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ORIGINAL ARTICLE

Thermodynamic Energy-Exergy Performances of Cascaded VCRS using ultra-low GWP of HFO/HCFO refrigerants in the low temperature applications

R.S. Mishra

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

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Abstract

Research on unconventional refrigerants has paying more attention in current years' research on alternative refrigerants due to increase of public alertness on global warming & ozone depleting effect, several investigators had carried out lot of work for replacing high GWP refrigerants in the HTC & LTC cycles of cascaded VCR Systems. In the recent years, a new generation of refrigerants have been developed. in the replacement of CFC, HCFC & high GWP HFC refrigerants, and searching ultra-low GWP alternative refrigerants in LT& high temperature HT cycles in the Cascaded VCRS. In this paper, energy-exergy performance at -75ºC using HCFO-1224yd(Z), HFO1234ze(Z), HFO1243zf, HFO1234ze(E), HFO1234yf in HT cycle & HCFO-1233zd(E), HFO-1336mzz(Z), HFO-1225ye(Z) in LT cycle. Temperature have been computed and was found that HFO-1234ze(Z) in HTC and HCFO-1233zd(E) in LT Cycle gives better thermodynamic energy-exergy performances up to -70ºC. It was also found that the HFO-1336mzz(Z) & HFO-1225ye(Z) can also be used for ultra-low temperature cycle applications up to -100ºC to -140ºC. The effect of varying performance parameters on the first law (energy) efficiency (COP) & second law exergy efficiency using HCFO/HFO in HT & LT cycles have been investigated and it was found that HFO-1336mzz(Z) in LT cycle gives lower thermodynamic performances than using HFO-1225ye(Z) in LT cycle. for -100ºC.

1. Introduction

In human production and life, refrigeration technology plays a significant role. It is extensively used in daily life, commerce, and industrial production. The meaning of refrigeration is the continuous extraction of heat from a body whose temperature is already lowered to the temperature of its surroundings. In many industrial and medical applications, very low temperatures are required. A temperature of around 80 C is required to freeze and store blood. Ultra-low temperatures, such as 90 oC, are required for precipitation hardening of special alloy steels. The conventional refrigeration systems, i.e., VCR & VAR systems, are inadequate due to their temperature ranges of-10°C to-30°C; the refrigeration system is extensively operated between ranges of 50oC to-10oC. Therefore, it has no option except cascading of refrigeration cycles, which consists of using two different compression cycles working with other refrigerants and attaching them so that the condensing of low VC stage vapour is achieved through evaporation of HT stage fluid [1].

2. Cascade VCR System for low temperature applications

Cascade VCR System is used to attain lower evaporator temperatures of up to -70oC to -80oC. It is an effective system which can achieve the temperature range of usual compression refrigeration systems. For the production of low or ultra-low temperatures, the VCR system's role is significant. It can be

Corresponding author: R. S. Mishra
Email Address: rsmishra@dtu.ac.in
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used as a universal substitute in the stage compression of the cascade VCR system [2].
The feasibility alternatives to natural refrigerants for ultra-low temperature applications and the comparison of these refrigerants with synthetic refrigerants in terms of energy-thermodynamic performances by considering environmental aspects has been carried out by Barış Yilmaz Et al. [2] and found that the natural HC refrigerant using HC1270 in LT cycle and HC170 in the HT cycle gives around 5% better COP results as compared to synthetic refrigerant using HFC404A in LT cycle and R508B refrigerant in the HT cycle and developed a thermodynamic model using EES software in the range between-50oC and-100oC to examine the different designs and operation parameters effects on thermodynamic performances of the cascade systems.
To utilize 45 to 60 oC waste heat, Yijian, et. al. [3] developed a cascade refrigeration system. Two-stage VAR with LiBr/H2O in one subsystem and conventional VCRs in the second subsystem using HFO1234yf & HFO1234ze(E) refrigerants. The VAR subsystem was operated by consuming low-grade heat of renewable energy and recycling condensing heat of the VCR subsystem and evaluating thermodynamic performance theoretically. The literature review of the cascade refrigeration system can achieve an ultra-low 170oC evaporating temperature and compare the performances with conventional refrigeration systems [3]. Mingzhang Pan et al. [4] & Yousuf Alhendal et al. [5] carried out the energy and exergy analysis of VCR systems using GWP refrigerants. They concluded that in automotive air-conditioning systems, HFC refrigerants with a GWP of ≤ 150 and HFO/HCFO refrigerants could be sufficient for bringing down emissions. Also suggested the three low-GWP refrigerants, HFC152a, HFO1234yf, and HFO1234ze(E), and compared them with the currently used HFC134a of high-GWP, and concluded that the HFO refrigerant HFO1234ze(E) has the highest energetic and exergetic performance. The performance analysis of different refrigerants such as HFC 134a/HFC23, HFC 410A/ HFC 23, and HFC 404A/HC170 in the cascade VCRs has been carried out by K.Logesh Et al. [6]. The effect of the superheating range of 10°C and 5 °C in the LT evaporator and sub-cooling range of 10°C and 5 °C in the HT condenser have also been investigated. Similarly, the variation of condenser temperature from 30 to 50 °C in HT cycle and evaporator temperature in the range of -70°C to -50 °C of the low-temperature circuit has also been computed. The comparative thermodynamic performance of cascaded VCR system using different refrigerants for cooling and heating applications have been carried out by Fatih Yilmaz Et al. [7] carried out. In the cascaded VCRs, the working fluid HFC 134a, HFC152a, HFC32, HFO1234yf, R365mfc & HFE 7000 were used in HT cycle, and refrigerants R744 (CO2) were used in LT cycle. The three different mixed refrigerants: R744 in LT cycle and R1270 in HT cycle, R744 in LT cycle /R717 in HT cycle and R744 in LT cycle /RE170 in HT cycle of three cascade VCR systems consisting of two VCR cycles have been recommended by Luiz Henrique Et al. [8] and evaluated the thermodynamic performances of above three systems and found that the COP was increased around 18% to 30% when compared with the results obtained for pure refrigerants. However, the R744 in LT cycle and HC 170 in HT cycle give the best COP results.
Ebru Mançuhan Et al. [9] developed theoretical model by analyzing the energy efficient and environment-friendly cascade VCRS system using different refrigerants. In The Cascade system CO2 (as natural refrigerant) is used by replacing high Global Warming Potential, HFC404A refrigerant in the LT cycle and HFC134a, HFC152a and NH3 as natural refrigerants in the HT cycle (HTC) and calculated the of maximum COP compared for various operating conditions. The numerical investigation of a 50-kW cooling capacity cascade refrigeration system energetic, exergetic, economic and environmental performances have been carried out by Ranendra Roy et. al. [10] using four different refrigerant couples, namely HFC 41in LT cycle & HFC 404A in HT cycle, R170– HFC 404A in HT cycle, HFC 41 in LT cycle – HFC 161 in HT cycle and R170 in LT cycle –R161 in HT cycle. studied parametrically the effects of LTC evaporator temperature, HTC condenser temperature, and cascade condenser temperature and evaluated optimum COPin terms of coefficient of performance (COP) & optimum second law efficiency in terms of exergy efficiency using HFC41 in LT cycle -HFC-161 in HT cycle refrigerant couples followed by HC170 in LT cycle -HFC161 in HT cycle in the comparable operating conditions. For improving the performance, Canan Cimsit [11] has designed, the absorption part of absorption–cascade VAR cycle as serial flow double effect and carried out the comprehensive thermodynamic analysis of double effect absorption –cascade VAR cycle using working fluid as HFC-134a for vapour compression section and LiBr-H2O for absorption section and compared with single effect absorption cascade VAR cycle. Leonardo Arrieta Mondragon Et al. [12] studied the combined refrigeration system consisting of two VCR cycles connected by a heat exchanger for reducing the work of the compressor however also increases the amount of heat absorbed by the refrigerated space as a result of the cascaded stages & improved the COP of a VCR system.
Jinkun Zhou Et al. [13] found the lower temperature than the conventional VAR system due to the non-azeotropic mixed refrigerants with large temperature glides and evaluated the performance of a cascade VAR system using working substance as R23/R134a/DMF solutions as the, presented in the variation in thermodynamic performances. and found the increment in COP, when the low pressure of the system decreased or the high pressure increased.
R.S. Mishra [14] carried out the thermodynamic analysis of three stages cascade VCR systems using environmental friendly refrigerants used for low temperature applications and optimized The effectiveness of HFO1234ze and HFO1234yf and in the HT cycle and new eco-friendly refrigerants in the intermediates temperature cycle and HFC134a or HFC404a in the LT cycle and found that the low temperature (between -50oC to -100oC) applications, the best combination in terms of HFC1234ze in HT cycle, HFC134a in IT cycle & HFC404a in LT cycle gives enhanced thermodynamic performances than

using HFC1234yf in HT cycle, -HFC134a in IT cycle -HFC404a in LT cycle. Similarly, other combination in terms of HFO1234ze in HT cycle -HFC134a in IT cycle -HFC404a in LT cycle gives better thermal performance than using HFO1234ze in HT cycle -HFO1234yf in IT cycle and HFC404a in HT cycle. The theoretical thermodynamic performances of cascade VCR systems have been compared by Zhili Sun [15,16] for different refrigerant couples R41in LT cycle and HFO 404A in HT cycle and R23 in LT cycle & HFO 404A in in HT cycle to find out whether R41 is a appropriate substitute for R23. The computed results indicate that the optimum condenser temperature exists for LTC at which COP obtains maximum value. Under the similar operating condition, the input power of R41in in LT cycle and HFO 404A in HT cycle in the cascade VCR system is lower than that of R23 in LT cycle / HFO 404A in HT cycle of cascade VCR systems, and the optimum COP was higher than that of R23 in LT cycle / HFO 404A in HT cycle of cascade VCR system. The maximum exergy efficiency of cascaded VCR systems using R41 in LT cycle /R404A in HT cycle and R23 in LT cycle, and HFO 404A in HT cycle are approximately 44% and 43. % respectively, and concluded that the cascade VCR system using R41 in LT cycle / HFO 404A in HT cycle is a more possible refrigerant couple than the cascade VCR system using R23 in LT cycle / HFO 404A in HT cycle

