruction Ratio of two stage Cascade EDR $_{MTC}$	First law Efficiency of HT Cycle COP$_{HTC}$	First law Efficiency of MT Cycle COP$_{MTC}$	Second law Exergetic Efficiency of HT Cycle $_{HTC}$	Exergy destruction Ratio of HT Cycle EDR$_{HTC}$
-100	0.5517	0.3986	1.509	2.972	0.9054	0.3955	1.528
-95	0.6075	0.4096	1.442	2.972	1.021	0.3955	1.528

-90	0.6676	0.4195	1.384	2.972	1.151	0.3955	1.528
-85	0.7322	0.4284	1.334	2.972	1.298	0.3955	1.528
-80	0.8018	0.4362	1.292	2.972	1.467	0.3955	1.528
-75	0.8768	0.4422	1.258	2.972	1.662	0.3955	1.528
-70	0.9577	0.4482	1.231	2.972	1.888	0.3955	1.528
-65	1.045	0.4522	1.211	2.972	2.154	0.3955	1.528
-60	1.140	0.4547	1.199	2.972	2.47	0.3955	1.528
-55	1.242	0.4557	1.194	2.972	2.851	0.3955	1.528
-50	1.353	0.4549	1.198	2.972	3.318	0.3955	1.528

Table-10(a): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$	First law Efficiency of LT Cycle $COP_{\_\_LTC}$
-100	0.4570	0.3518	1.843	2.972	0.3955	1.528	1.808
-95	0.4904	0.3905	1.561	2.972	0.3955	1.528	1.923
-90	0.5252	0.4325	1.312	2.972	0.3955	1.528	2.046
-85	0.5616	0.4781	1.091	2.972	0.3955	1.528	2.178
-80	0.5999	0.5278	0.8948	2.972	0.3955	1.528	2.320
-75	0.6406	0.5819	0.7184	2.972	0.3955	1.528	2.476
-70	0.6840	0.6413	0.5593	2.972	0.3955	1.528	2.649
-65	0.7308	0.7067	0.4150	2.972	0.3955	1.528	2.843
-60	0.7818	0.7792	0.2833	2.972	0.3955	1.528	3.064
-55	0.8380	0.8601	0.1626	2.972	0.3955	1.528	3.321
-50	0.9009	0.9512	0.0513	2.972	0.3955	1.528	3.627

Table-10(b): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd(Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-100	0.5663	0.4092	1.444	0.9350	2.972	0.3955	1.528
-95	0.6207	0.4186	1.390	1.048	2.972	0.3955	1.528
-90	0.6792	0.4268	1.343	1.177	2.972	0.3955	1.528
-85	0.7423	0.4343	1.302	1.322	2.972	0.3955	1.528
-80	0.8104	0.4409	1.268	1.489	2.972	0.3955	1.528
-75	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-70	0.9631	0.4507	1.219	1.904	2.972	0.3955	1.528
-65	1.049	0.4539	1.203	2.167	2.972	0.3955	1.528
-60	1.142	0.4557	1.194	2.478	2.972	0.3955	1.528
-55	1.243	0.4561	1.193	2.855	2.972	0.3955	1.528
-50	1.352	0.4549	1.198	3.317	2.972	0.3955	1.528

Table-11(a): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP_{\_\_LTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-75	0.5372	0.5206	0.9209	1.907	2.972	0.3955	1.528

-70	0.5755	0.5753	0.7383	2.044	2.972	0.3955	1.528
-65	0.6168	0.6355	0.5736	2.197	2.972	0.3955	1.528
-60	0.662	0.7022	0.4240	2.372	2.972	0.3955	1.528
-55	0.7121	0.7768	0.2873	2.575	2.972	0.3955	1.528
-50	0.7685	0.8610	0.1615	2.815	2.972	0.3955	1.528

Table-11(b): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-75	0.8954	0.4520	1.211	2.972	1.713	2.972	0.3955	1.528
-70	0.9759	0.4567	1.190	2.972	1.942	2.972	0.3955	1.528
-65	1.063	0.4598	1.175	2.972	2.210	2.972	0.3955	1.528
-60	1.155	0.4614	1.167	2.972	2.529	2.972	0.3955	1.528
-55	1.557	0.4614	1.167	2.972	2.913	2.972	0.3955	1.528
-50	1.367	0.4598	1.175	2.972	3.383	2.972	0.3955	1.528

Table-12(a): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP_{\_\_LTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-75	0.4907	0.4883	1.048	1.683	2.972	0.3955	1.528
-70	0.5285	0.5418	0.8457	1.816	2.972	0.3955	1.528
-65	0.5695	0.6009	0.6642	1.964	2.972	0.3955	1.528
-60	0.6144	0.6665	0.5003	2.132	2.972	0.3955	1.528
-55	0.6643	0.7401	0.3512	2.328	2.972	0.3955	1.528
-50	0.7205	0.8233	0.2146	2.559	2.972	0.3955	1.528