By considering environmental factors, safety and energetic efficiency Zhiqiang Yang, et al, [17] found none of the pure refrigerant to be suitable for replacing hydrofluoro carbons(HFCs)and hydrochlorofluorocarbons(HCFCs)and then introduced a blend of R1243zf+R1234ze(Z) which can be possibly used as a long-term replacement of R134a

The drop-in test result for better performance than the predicted thermodynamic simulation of the most interesting HFOs is carried by Kaida T.et.al., [18] found HCFO1224yd(Z) can be used for high-temperature heat pump as an alternative of HFC 245fa due to its excellent thermodynamic and environmental properties. Zhiqiang Yanga,et.al. [19] carried out detailed studies. The thermodynamic assessment carried out by Fukuda,et.al. [20] and found theoretical maximized COP at 20 K of condenser temperature; however, the actual COP differs from the theoretical COP for the reason that the larger pressure drop. The irreversible losses, were computed at a condenser temperature of 75°C, and concluded that the HFO1234ze(Z) is most suitable for high-temperature applications instead of low-temperature applications (in the window air conditioners). Also found the critical factor of selecting of refrigerant. and concluded that the utility of mixed/blended HFO/HFC refrigerants was used as alternatives of R134a. However, the characteristics of refrigerant blends can be optimized for particular applications in terms of environmental factor, safety, and energetic efficiency.

2.1 Multistaged Cascade VCR System

The optimum temperature of evaporator can be reached by two staged cascaded VCRS is -80°C.However If need of evaporation temperature lower than -80°C, then three stage cascade VCRS or multistage cascade VCRS can be used [14]. The additional advantage of a cascade VCRS over the multistage compression system is that the lubricating oil from one compressor cannot be used in other compressors [15,16].

2.2 Selection of Refrigerants used in Cascaded VCRS

In the cascaded VCRS thermodynamic performances the selection of working refrigerants has a enormous influence. In the working refrigerant’s selection, the thermodynamic properties (i.e. physical and chemical properties) and atmospheric environmental friendliness of working refrigerants must also be considered. in addition to other properties such as (i) lower boiling temperature (ii) toxicity (iii) combustibility, (iv)explosively(v) interaction with metal materials(vi) interaction with lubricants will also affect the thermodynamic performances [14,15,16,17].

For calculating thermodynamic(energy-exergy) performances of the cascade vapour refrigeration system operated by different refrigerant pairs., several researchers found with zero ODP and low GWP value HFCs, HFOs & HCFOs, HCs refrigerants used in cascaded VCR system., several research possibilities such as various designs of cascade VCR system, detail studies of refrigerants, using different combination of refrigerant for improving overall coefficient of performance(COP) and finding optimum system(energy-exergy) performances. However, the influence of thermodynamic parameters on system thermal performances using experimental and analytical studies have been investigated by several investigators [14,15,16]

In cascaded VCR system, the following popular properties of used refrigerants are

- Condensation temperature must be lower. while critical temperature of refrigerant must be higher:
- For producing a lower temperature, the boiling point must be as low as possible.
- Zero ozone depletion potential [ODP] and low GWP value is the urgent need of replacement of high GWP refrigerants by examining the refrigerant alternative in LTC and HTC of cascade VCR system.
- The freezing point should be as low as possible.
- The refrigerants used in cascaded vapour compression system should has superior COP.
- The main factors in selection of working refrigerants should be Lowest cost, simply and frequently available.
- Non corrosive to metal, nontoxic, nonflammable and non-explosive are also some consideration in selection of working refrigerants.

Fedele L.et.al.[16] found is suitability of HCFO1224yd(Z)), in organic Rankine cycles (ORC), industrial high temperature heat pumps or centrifugal chillers due to its relatively high NBP (287.15 K) and its low vapour pressure, to replace HFC134a. Similarly, environmental friendly refrigerants HFO1234zf and HFO1234ze(E) are used due to because environmental performances. The simulation of Fourth generation refrigerant R1243zf in single stage and double stage

VCR System was carried out Vipin Kumar, et.al. [21] concluded that a single stage vapour compression system does not perform well in low temperature cooling applications, while a cascade VCR system is the suitable for the given pressure limit, in the double stage vapour compression system, and found that around increase in COP of 15% along with 11.5%. decrease in compression work. Also analyzed the effects of evaporator temperature and condenser temperature on COP for both the systems and concluded that that with increase in evaporator temperature, the COP is increased, whereas with increase in condenser temperature COP is decreased. Florian Kaufmann, et.al.[22] found experimentally HCFO1224yd(Z) and HCFO1233zd(E) are more appropriate low-GWP alternatives for replacing HFC245fa. Similarly, HFO1336mzz(Z) also shown the considerably lower system thermal efficiencies and power outputs as compared to the other refrigerants. However, the maximum power output and system efficiency can be achieved by using ecofriendly HFC-245fa refrigerant, which has significantly lower performances than HCFO-1233zd(E) and HCFO-1224yd(Z).

3. Results and Discussion

Numerical computation was carried out with the variation of performance parameters (i.e. HTC condenser temperature (from 40ºC to 60ºC), HTC evaporator temperature (from -30ºC to 0ºC), LTC evaporator temperature (from -100ºC to -70ºC) and temperature over lapping (from 0ºC to 15ºC) on the thermodynamic performances for three ultra-low GWP refrigerants.

3.1 Cascaded vapour compression system using HFOs/HCFOs in HT cycle and three HCFO/HFOs) in LT cycle for low temperature applications

The thermodynamic performances of cascaded vapour compression system using following HFOs/HCFOs in the HT cycle and three HCFO/HFOs (i.e. HCFO 1233zd(E), HFO-R1225ye(Z)&HFO1336mzz(Z))in low temperature cycle for low evaporator temperatures have been shown in Table- 1(a) toTable-1(c) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is highest using HFO1234ze(Z) in HT cycle (at HTC evaporator temperature (0ºC) and HCFO1233zd(E) in low temperature cycle at lower evaporator temperature(-75ºC) However cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is slightly lower (means second highest) using HCFO1224yd(Z) in HT cycle (at evaporator temperature (0ºC) and HCFO1233zd(E) in low temperature cycle at lower evaporator temperature(-75ºC)and lowest was found by using R1234yf in HT cycle (at evaporator temperature (0ºC) and HFO1336mzz(Z)in low temperature cycle at low evaporator temperature(-75ºC)

Table-1(a): Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=t0ºC, $T_{\_Eva\_HTC}$=0ºC, $T_{\_Eva\_LTC}$=-70ºC,Comp. Eff.$_{\_HTC}$=0.80, Comp. Eff.$_{\_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach=10ºC)

HTC Refrigerant.	R1234ze(Z)	R1224yd(Z)	R1336 mzz(Z)	R1234ze(E)	R1243Zf	R1225ye(Z)	R1234 yf
LTC Refrigerant.	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)
COP_Cascade	0.8705	0.8487	0.8440	0.8239	0.8188	0.8178	0.7975
Exergy Destruction Ratio (EDR_Cascade)	1.457	1.520	1.534	1.596	1.612	1.615	1.681
Exergetic Efficiency_Cascade	0.4071	0.3969	0.3947	0.3853	0.3829	0.3824	0.3729
Exergy of Fuel_Cascaded "kW"	40.4	41.44	41.67	42.68	42.95	43.0	44.10
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	16.19	17.22	17.45	18.47	18.74	18.74	19.88
LTC compressor Work"kW"	24.21	24.21	24.21	24.21	24.21	24.21	24.21
Heat Rejected by HTC Condenser"kW"	75.57	76.60	76.83	77.85	78.85	78.12	78.17
Heat Rejected by LTC Condenser"kW"	59.38	59.38	59.38	59.38	59.38	59.38	59.38
HTC_Evaporator Load"kW"	59.38	59.38	59.38	59.38	59.38	59.38	59.38
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.3693	0.5013	0.4990	0.5223	0.4683	0.6189	0.6362
LTC Mass flow Rate_ (Kg/sec)	0.2453	0.2453	0.2453	0.2453	0.2453	0.2453	0.2453
COP_LTC	1.452	1.452	1.452	1.452	1.452	1.452	1.452
COP_HTC	3.669	3.448	3.402	3.215	3.169	3.160	2.986
Total Exergy destruction (EDR_HTC	1.978	2.169	2.212	2.398	0.2444	2.458	2.659
Exergetic Efficiency_HTC	0.3358	0.3155	0.3114	0.2943	0.290	0.2892	0.2733
Exergy of Fuel_HTC	16.19	17.22	17.45	18.47	18.74	18.79	19.88
Exergy of Product_HTC	5.435	5.435	5.435	5.435	5.435	5.435	5.435