Table-12(b): Effect of MTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233yd (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1225ye (Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

MTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-75	0.8954	0.4522	1.211	1.713	2.972	0.3955	1.528
-70	0.9759	0.4567	1.190	1.942	2.972	0.3955	1.528
-65	1.063	0.4598	1.175	2.21	2.972	0.3955	1.528
-60	1.156	0.4614	1.167	2.529	2.972	0.3955	1.528
-55	1.257	0.4614	1.167	2.913	2.972	0.3955	1.528
-50	1.367	0.4598	1.175	3.383	2.972	0.3955	1.528

2.4 Effect of LTC evaporator temperature on thermodynamic performances of three stages cascade VCRS

The Performance improvement using cascading have been observed using different combinations of cascading using HFO refrigerants in the high temperature cycle (HTC) to intermediate and low temperature cycles and variation of thermodynamic performance parameters with varying LTC evaporator temperature are computed results are shown in Table-13(a) to table-16(b) respectively. It was observed that when LTC evaporator temperature (ºC) increasing, the thermodynamic first law performances (cascade COP) of whole system is decreasing and second law (exergetic) performances is increasing however exergy destruction ratio of cascade system is decreasing. Similarly cycle thermodynamic performance is also decreasing.

Table-13(a): Effect of LTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and R-1225ye(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of three stages $COP\_{Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP\_{\_LTC}$	First law Efficiency of HT Cycle $COP\_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$
-155	0.4736	0.6262	0.5970	1.605	2.972	0.3955
-150	0.4777	0.5877	0.7016	1.629	2.972	0.3955
-145	0.4819	0.5521	0.8114	1.642	2.972	0.3955
-140	0.4862	0.5190	0.9266	1.662	2.972	0.3955
-135	0.4907	0.4883	1.048	1.683	2.972	0.3955
-130	0.4954	0.4596	1.176	1.705	2.972	0.3955
-125	0.5001	0.4327	1.31	1.727	2.972	0.3955
-120	0.5050	0.4074	1.455	1.750	2.972	0.3955

Table-13(b): Effect of LTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233zd (E) in Intermediate /medium temperature cycle at evaporator temperature of -75ºC and R-1225ye(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of two stage $COP\_{Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP\_{\_MTC}$	First law Efficiency of HT Cycle $COP\_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-150	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-145	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-140	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-135	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-130	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-125	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970
-120	0.8954	0.4522	0.5970	1.713	2.972	0.3955	0.5970

Table-14(a): Effect of LTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233zd (E) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of three stages $COP\_{Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP\_{\_LTC}$	First law Efficiency of HT Cycle $COP\_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.5147	0.6646	0.5047	1.796	2.972	0.3955	1.528
-150	0.5202	0.6246	0.6011	1.823	2.972	0.3955	1.528
-145	0.5258	0.5874	0.7024	1.850	2.972	0.3955	1.528
-140	0.5315	0.5529	0.8088	1.878	2.972	0.3955	1.528
-135	0.5372	0.5206	0.9209	1.907	2.972	0.3955	1.528
-130	0.5430	0.4904	1.039	1.936	2.972	0.3955	1.528
-125	0.5489	0.4619	1.165	1.965	2.972	0.3955	1.528
-120	0.5548	0.4352	1.298	1.995	2.972	0.3955	1.528

Table-14(b): Effect of LTC evaporator temperature on thermodynamic performances of three stages cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1233zd (E) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and R-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of HT Cycle $COP_{\_HTC}$	First law Efficiency of MT Cycle $COP_{\_MTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-150	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-145	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-140	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-135	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-130	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-125	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528
-120	0.8954	0.4522	1.211	2.972	1.713	0.3955	1.528

Table-15(a): Effect of LTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of HT Cycle $COP_{\_HTC}$	First law Efficiency of LT Cycle $COP_{\_LTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.6158	0.7459	0.3417	2.972	1.796	0.3955	1.528
-150	0.6219	0.7002	0.4281	2.972	1.823	0.3955	1.528
-145	0.628	0.6580	0.5198	2.972	1.850	0.3955	1.528
-140	0.6343	0.6186	0.6165	2.972	1.878	0.3955	1.528
-135	0.6406	0.5819	0.7184	2.972	1.907	0.3955	1.528
-130	0.6469	0.5476	0.8262	2.972	1.936	0.3955	1.528
-125	0.6538	0.5154	0.9404	2.972	1.965	0.3955	1.528
-120	0.6599	0.4850	1.062	2.972	1.995	0.3955	1.528