Table-1(b): Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50ºC, $T_{\_Eva\_HTC}$=0ºC, $T_{\_Eva\_LTC}$=-75ºC, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10ºC)

HTC Refrigerant.	R1234ze(Z)	R1224yd(Z)	R1225ye(Z)	R1233zd(E)	R1234ze(E)	R1243zf	R1234yf
LTC Refrigerant.	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)
COP_Cascade	0.8404	0.8194	0.827	0.7963	0.7904	0.7904	0.7711

Exergy Destruction Ratio (EDR_Cascade)	1.544	1.608	1.586	1.685	1.702	1.705	1.773
Exergetic Efficiency_Cascade	0.3931	0.3834	0.3868	0.3724	0.3701	0.3696	0.3606
Exergy of Fuel_Cascaded "kW"	41.84	42.60	42.52	44.16	44.44	44.49	45.61
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	16.49	17.55	17.18	18.82	19.10	19.15	20.26
LTC compressor Work"kW"	25.34	25.34	25.34	25.34	25.34	25.34	25.34
Heat Rejected by HTC condenser"kW"	77.0	78.06	77.69	79.33	79.61	79.66	80.77
Heat Rejected by LTC Condenser"kW"	60.51	60.51	60.51	60.51	60.51	60.51	60.51
HTC_Evaporator Load"kW"	60.51	60.51	60.51	60.51	60.51	60.51	60.51
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.3764	0.5018	0.4246	0.5322	0.4772	0.6307	0.6483
LTC Mass flow Rate (Kg/sec)	0.2974	0.2974	0.2974	0.2974	0.2974	0.2974	0.2974
COP_LTC	1.388	1.388	1.388	1.388	1.388	1.388	1.388
COP_HTC	3.669	3.448	3.523	3.215	3.169	3.160	2.986
Total Exergy destruction (EDR_HTC	1.971	2.169	2.102	2.398	2.448	2.458	2.659
Exergetic Efficiency_HTC	0.3358	0.3155	0.3224	0.2943	0.290	0.2892	0.2733
Exergy of Fuel_HTC	16.49	17.55	17.18	18.82	19.10	19.15	20.26
Exergy of Product_HTC	5.538	5.538	5.538	5.538	5.538	5.538	5.538

Table-1(c): Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}=50^oC$, $T_{\_Eva\_HTC}=0^oC$, $T_{\_Eva\_LTC}=-75^oC$, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234 ze(Z)	R1224 yd(Z)	R1336 mzz(Z)	R1234 ze(E)	R1243 zf	R1233 zd(E)	R1234yf
LTC Refrigerant.	R1225 ye(Z)	R1225 ye(Z)	R1225ye(Z)	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)
COP_Cascade	0.8413	0.8206	0.8161	0.7970	0.7921	0.8278	0.7718
Exergy Destruction Ratio (EDR_Cascade)	1.542	1.606	1.620	1.683	1.70	1.583	1.771
Exergetic Efficiency_Cascade	0.3934	0.3837	0.3816	0.3727	0.3704	0.3871	0.3609
Exergy of Fuel_Cascaded "kW"	41.80	42.86	43.09	44.12	44.40	42.48	45.57
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	16.49	17.54	17.78	18.81	19.09	17.17	20.25
LTC compressor Work"kW"	25.31	25.31	25.31	25.31	25.31	25.31	25.31
Heat Rejected by HTC Condenser"kW"	76.91	78.02	78.26	79.29	79.51	77.65	80.73
Heat Rejected by LTC Condenser"kW"	60.48	60.48	60.48	60.48	60.48	60.48	60.48
HTC_Evaporator Load"kW"	60.48	60.48	60.48	60.48	60.48	60.48	60.48
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.3762	0.5105	0.5082	0.5319	0.477	0.4244	0.6480
LTC Mass flow Rate (Kg/sec)	0.3332	0.3332	0.3332	0.3332	0.3332	0.3332	0.3332
COP_LTC	1.389	1.389	1.389	1.389	1.389	1.389	1.389
COP_HTC	3.669	3.448	3.402	3.215	3.169	3.523	2.986
Total Exergy destruction (EDR_HTC	1.978	2.169	2.212	2.398	2.448	2.102	2.659
Exergetic Efficiency_HTC	0.3358	0.3155	0.3224	0.2943	0.290	0.2892	0.2733
Exergy of Fuel_HTC	16.49	17.54	17.78	18.81	19.09	17.17	20.25
Exergy of Product_HTC	5.535	5.535	5.535	5.535	5.535	5.535	5.535

3.2 Cascaded VCR system using HFOs/HCFOs in the HT cycle and three HCFO/HFOs) in low temperature cycle for low temperature applications at HTC evaporator of 10°C

The thermodynamic performances of cascaded vapour compression system using following HFOs/HCFOs in the HT cycle and three HCFO/HFOs (i.e. HCFO 1233zd(E), HFO-R1225ye(Z)& HFO1336mzz(Z))in low temperature cycle for low evaporator temperatures have been shown in Table- 2(a) toTable-2(c) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is highest using HCFO1224ye(Z) in HT cycle (at HTC evaporator temperature (-10°C) and HCFO1233zd(E) in low temperature cycle at lower evaporator temperature(-75°C) However cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is slightly lower (means second highest) using HFO1225ye(Z)in HT cycle (at evaporator temperature (0°C) and HCFO1233zd(E) in low temperature cycle at lower evaporator temperature(-75°C) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-10°C) and HFO1336mzz(Z) in low temperature cycle at low evaporator temperature(-75°C)

Table-2(a) : Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant of R1233zd(E) in LTC and following ultra-low GWP refrigerants in HTC for ultra-low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-10°C, $T_{\_Eva\_LTC}$=-70°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234 ze(E)	R1243 zf	R1336 mzz(Z)	R1225 ye(Z)	R1224 yd(E)	R1234 yf
LTC Refrigerant.	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)	R1233 zd(E)
COP_Cascade	0.8213	0.8162	0.8137	0.8473	0.8565	0.7843
Exergy Destruction Ratio (EDR_Cascade)	1.604	1.621	1.628	1.524	1.497	1.727
Exergetic Efficiency_Cascade	0.3841	0.3817	0.3805	0.3962	0.4005	0.3667
Exergy of Fuel_Cascaded "kW"	42.82	43.08	43.22	41.50	41.06	44.84
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	22.80	23.07	23.20	21.49	21.04	24.82
LTC compressor Work"kW"	20.02	20.02	20.02	20.02	20.02	20.02
Heat Rejected by HTC Condenser"kW"	77.99	78.25	78.39	76.67	76.23	80.01
Heat Rejected by LTC Condenser"kW"	51.18	51.18	51.18	51.18	51.18	51.18
HTC_Evaporator Load"kW"	51.18	51.18	51.18	51.18	51.18	51.18
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5171	0.4591	0.6116	0.4957	0.4928	0.6358
LTC Mass flow Rate (Kg/sec)	0.2259	0.2259	0.2259	0.2259	0.2259	0.2259
COP_LTC	1.757	1.757	1.757	1.757	1.757	1.757
COP_HTC	2.420	2.392	2.378	2.691	2.622	2.223
Total Exergy destruction (EDR_HTC	2.107	2.143	2.162	1.794	1.867	2.382
Exergetic Efficiency_HTC	0.3219	0.3182	0.3163	0.3579	0.3488	0.2957
Exergy of Fuel_HTC	22.80	23.07	23.20	21.49	21.04	24.82
Exergy of Product_HTC	7.340	7.340	7.340	7.340	7.340	7.340

Table-2(b): Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant R1225ye(Z)*for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-10°C, $T_{\_Eva\_LTC}$ = -70°C, Comp.Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)*

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R1224yd(Z)	R1234yf
LTC Refrigerant.	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)
COP_Cascade	0.8035	0.7986	0.7961	0.8486	0.8376	0.7676
Exergy Destruction Ratio (EDR_Cascade)	1.661	1.678	1.686	1.520	1.553	1.786
Exergetic Efficiency_Cascade	0.3757	0.3734	0.3723	0.3968	0.3917	0.3590
Exergy of Fuel_Cascaded "kW"	43.77	44.04	44.17	41.44	41.99	45.81
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	23.08	23.35	23.49	20.76	21.30	25.13
LTC compressor Work"kW"	20.69	20.69	20.69	20.69	20.69	20.69
Heat Rejected by HTC Condenser"kW"	78.94	79.20	79.20	76.61	77.15	80.98
Heat Rejected by LTC Condenser"kW"	55.85	55.85	55.85	55.85	55.85	55.85
HTC_Evaporator Load"kW"	55.85	55.85	55.85	55.85	55.85	55.85
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5234	0.4647	0.6191	0.4127	0.4988	0.6435
LTC Mass flow Rate (Kg/sec)	0.2695	0.2695	0.2695	0.2695	0.2695	0.2695
COP_LTC	1.70	1.70	1.70	1.70	1.70	1.70
COP_HTC	2.42	2.392	2.378	2.691	2.622	2.223
Total Exergy destruction (EDR_HTC	2.107	2.143	2.162	1.794	1.867	2.382
Exergetic Efficiency_HTC	0.3279	0.3182	0.3163	0.3579	0.3488	0.2957
Exergy of Fuel_HTC	23.08	23.35	23.49	20.76	21.30	25.13
Exergy of Product_HTC	7.429	7.429	7.429	7.429	7.429	7.429

Table-2(c): Evaluation of Thermodynamic Performances of cascaded VCR systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-10°C, $T_{\_Eva\_LTC}$ = -70°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234 ze(E)	R1243 zf	R1336 mzz(Z)	R1233 zd(E)	R1224 yd(Z)	R1234yf
LTC Refrigerant.	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)	R1225 ye(Z)
COP_Cascade	0.807	0.8021	0.8324	0.8524	0.8413	0.7709
Exergy Destruction Ratio (EDR_Cascade)	1.650	1.666	1.569	1.509	1.542	1.774
Exergetic Efficiency_Cascade	0.3774	0.3751	0.3893	0.3986	0.3934	0.3605
Exergy of Fuel_Cascaded "kW"	43.58	43.84	42.25	41.26	41.82	45.62
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	23.02	23.29	21.7	20.71	21.25	25.07
LTC compressor Work"kW"	20.55	20.55	20.55	20.55	20.55	20.55
Heat Rejected by HTC Condenser"kW"	78.74	79.01	77.41	76.42	76.97	80.78
Heat Rejected by LTC Condenser"kW"	55.72	55.72	55.72	55.72	55.72	55.72
HTC_Evaporator Load"kW"	55.72	55.72	55.72	55.72	55.72	55.72
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5222	0.4636	0.5005	0.4117	0.4976	0.6419
LTC Mass flow Rate (Kg/sec)	0.3009	0.3009	0.3009	0.3009	0.3009	0.3009
COP_LTC	1.711	1.711	1.711	1.711	1.711	1.711
COP_HTC	2.42	2.392	2.568	2.691	2.622	2.223
Total Exergy destruction (EDR_HTC	2.107	2.143	1.928	1.794	1.867	2.382
Exergetic Efficiency_HTC	0.3219	0.3182	0.3416	0.3579	0.3488	0.2957
Exergy of Fuel_HTC	23.02	23.29	21.7	20.71	21.25	25.07
Exergy of Product_HTC	7.411	7.411	7.411	7.411	7.411	7.411

Table-3(a) : Evaluation of Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant of R1233zd(E) in LTC and following ultra-low GWP refrigerants in HTC for ultra-low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-20°C, $T_{\_Eva\_LTC}$=-70°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1336mzz(Z)	R1234yf
LTC Refrigerant.	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)	R1233zd(E)
COP_Cascade	0.7995	0.7959	0.7912	0.8312	0.7512
Exergy Destruction Ratio (EDR_Cascade)	1.675	1.687	1.703	1.573	1.847
Exergetic Efficiency_Cascade	0.3739	0.3722	0.370	0.3887	0.3513
Exergy of Fuel_Cascaded "kW"	43.99	44.19	45.45	42.31	46.81
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	27.68	27.87	28.14	26.0	30.5
LTC compressor Work"kW"	16.31	16.31	16.31	16.31	16.31
Heat Rejected by HTC Condenser"kW"	79.15	79.35	79.62	77.48	81.98
Heat Rejected by LTC Condenser"kW"	51.48	51.48	51.48	51.48	51.48
HTC_Evaporator Load"kW"	51.48	51.48	51.48	51.48	51.48
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5166	0.4536	0.6095	0.4962	0.6421
LTC Mass flow Rate (Kg/sec)	0.2095	0.2095	0.2095	0.2095	0.2095
$COP_{\_LTC}$	2.157	2.157	2.157	2.157	2.157
$COP_{\_HTC}$	1.86	1.847	1.83	1.98	1.688
Total Exergy destruction (EDR_HTC	2.024	2.046	2.075	1.841	2.333
Exergetic Efficiency_HTC	0.3307	0.3283	0.3252	0.3520	0.30
Exergy of Fuel_HTC	27.68	27.87	28.14	26.0	30.5
Exergy of Product_HTC	9.151	9.151	9.151	9.151	9.151

3.3 Cascaded VCR system using HFOs/HCFOs in the HT cycle and three HCFO/HFOs) in LT cycle for low temperature applications at HTC evaporator of -20°C

The thermodynamic performances of cascaded vapour compression system using following HFOs/HCFOs in the HT cycle and three HCFO/HFOs (i.e. HCFO 1233zd(E), HFO-R1225ye(Z) & HFO1336mzz(Z))in low temperature cycle for low evaporator temperatures have been shown in Table- 2(a) toTable-2(c) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is highest using HCFO1233zd(E)in HT cycle (at HTC evaporator temperature (-20°C) and HCFO1225ye(Z) in low temperature cycle at lower evaporator temperature(-75°C) However cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is slightly lower (means second highest) using HCFO1233zd(E) in HT cycle (at evaporator temperature (0°C) and HFO1336mzz(Z) in low temperature cycle at lower evaporator temperature(-75°C) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-20°C) and HFO1336mzz(Z) in low temperature cycle at low evaporator temperature(-75°C).

Table-3(b) :Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant of in LTC and following ultra-low GWP refrigerants in HTC for ultra-low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-20°C, $T_{\_Eva\_LTC}$=-80°C, Comp_Eff_HTC=0.80, Comp efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)	R1336mzz(Z)
COP_Cascade	0.7889	0.7853	0.7807	0.8504	0.7415
Exergy Destruction Ratio (EDR_Cascade)	1.711	1.723	1.739	1.514	1.884
Exergetic Efficiency_Cascade	0.3689	0.3672	0.3651	0.3977	0.3468
Exergy of Fuel_Cascaded "kW"	44.54	44.78	45.05	41.35	47.43
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	27.88	28.08	28.35	24.65	30.73
LTC compressor Work"kW"	16.70	16.70	16.70	16.70	16.70
Heat Rejected by HTC Condenser"kW"	79.75	79.95	80.21	76.52	82.59
Heat Rejected by LTC Condenser"kW"	51.86	51.86	51.86	51.86	51.86
HTC_Evaporator Load"kW"	51.86	51.86	51.86	51.86	51.86
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5204	0.4570	0.6141	0.4076	0.6469
LTC Mass flow Rate (Kg/sec)	0.2465	0.2465	0.2465	0.2465	0.2465
$COP_{\_LTC}$	2.106	2.106	2.106	2.106	2.106
$COP_{\_HTC}$	1.86	1.847	1.83	2.104	1.688
Total Exergy destruction (EDR_HTC	2.024	2.046	2.075	1.674	2.333
Exergetic Efficiency_HTC	0.3307	0.3283	0.3252	0.3739	0.30
Exergy of Fuel_HTC	27.88	28.08	28.35	24.65	30.73
Exergy of Product_HTC	9.219	9.219	9.219	9.219	9.219

Table-3(c):Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-20°C, $T_{\_Eva\_LTC}$ = -70°C, Comp_Eff_HTC=0.80, Comp. efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1336 mzz(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
COP_Cascade	0.7932	0.7896	0.8246	0.8553	0.7455
Exergy Destruction Ratio (EDR_Cascade)	1.692	1.708	1.593	1.50	1.869
Exergetic Efficiency_Cascade	0.3709	0.3693	0.3856	0.40	0.3486
Exergy of Fuel_Cascaded "kW"	44.34	44.54	42.65	41.62	47.17
Exergy of Product _ Cascaded"kW"	16.45	16.45	16.45	16.45	16.45
HTC compressor Work"kW"	27.80	28.0	26.11	24.58	30.64
LTC compressor Work"kW"	16.54	16.54	16.54	16.54	16.54
Heat Rejected by HTC Condenser"kW"	79.50	79.7	77.82	76.29	82.34
Heat Rejected by LTC Condenser"kW"	51.71	51.71	51.71	51.71	51.71
HTC_Evaporator Load"kW"	51.71	51.71	51.71	51.71	51.71
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5189	0.4556	0.4983	0.4033	0.6449
LTC Mass flow Rate (Kg/sec)	0.2750	0.2750	0.2750	0.2750	0.2750
$COP_{\_LTC}$	1.711	1.711	1.711	1.711	1.711
$COP_{\_HTC}$	1.86	1.847	1.98	2.104	1.688
Total Exergy destruction (EDR_HTC	2.024	2.046	1.841	1.674	2.333
Exergetic Efficiency_HTC	0.3307	0.3283	0.352	0.3739	0.30
Exergy of Fuel_HTC	27.80	28.0	26.11	24.58	30.64
Exergy of Product_HTC	9.191	9.191	9.191	9.191	9.191

3.4 Cascaded VCR system for ultra-low temperature applications

The thermodynamic performances of cascaded vapour VCR system using following HFOs/HCFOs in the HT cycle and HFO- R1225ye(Z) in low temperature cycle for ultra-low evaporator temperatures have been shown in Table- 4(a) and Table-4(b) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-100ºC) as shown in Table-4(a) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z)in low temperature cycle at ultra-low evaporator temperature(-100ºC) .Similarly cascaded VCR system, the cascaded COP(COP) & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-100ºC) as shown in Table-4(b) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30ºC) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-100ºC) By comparing thermodynamic performances of cascaded VCR Systems using different HFOs/HCFOs refrigerant pairs , The optimum performance was observed in the cascaded VCR Systems using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-100ºC). However lowest COP(COP) was observed using HFO1234yf in HT cycle and R1225ye(Z)in LT cycle . similarly second law (exergy)efficiency using HFO-1234yf in HTC and HFO-1336mzz(Z) in LTC is lower than the cascaded system using R1234yf in HTC and R1225ye(z) in LTC