Table-15(b): Effect of LTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_MTC}$	First law Efficiency of HT Cycle $COP_{\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-150	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-145	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-140	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-135	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-130	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-125	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528
-120	0.8838	0.4464	1.240	1.681	2.972	0.3955	1.528

Table-16(a): Effect of LTC evaporator temperature on thermodynamic performances of Three stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of three stages $COP_{\_Cascade\_LTC}$	Second law Exergetic Efficiency of three stage $_{\_LTC}$	Exergy destruction Ratio of three stage Exergy $EDR_{\_LTC}$	First law Efficiency of LT Cycle $COP_{\_\_LTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.5234	0.6641	0.5057	1.851	2.972	0.3955	1.528
-150	0.5277	0.6230	0.6051	1.872	2.972	0.3955	1.528
-145	0.5322	0.585	0.7094	1.895	2.972	0.3955	1.528
-140	0.5368	0.5497	0.8190	1.918	2.972	0.3955	1.528
-135	0.5416	0.5169	0.9345	1.942	2.972	0.3955	1.528
-130	0.5465	0.4863	1.056	1.967	2.972	0.3955	1.528
-125	0.5515	0.4576	1.185	1.992	2.972	0.3955	1.528
-120	0.5566	0.4306	1.322	2.019	2.972	0.3955	1.528

Table-16(b): Effect of LTC evaporator temperature on thermodynamic performances of Two stages Cascade VCRS using R1234ze(Z) in high temperature cycle at HTC evaporator temperature -10ºC R-1225ye (Z) in Intermediate / medium temperature cycle at evaporator temperature of -75ºC and HFO-1336mzz(Z) in lowest temperature cycle (LTC) at evaporator temperature of -135ºC

LTC evaporator temperature (ºC)	First law Efficiency of two stage $COP_{\_Cascade\_MTC}$	Second law Exergetic Efficiency of two stage $_{\_MTC}$	Exergy destruction Ratio of two stage Cascade EDR_{MTC}	First law Efficiency of MT Cycle $COP_{\_\_MTC}$	First law Efficiency of HT Cycle $COP_{\_\_HTC}$	Second law Exergetic Efficiency of HT Cycle $_{\_HTC}$	Exergy destruction Ratio of HT Cycle $EDR_{\_HTC}$
-155	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-150	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-145	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-140	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-135	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-130	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-125	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528
-120	0.8768	0.4428	1.258	1.662	2.972	0.3955	1.528

3. Conclusions

Cascade refrigeration is a method of refrigeration used for achieving low temperatures which is below -40ºC. By cascading more than two VCR stages in which we can achieve temperature up to -140ºC using HFO refrigerants in three stages cascading of VCRS. i.e. it is also a, method used for cryogenics applications up to a range of -145ºC to -155ºC using HFO-1336mzz(Z) an R1225ye(Z) refrigerants and up to -160ºC using hydro carbons in LTC. Numerical computations have been carried out by using two methods entropy generation and energy exergy principles and for finding exergetic efficiency an rational efficiency of the cascade systems. It is found that maximum exergetic efficiency was found by using energy exergy principles an R1233yd (Z) in HTC an R1225ye(Z) in LTC. By designing the cascade refrigeration system using HFO refrigerants in high temperature cycle side and using HFO-1336mzz(Z) and R1225ye(Z) refrigerants in low temperature cycle side. The following conclusions were drawn from present investigation

- when HTC evaporator temperature (ºC) increasing, the thermodynamic first and second law performances are
- LTC evaporator temperature of -135ºC gives maximum decreasing however exergy destruction ratio of cascade system is increasing. Similarly cycle thermodynamic performances is also decreasing.
- when MTC evaporator temperature (ºC) increasing, the thermodynamic first law performances (cascade COP) of whole system is decreasing and second law (exergetic) performances is also decreasing however exergy destruction ratio of cascade system is increasing. Similarly cycle thermodynamic performance is also decreasing
- when LTC evaporator temperature (ºC) increasing, the thermodynamic first law performances (cascade COP) of whole system is decreasing and second law (exergetic) performances is increasing however exergy destruction ratio of cascade system is decreasing. Similarly cycle thermodynamic performance is also decreasing.
- Optimum (Best) combination of cascade system is R1233zd (E)high temperature cycle at HTC evaporator temperature of -10ºC using HTC condenser temperature of 50ºC & HFO -1336mzz(Z) refrigerant in Intermediate/medium temperature cycle at evaporator temperature of -75ºC and ecofriendly R1225ye(Z) refrigerant in low temperature cycle (LTC) at thermodynamic first and second law performance.

- HFO 1234ze(Z) refrigerants used in the HTC gives better (2.59% higher) thermodynamic performances than using HFO 1234ze(E) refrigerants used in the HTC up to HTC evaporator temperature of -10°C with temperature overlapping of 10°C.

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