Table-4(a):Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-100ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach 10ºC)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1336mzz(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
COP_Cascade	0.4845	0.4843	0.5052	0.5269	0.4523
Exergy Destruction Ratio (EDR_Cascade)	1.859	1.860	1.747	1.629	2.063
Exergetic Efficiency_Cascade	0.3496	0.3496	0.3640	0.3804	0.3265
Exergy of Fuel_Cascaded "kW"	72.58	72.62	69.75	66.74	77.75
Exergy of Product _ Cascaded"kW"	25.39	25.39	25.39	25.39	25.39
HTC compressor Work"kW"	44.02	44.06	41.19	38.18	49.19
LTC compressor Work"kW"	28.56	28.56	28.56	28.56	28.56
Heat Rejected by HTC Condenser"kW"	107.7	107.8	104.9	101.9	112.9
Heat Rejected by LTC Condenser"kW"	63.73	63.73	63.73	63.73	63.73
HTC_Evaporator Load"kW"	63.73	63.73	63.73	63.73	63.73
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.6886	0.5960	0.6616	0.5263	0.8673
LTC Mass flow Rate (Kg/sec)	0.2858	0.2858	0.2858	0.2858	0.2858
COP_LTC	1.231	1.231	1.231	1.231	1.231
COP_HTC	1.448	1.446	1.547	1.669	1.295
Total Exergy destruction (EDR_HTC	2.054	2.057	1.858	1.649	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.350	0.3776	0.293
Exergy of Fuel_HTC	44.02	44.06	41.19	38.18	49.19
Exergy of Product_HTC	14.41	14.41	14.41	14.41	14.41

Table-4(b): Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-100ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10ºC)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)
COP_Cascade	0.4740	0.4738	0. 4699	0. 5152	0.4427
Exergy Destruction Ratio (EDR_Cascade)	1.922	1.924	1.948	1.689	2.129
Exergetic Efficiency_Cascade	0.3422	0.3420	0.3393	0.3719	0.3196
Exergy of Fuel_Cascaded "kW"	74.19	74.23	74.83	68.26	79.44
Exergy of Product _ Cascaded"kW"	25.39	25.39	25.39	25.39	25.39
HTC compressor Work"kW"	44.68	44.72	45.32	38.75	49.93
LTC compressor Work"kW"	29.51	29.51	29.51	29.51	29.51
Heat Rejected by HTC Condenser"kW"	109.4	109.4	110.0	103.4	114.6
Heat Rejected by LTC Condenser"kW"	64.68	64.68	64.68	64.68	64.68
HTC_Evaporator Load"kW"	64.68	64.68	64.68	64.68	64.68

LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.6989	0.6057	0.8220	0.5342	0.8802
LTC Mass flow Rate (Kg/sec)	0.2591	0.2591	0.2591	0.2591	0.2591
COP_LTC	1.192	1.192	1.192	1.192	1.192
COP_HTC	1.448	1.446	1.427	1.669	1.295
Total Exergy destruction (EDR_HTC	2.054	2.057	2.098	1.689	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.3228	0.3776	0.293
Exergy of Fuel_HTC	44.68	44.72	45.32	38.75	49.93
Exergy of Product_HTC	14.63	14.63	14.63	14.63	14.63

3.5 The thermodynamic performances of cascaded vapour compression systems for different ultra-low temperatures (-90°C)

The thermodynamic performances of cascaded vapour compression system using following HFOs/HCFOs in the HT cycle and HFO- R1225ye(Z) in low temperature cycle for ultra-low evaporator temperatures have been shown in Table-5(a) and Table-5(b) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30°C) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-90°C) as shown in Table-5(a) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30°C) and HFO1225ye(Z)in low temperature cycle at ultra-low evaporator temperature(-90°C). Similarly cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30°C) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-90°C) as shown in Table-5(b) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30°C) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-90°C) By comparing thermodynamic performances of cascaded VCR Systems using different HFOs/HCFOs refrigerant pairs , The optimum performance was observed in the cascaded VCR Systems using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30°C) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-90°C). However lowest COP(COP) was observed using HFO1234yf in HT cycle and R1225ye(Z)in LT cycle. similarly second law (exergy)efficiency using HFO-1234yf in HTC and HFO-1336mzz(Z) in LTC is lower than the cascaded system using R1234yf in HTC and R1225ye(z) in LTC

Table-5(a):Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant of R1225ye(Z) in LTC and following ultra-low GWP refrigerants in HTC for ultra-low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-90°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1233zd(E)	R1336mzz(Z)	R1234yf
LTC Refrigerant.	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
COP_Cascade	0.5666	0.5663	0.6163	0.5910	0.5270
Exergy Destruction Ratio (EDR_Cascade)	1.811	1.812	1.572	1.695	2.020
Exergetic Efficiency_Cascade	0.3538	0.3556	0.3888	0.3711	0.3309
Exergy of Fuel_Cascaded "kW"	62.06	62.10	56.79	59.51	66.73
Exergy of Product _ $_{Cascaded}$"kW"	22.08	22.08	22.08	22.08	22.08
HTC compressor Work"kW"	39.72	39.72	34.45	37.17	44.39
LTC compressor Work"kW"	13.01	13.01	13.01	13.01	13.01
Heat Rejected by HTC Condenser"kW"	97.23	97.26	61.96	94.68	101.90
Heat Rejected by LTC Condenser"kW"	57.51	57.51	57.51	57.51	57.51
HTC_Evaporator Load"kW"	57.51	57.51	57.51	57.51	57.51
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.6214	0.5386	0.4750	0.597	0.7826
LTC Mass flow Rate (Kg/sec)	0.2747	0.2747	0.2747	0.2747	0.2747
COP_LTC	1.574	1.574	1.574	1.574	1.574
COP_HTC	1.448	1.446	1.669	1.547	1.295
Total Exergy destruction (EDR_HTC	2.054	2.057	1.649	1.858	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.3776	0.350	0.293
Exergy of Fuel_HTC	39.72	39.72	34.45	37.17	44.39
Exergy of Product_HTC	13.01	13.01	13.01	13.01	13.01

Table-5(b): Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications (T_{Cond_HTC}=50ºC, T_{Eva_HTC}=-30ºC, T_{Eva_LTC}=-90ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10ºC)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)
COP_Cascade	0.5584	0.5581	0.5534	0.610	0.5196
Exergy Destruction Ratio (EDR_Cascade)	1.852	1.853	1.878	1.611	2.065
Exergetic Efficiency_Cascade	0.3506	0.3505	0.3475	0.3830	0.3262
Exergy of Fuel_Cascaded "kW"	62.97	63.01	63.55	57.65	67.68
Exergy of Product _ Cascaded"kW"	22.08	22.08	22.08	22.08	22.08
HTC compressor Work"kW"	40.10	40.13	40.67	34.77	44.81
LTC compressor Work"kW"	13.13	13.13	13.13	13.13	13.13
Heat Rejected by HTC Condenser"kW"	98.14	98.18	98.72	92.82	102.90
Heat Rejected by LTC Condenser"kW"	58.04	58.04	58.04	58.04	58.04
HTC_Evaporator Load"kW"	58.04	58.04	58.04	58.04	58.04
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.6214	0.5386	0.7350	0.4794	0.7895
LTC Mass flow Rate (Kg/sec)	0.2479	0.2479	0.2479	0.2479	0.2479
COP_LTC	1.537	1.537	1.537	1.537	1.537
COP_HTC	1.448	1.446	1.427	1.669	1.295
Total Exergy destruction (EDR_HTC	2.054	2.057	2.098	1.649	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.3228	0.3776	0.293
Exergy of Fuel_HTC	40.10	40.13	40.67	34.77	44.81
Exergy of Product_HTC	13.01	13.01	13.01	13.01	13.01

3.6 The thermodynamic performances of cascaded vapour compression systems for different ultra-low temperatures (-80ºC)

The thermodynamic performances of cascaded vapour compression system using following HFOs/HCFOs in the HT cycle and HFO- R1225ye(Z) in low temperature cycle for ultra-low evaporator temperatures have been shown in Table-5(c) and Table-5(d) respectively and it was found that cascaded vapour compression system, the cascaded COP(COP) & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-80ºC) as shown in Table-5(a) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z)in low temperature cycle at ultra-low evaporator temperature(-80ºC) .Similarly cascaded vapour compression system, the cascaded COP & second law (exergy) efficiency is higher using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-80ºC) as shown in Table-5(d) and lowest was found by using R1234yf in HT cycle (at evaporator temperature (-30ºC) and HFO1336mzz(Z)in low temperature cycle at ultra-low evaporator temperature(-80ºC) By comparing thermodynamic performances of cascaded VCR Systems using different HFOs/HCFOs refrigerant pairs , The optimum performance was observed in the cascaded VCR Systems using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30ºC) and HFO1225ye(Z) in low temperature cycle at ultra-low evaporator temperature(-80ºC). However lowest COP(COP) was observed using HFO1234yf in HT cycle and R1225ye(Z)in LT cycle. However, second law (exergy)efficiency using HFO-1234yf in HTC and HFO-1336mzz(Z) in LTC is higher than the cascaded system using R1234yf in HTC and R1225ye(z) in LTC

Table-5(c): Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerant of R1225ye(Z) in LTC and following ultra-low GWP refrigerants in HTC for ultra-low temperature applications (T_{Cond_HTC}=50ºC, T_{Eva_HTC}=-30ºC, T_{Eva_LTC}=-80ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10ºC)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1336mzz(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)	R1225ye(Z)
COP_Cascade	0.6576	0.6572	0.6875	0.7225	0.6091
Exergy Destruction Ratio (EDR_Cascade)	1.797	1.799	1.676	1.546	2.02
Exergetic Efficiency_Cascade	0.3575	0.3573	0.3738	0.3928	0.3311
Exergy of Fuel_Cascaded "kW"	53.48	53.51	51.15	48.67	57.73
Exergy of Product _ Cascaded"kW"	19.12	19.12	19.12	19.12	19.12
HTC compressor Work"kW"	36.22	36.22	33.89	31.41	40.47
LTC compressor Work"kW"	17.26	17.26	17.26	17.26	17.26
Heat Rejected by HTC Condenser"kW"	88.64	88.68	86.32	83.84	92.9
Heat Rejected by LTC Condenser"kW"	52.43	52.43	52.43	52.43	52.43
HTC_Evaporator Load"kW"	52.43	52.43	52.43	52.43	52.43

LTC_Evaporator Load“kW”	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5666	0.4910	0.5443	0.4330	0.7135
LTC Mass flow Rate (Kg/sec)	0.2641	0.2641	0.2641	0.2641	0.2641
COP_LTC	2.037	2.037	2.037	2.037	2.037
COP_HTC	1.448	1.446	1.547	1.669	1.245
Total Exergy destruction (EDR_HTC	2.054	2.057	1.858	1.649	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.350	0.3776	0.293
Exergy of Fuel_HTC	36.22	36.22	33.89	31.41	40.47
Exergy of Product_HTC	11.86	11.86	11.86	11.86	11.86

Table-5(d): Thermodynamic Performances of cascaded VCR Systems using ultra-low GWP refrigerants for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$ = -80°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 “kW”, Approach =10°C)

HTC Refrigerant.	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R1234yf
LTC Refrigerant.	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)	R1336 mzz(Z)
COP_Cascade	0.6517	0.6513	0.6454	0.7158	0.6038
Exergy Destruction Ratio (EDR_Cascade)	1.823	1.824	1.850	1.570	2.046
Exergetic Efficiency_Cascade	0.3543	0.3541	0.3509	0.3891	0.3283
Exergy of Fuel_Cascaded “kW”	53.96	53.99	54.49	48.67	53.48
Exergy of Product _ Cascaded“kW”	19.12	19.12	19.12	19.12	19.12
HTC compressor Work“kW”	36.41	36.45	36.94	31.58	40.69
LTC compressor Work“kW”	17.55	17.55	17.55	17.55	17.55
Heat Rejected by HTC Condenser“kW”	89.13	89.16	89.65	84.30	93.41
Heat Rejected by LTC Condenser“kW”	52.72	52.72	52.72	52.72	52.72
HTC_Evaporator Load“kW”	52.72	52.72	52.72	52.72	52.72
LTC_Evaporator Load“kW”	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5697	0.4937	0.4670	0.4354	0.7174
LTC Mass flow Rate (Kg/sec)	0.2372	0.2372	0.2372	0.2372	0.2372
COP_LTC	2.004	2.004	2.004	2.004	2.004
COP_HTC	1.448	1.446	1.427	1.649	1.295
Total Exergy destruction (EDR_HTC	2.054	2.057	2.098	1.649	2.413
Exergetic Efficiency_HTC	0.3275	0.3272	0.3228	0.3776	0.2930
Exergy of Fuel_HTC	36.41	36.45	36.94	31.58	40.69
Exergy of Product_HTC	11.92	11.92	11.92	11.92	11.92

3.7 Dynamic performances Evaluation

Effect of approach on thermodynamic performances of cascaded VCR system using HFO1234ze(E) in the HT cycle and HCFO-1233zd(E) in low temperature cycle for low temperature applications have been shown in Table- 6(a) to Table-6(c) respectively and it was found that by the increasing. Approach of the cascaded vapour compression system, the cascaded COP(COP) & exergetic efficiency(both) are decreased and exergy of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is increased. While COP of LTC circuit is decreased and mass flow rates in each circuit is also increased.

Table-6(a) Effect of Approach ($T_{\_LTC\_Cond}$ - $T_{\_HTC\_Eva}$) on thermodynamic (energy-exergy) performances of cascaded VCR Systems using ultra low GWP refrigerant(R1234ze(E) in HT cycle and HCFO-1233zd(E) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp_Eff_HTC*=0.80,* Comp *Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167kW*

Approach (°C)	0	5	10	15
COP_Cascade	0.7959	0.7505	0.7081	0.6684
Exergy Destruction Ratio (EDR_Cascade)	1.490	1.640	1.798	1.965
ExergeticEfficiency_Cascade	0.4017	0.3787	0.3573	0.3373
Exergy of Fuel_Cascaded “kW”	44.18	46.86	49.67	52.61
Exergy of Product _ Cascaded“kW”	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser“kW”	79.35	82.03	84.83	87.78
Heat Rejected by LTC Condenser“kW”	46.93	48.51	50.17	51.92
HTC_EvaporatorLoad“kW”	46.93	48.51	50.17	51.92
LTC_EvaporatorLoad“kW”	35.167	35.167	35.167	35.167
HTC_compressorwork“kW”	32.42	33.51	34.66	35.86
LTC_ compressor work “kW”	11.76	13.35	15.01	16.75
HTC Mass flow Rate (Kg/sec)	0.5072	0.5243	0.5422	0.5610

LTC Mass flow Rate (Kg/sec)	0.1861	0.1923	0.1990	0.2061
COP_LTC	2.989	2.635	2.343	2.10
COP_HTC	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054
ExergeticEfficiency_HTC	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.42	33.51	34.66	35.86
Exergy of Product_HTC	10.62	10.97	11.35	11.76

Table-6(b) Effect of Approach $T_{\_LTC\_Cond}$ - $T_{\_HTC\_Eva}$) on thermodynamic (energy-exergy) performances of cascaded VCR Systems using ultra low GWP refrigerant(R1234ze(E) in HT cycle and HCFO-1233zd(E) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=50ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-75ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW",)

. Effect of Approach (ºC)	3	6	9	12	15
COP_Cascade	0.7683	0.7418	0.7163	0.6919	0.6684
Exergy Destruction Ratio (EDR_Cascade)	1.579	1.671	1.766	1.864	1.965
ExergeticEfficiency_Cascade	0.3877	0.3743	0.3615	0.3492	0.3373
Exergy of Fuel_Cascaded "kW"	45.78	47.41	49.09	50.83	52.61
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	80.94	82.58	84.26	85.99	87.78
Heat Rejected by LTC Condenser"kW"	47.87	48.84	49.84	50.86	51.92
HTC_EvaporatorLoad"kW"	47.87	48.84	49.84	50.86	51.92
LTC_EvaporatorLoad"kW"	35.167	35.167	35.167	35.167	35.167
HTC_compressorwork"kW"	33.07	33.74	34.42	35.13	35.86
LTC_ compressor work "kW"	12.71	13.67	14..67	15.69	16.75
HTC Mass flow Rate (Kg/sec)	0.5173	0.5278	0.5349	0.5496	0.5610
LTC Mass flow Rate (Kg/sec)	0.1898	0.1936	0.1963	0.2017	0.2061
COP_LTC	2.768	2.572	2.397	2.241	2.10
COP_HTC	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054
ExergeticEfficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	33.07	33.74	34.42	35.13	35.86
Exergy of Product_HTC	10.83	11.05	11.27	11.50	11.76

Table-6(c) Effect of Approach ($T_{\_LTC\_Cond}$ - $T_{\_HTC\_Eva}$) on thermodynamic (energy-exergy) performances of cascaded VCR Systems using ultra low GWP refrigerant(R1234ze(E) in HT cycle and HCFO-1233zd(E) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=50ºC, $T_{\_Eva\_HTC}$=-30ºC, $T_{\_Eva\_LTC}$=-75ºC, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW",)

Effect of Approach (ºC)	0	4	8	12	15
COP_Cascade	0.7959	0.7593	0.7247	0.6919	0.6684
Exergy Destruction Ratio (EDR_Cascade)	1.490	1.61	1.734	1.864	1.965
ExergeticEfficiency_Cascade	0.4017	0.3832	0.3657	0.3492	0.3373
Exergy of Fuel_Cascaded "kW"	44.18	46.32	48.53	50.83	52.61
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	79.35	81.48	83.69	85.99	87.78
Heat Rejected by LTC Condenser"kW"	46.93	48.19	49.5	50.86	51.92
HTC_EvaporatorLoad"kW"	46.93	48.19	49.5	50.86	51.92
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC_compressor work"kW"	32.42	33.29	34.19	35.13	35.86
LTC_ compressor work "kW"	11.76	13.03	14.33	15.69	16.75
HTC Mass flow Rate (Kg/sec)	0.5072	0.5208	0.5349	0.5496	0.5610
LTC Mass flow Rate (Kg/sec)	0.1861	0.1911	0.1963	0.2017	0.2061
COP_LTC	2.989	2.70	2.453	2.241	2.10
COP_HTC	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054
Exergetic Efficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.42	33.29	34.19	35.13	35.86
Exergy of Product_HTC	10.62	13.03	14.33	11.50	11.76

Effect of Approach on thermodynamic performances of cascaded vapour compression system using HFO1234ze(E) in the HT cycle and HFO-1336mzz(Z)in low temperature cycle for low temperature applications have been shown in Table-7(a) to Table-7(c) respectively and it was found that by the increasing Approach of the cascaded vapour compression system, the cascaded COP(COP) & exergetic efficiency(both) are decreased and exergy of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is increased. while COPof LTC circuit is decreased and mass flow rates in each circuit is also increased.

Table-7(a) Effect of Approach on Thermodynamic Performances of cascaded VCR Systems using R1234ze(E) ultra low GWP refrigerant in HTC and R1336mzz(Z) in LTC for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW",)

Approach(°C)	0°C	4 °C	5°C	8 °C	10°C	12 °C	15°C
COP(COP$_{_Cascade}$)	0.7918	0.7544	0.7454	0.7189	0.7018	0.6852	0.6609
Exergy Destruction Ratio (EDR_Cascade)	1.502	1.627	1.658	1.756	1.823	1.892	1.998
ExergeticEfficiency_Cascade	0.3996	0.3807	0.3762	0.3628	0.3542	0.3458	0.3335
Exergy of Fuel_Cascaded "kW"	44.41	46.62	47.18	48.92	50.11	51.33	53.21
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	79.58	81.78	82.05	84.08	85.27	86.49	88.38
Heat Rejected by LTC Condenser"kW"	47.07	48.37	48.53	49.73	50.41	51.16	52.27
HTC_EvaporatorLoad"kW"	47.07	48.37	48.53	49.73	50.41	51.16	52.27
LTC_EvaporatorLoad"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC_compressorwork"kW"	32.51	33.41	33.52	34.35	34.84	35.34	36.11
LTC_ compressor work "kW"	11.90	13.20	13.36	14.56	15.06	15.99	17.10
HTC Mass flow Rate (Kg/sec)	0.5086	0.5227	0.5244	0.5374	0.5450	0.5528	0.5648
LTC Mass flow Rate (Kg/sec)	0.2149	0.2215	0.2494	0.2284	0.2321	0.2359	0.2418
COP_LTC	2.995	2.664	2.598	2.415	2.303	2.20	2.056
COP_HTC	1.448	1.448	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054	2.054	2.054
ExergeticEfficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.51	33.41	33.64	34.35	34.84	35.34	36.11
Exergy of Product_HTC	10.65	10.90	11.02	11.25	11.41	11.52	11.77

Table-7(b) Thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant of R1336mzz(Z) in LTC and following ultra-low GWP refrigerantR1234ze(E) in HTC for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW")

Approach	0°C	3 °C	6 °C	9°C	12 °C	15°C
COP_Cascade	0.7918	0.7634	0.7364	0.7103	0.6852	0.6609
Exergy Destruction Ratio (EDR_Cascade)	1.502	1.595	1.691	1.790	1.892	1.998
ExergeticEfficiency_Cascade	0.3996	0.3854	0.3717	0.3585	0.3458	0.3335
Exergy of Fuel_Cascaded "kW"	44.41	46.06	47.75	49.51	51.33	53.21
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	79.58	81.22	82.92	84.67	86.49	88.38
Heat Rejected by LTC Condenser"kW"	47.07	48.04	49.04	50.08	51.16	52.27
HTC_Evaporator Load"kW"	47.07	48.04	49.04	50.08	51.16	52.27
LTC_EvaporatorLoad"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC_compressor work"kW"	32.51	33.18	33.88	34.59	35.34	36.11
LTC_ compressor work "kW"	11.90	12.87	13.88	14.91	15.99	17.10
HTC Mass flow Rate (Kg/sec)	0.5086	0.5191	0.530	0.5412	0.5528	0.5648
LTC Mass flow Rate (Kg/sec)	0.2149	0.2198	0.2249	0.2303	0.2359	0.2418
COP_LTC	2.995	2.732	2.534	2.358	2.20	2.056
COP_HTC	1.448	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054	2.054
ExergeticEfficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.51	33.18	33.88	34.59	35.34	36.11
Exergy of Product_HTC	10.65	10.87	11.09	11.33	11.52	11.77

Effect of Approach on thermodynamic performances of cascaded vapour compression system using HFO1234ze(E) in the HT cycle and HFO-1225ye(Z)in low temperature cycle for low temperature applications have been shown in Table- 8(a) to Table-8(c) respectively and it was found that by the increasing Approach of the cascaded vapour compression system, the cascaded COP(COP) & exergetic efficiency(both) are decreased and exergy of fuel in terms of electrical energy consumption (i.e.total power required by both compressors) is increased. while COPof LTC circuit is decreased and mass flow rates in each circuit is also increased.

Table-8(a) Effect of Approach on Thermodynamic Performances of cascaded VCR Systems using R1234ze(E) ultra low GWP refrigerant in HTC and R1225ye(Z) in LTC for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp_Eff_HTC=0.80, Comp Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW",)

Approach	0°C	4 °C	5°C	8 °C	10°C	12 °C	15°C
COP(COP$_{_Cascade}$)	0.7965	0.7592	0.7502	0.7238	0.7067	0.690	0.6656
Exergy Destruction Ratio (EDR_Cascade)	1.488	1.610	1.640	1.738	1.804	1.872	1.977
ExergeticEfficiency_Cascade	0.4019	0.3831	0.3786	0.3653	0.3566	0.342	0.3359
Exergy of Fuel_Cascaded "kW"	44.14	46.32	46.88	48.59	49.76	50.97	52.83
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	79.32	81.49	82.05	83.76	84.93	86.13	88.0
Heat Rejected by LTC Condenser"kW"	46.91	48.20	48.53	49.54	50.23	50.94	52.05
HTC_EvaporatorLoad"kW"	46.91	48.20	48.53	49.54	50.23	50.94	52.05
LTC_EvaporatorLoad"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC_compressor work"kW"	32.41	33.29	33.52	34.22	11.36	11.52	11.77
LTC_ compressor work "kW"	11.75	13.03	13.36	14.37	15.06	15.75	16.88
HTC Mass flow Rate (Kg/sec)	0.507	0.5208	0.5244	0.5353	0.5428	0.5505	0.5624
LTC Mass flow Rate (Kg/sec)	0.2407	0.2476	0.2494	0.2550	0.2589	0.2630	0.2694
COP_LTC	2.994	2.699	2.633	2.447	2.334	2.229	2.083
COP_HTC	1.448	1.448	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054	2.054	2.054
Exergetic Efficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.41	33.29	33.52	34.22	11.36	11.52	11.77
Exergy of Product_HTC	10.75	10.90	10.98	11.27	11.36	11.52	11.77

Table-8(b) Thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant of R1225ye(Z) in LTC and following ultra-low GWP refrigerantR1234ze(E) in HTC for low temperature applications ($T_{\_Cond\_HTC}$=50°C, $T_{\_Eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW")

Approach	0°C	3 °C	6 °C	9°C	12 °C	15°C
COP_Cascade	0.7965	0.7683	0.7413	0.7152	0.690	0.6656
Exergy Destruction Ratio (EDR_Cascade)	1.488	1.579	1.673	1.771	1.872	1.977
ExergeticEfficiency_Cascade	0.4019	0.3877	0.3741	0.3605	0.342	0.3359
Exergy of Fuel_Cascaded "kW"	44.14	45.77	47.44	49.17	50.97	52.83
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75	17.75
Heat Rejected by HTC Condenser"kW"	79.32	80.94	82.61	84.34	86.13	88.0
Heat Rejected by LTC Condenser"kW"	46.91	47.87	48.86	49.88	50.94	52.05
HTC_EvaporatorLoad"kW"	46.91	47.87	48.86	49.88	50.94	52.05
LTC_EvaporatorLoad"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC_compressorwork"kW"	32.41	33.07	33.75	34.46	35.19	11.77
LTC_ compressor work "kW"	11.75	12.70	13.69	14.72	15.75	16.88
HTC Mass flow Rate (Kg/sec)	0.507	0.5173	0.5280	0.5390	0.5505	0.5624
LTC Mass flow Rate (Kg/sec)	0.2407	0.2459	0.2513	0.2570	0.2630	0.2694
COP_LTC	2.994	2.768	2.568	2.390	2.229	2.083
COP_HTC	1.448	1.448	1.448	1.448	1.448	1.448
Total Exergy destruction (EDR_HTC	2.054	2.054	2.054	2.054	2.054	2.054
ExergeticEfficiency_HTC	0.3275	0.3275	0.3275	0.3275	0.3275	0.3275
Exergy of Fuel_HTC	32.41	33.07	33.75	34.46	35.19	11.77
Exergy of Product_HTC	11.75	10.83	11.05	11.28	11.52	11.77

3.8 Effect of LTC evaporator temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems

Effect of LTC evaporator temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (HCFO-1224yd(Z)) in HT cycle and(HCFO-1233zd(E))in low temperature cycle for low temperature applications have been shown in Table- 9(a) to Table-9(c) respectively and it was found that by the increasing LTC evaporator temperature of the cascaded vapour compression system, the cascaded COP(COP) is increased while exergy efficiency (i.e. exergetic efficiency)is started increasing. and exergy of fuel in terms of electrical energy consumption (i.e. Total power required by both compressors) is decreased. while COP of LTC circuit is increased and mass flow rates in each circuit is also decreased.

Table-9(a):Effect of LTC evaporator temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (HCFO-1224yd(Z)) in HT cycle and(HCFO-1233zd(E))in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$ =0.80, Comp. Efficienc$_{_LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

LTC Evaporating temperature (°C)	-75	-70	-65	-60	-55	-50
COP_Cascade	0.6965	0.7537	0.8144	0.8788	0.9471	1.02
Exergy Destruction Ratio (EDR_Cascade)	1.845	1.837	1.840	1.854	1.879	1.918
Exergetic Efficiency_Cascade	0.3515	0.3525	0.3521	0.3504	0.3473	0.3427
Exergy of Fuel_Cascaded "kW"	50.49	46.66	43.18	40.02	37.13	34.49
Exergy of Product _ Cascaded"kW"	17.75	16.45	15.02	14.02	12.9	11.82
HTC compressor Work"kW"	27.89	26.64	25.51	24.28	23.54	22.68
LTC compressor Work"kW"	22.60	20.02	17.67	15.54	13.59	11.81
Heat Rejected by HTC Condenser"kW"	85.66	81.82	78.35	75.19	72.13	69.66
Heat Rejected by LTC Condenser"kW"	57.77	55.18	52.84	50.71	48.76	48.58
HTC_Evaporator Load"kW"	57.77	55.18	52.84	50.71	48.76	48.58
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5782	0.5523	0.5288	0.5075	0.4880	0.4702
LTC Mass flow Rate (Kg/sec)	0.2309	0.2259	0.2211	0.2165	0.4880	0.2076
COP_LTC	1.556	1.757	1.99	2.263	2.587	2.977
COP_HTC	2.071	2.071	2.071	2.071	2.071	2.071
Total Exergy destruction (EDR_HTC	2.630	2.630	2.630	2.630	2.630	2.630
Exergetic Efficiency_HTC	0.2755	0.2755	0.2755	0.2755	0.2755	0.2755
Exergy of Fuel_HTC	27.89	26.64	25.51	24.28	23.54	22.68
Exergy of Product_HTC	7.683	7.340	7.028	6.744	6.485	6.248

Table-9(b): Effect of LTC evaporating temperature (°C)ondynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant R1336 mzz(Z) in HT cycle and(R-1225ye(Z))in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

LTC Evaporating temperature (°C)	-75	-70	-65	-60	-55	-50
COP_Cascade	0.6745	0.7298	0.7887	0.8513	0.9179	0.9888
Exergy Destruction Ratio (EDR_Cascade)	1.938	1.930	1.933	1.946	1.971	2.009
Exergetic Efficiency_Cascade	0.3404	0.3413	0.3410	0.3395	0.3366	0.3323
Exergy of Fuel_Cascaded "kW"	52.13	48.19	44.59	41.31	38.31	35.57
Exergy of Product _ Cascaded"kW"	17.75	16.45	15.02	14.02	12.9	11.82
HTC compressor Work"kW"	28.94	27.63	26.44	25.35	24.36	23.45
LTC compressor Work"kW"	23.19	20.55	18.15	15.96	13.95	12.12
Heat Rejected by HTC Condenser"kW"	87.30	83.35	79.76	76.48	73.48	70.73
Heat Rejected by LTC Condenser"kW"	58.36	55.72	53.32	51.12	49.12	47.28
HTC_Evaporator Load"kW"	58.36	55.72	53.32	51.12	49.12	47.28
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5930	0.5661	0.5417	0.5075	0.4991	0.4804
LTC Mass flow Rate (Kg/sec)	0.3080	0.3009	0.294	0.2873	0.2809	0.2747
COP_LTC	1.516	1.711	1.938	2.204	2.520	2.903
COP_HTC	2.016	2.016	2.016	2.016	2.016	2.016
Total Exergy destruction (EDR_HTC	2.729	2.729	2.729	2.729	2.729	2.729
Exergetic Efficiency_HTC	0.2682	0.2682	0.2682	0.2682	0.2682	0.2682
Exergy of Fuel_HTC	28.94	27.63	26.44	25.35	24.36	23.45
Exergy of Product_HTC	7.762	7.411	7.091	6.80	6.533	6.289

Table-9(c):Effect of LTC evaporating temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (R-1225ye(Z)) in HT cycle andR1336 mzz(Z) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach 10°C)

LTC Evaporating temperature (°C)	-75	-70	-65	-60	-55	-50
COP_Cascade	0.6277	0.6791	0.7335	0.7910	0.8517	0.9159
Exergy Destruction Ratio (EDR_Cascade)	2.157	2.149	2.153	2.170	2.202	2.249
Exergetic Efficiency_Cascade	0.3168	0.3176	0.3172	0.3154	0.3123	0.3078
Exergy of Fuel_Cascaded "kW"	56.03	51.78	47.94	44.46	41.29	38.40
Exergy of Product _ Cascaded"kW"	17.75	16.45	15.21	14.02	12.90	11.82
HTC compressor Work"kW"	32.61	31.09	29.72	28.41	27.34	26.31

LTC compressor Work"kW"	23.41	20.69	18.22	15.98	13.95	12.09
Heat Rejected by HTC Condenser"kW"	91.19	86.95	83.11	79.63	76.46	73.56
Heat Rejected by LTC Condenser"kW"	58.58	56.85	53.39	51.15	49.12	47.26
HTC_Evaporator Load"kW"	58.58	56.85	53.39	51.15	49.12	47.26
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.7644	0.7288	0.6966	0.6674	0.6409	0.6166
LTC Mass flow Rate (Kg/sec)	0.2765	0.2695	0.2627	0.2562	0.2499	0.2438
COP_LTC	1.502	1.70	1.93	2.20	2.521	2.909
COP_HTC	1.796	2.071	2.071	2.071	2.071	2.071
Total Exergy destruction (EDR_HTC	3.185	2.630	2.630	2.630	2.630	2.630
Exergetic Efficiency_HTC	0.2389	0.2755	0.2755	0.2755	0.2755	0.2755
Exergy of Fuel_HTC	32.61	31.09	29.72	28.41	27.34	26.31
Exergy of Product_HTC	7.792	7.429	7.101	6.803	6.533	6.285

3.9 Effect of HTC condensing temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant

The effect of HTC condensing temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (HCFO-1224yd(Z)) in HT cycle and(HCFO-1233zd(E))in low temperature cycle for low temperature applications have been shown in Table- 9(a) to Table-9(c) respectively and it was found that by the increasing HTC evaporator temperature of the cascaded vapour compression system, the cascaded COP(COP) is decreased similarly exergy efficiency (i.e. exergetic efficiency)is started increasing and then decreasing. and exergy of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is increased. while COPof HTC circuit is decreased and mass flow rates in each circuit is also increased.

Table-10(a): Effect of HTC condensing temperature (°C)on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (R-1224yd(Z)) in HT cycle and(R-1233zd(E))in low temperature cycle for low temperature applications ($T_{\_eva\_HTC}$=-30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC condenser temperature (°C	60	55	50	45	40
COP_Cascade	0.6965	0.7417	0.7880	0.8356	0.8849
Exergy Destruction Ratio (EDR_Cascade)	1.845	1.672	1.515	1.371	1.239
Exergetic Efficiency_Cascade	0.3515	0.3742	0.3977	0.4217	0.4466
Exergy of Fuel_Cascaded "kW"	50.49	47.42	44.63	42.09	39.74
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
HTC compressor Work"kW"	27.89	24.81	22.03	19.48	17.14
LTC compressor Work"kW"	22.60	22.60	22.60	22.60	22.60
Heat Rejected by HTC Condenser"kW"	85.66	82.58	79.8	77.25	74.91
Heat Rejected by LTC Condenser"kW"	57.77	57.77	57.77	57.77	57.77
HTC_Evaporator Load"kW"	57.77	57.77	57.77	57.77	57.77
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5782	0.5451	0.5159	0.4899	0.4666
LTC Mass flow Rate (Kg/sec)	0.2309	0.2309	0.2309	0.2309	0.2309
COP_LTC	1.556	1.556	1.556	1.556	1.556
COP_HTC	2.071	2.328	2.622	2.965	3.37
Total Exergy destruction (EDR_HTC	2.630	2.230	1.867	1.536	1.231
Exergetic Efficiency_HTC	0.2755	0.3096	0.3488	0.3943	0.4483
Exergy of Fuel_HTC	27.89	24.81	22.03	19.48	17.14
Exergy of Product_HTC	7.683	7.683	7.683	7.683	7.683

Table-10(b):Effect of HTC condenser temperature (°C)ondynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant R1336 mzz(Z) in HT cycle and(R-1225ye(Z))in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC condenser temperature (°C	60	55	50	45	40
COP_Cascade	0.6745	0.7197	0.7659	0.8133	0.8652
Exergy Destruction Ratio (EDR_Cascade)	1.935	1.753	1.587	1.436	1.298
Exergetic Efficiency_Cascade	0.3404	0.3632	0.3865	0.4104	0.4351
Exergy of Fuel_Cascaded "kW"	52.13	48.86	45.92	43.04	40.79
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
HTC compressor Work"kW"	28.94	25.67	22.72	20.05	17.06
LTC compressor Work"kW"	23.19	23.19	23.19	23.19	23.19

Heat Rejected by HTC Condenser“kW”	87.3	84.03	81.08	78.41	75.96
Heat Rejected by LTC Condenser“kW”	58.36	58.36	58.36	58.36	58.36
HTC_Evaporator Load“kW”	58.36	58.36	58.36	58.36	58.36
LTC_Evaporator Load“kW”	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5930	0.5563	0.5242	0.4958	0.4704
LTC Mass flow Rate (Kg/sec)	0.3080	0.3080	0.3080	0.3080	0.3080
COP_LTC	1.516	1.516	1.516	1.516	1.516
COP_HTC	2.016	2.273	2.568	2.911	2.273
Total Exergy destruction (EDR_HTC	2.729	2.307	1.928	1.583	1.267
Exergetic Efficiency_HTC	0.2682	0.3024	0.3416	0.3879	0.4411
Exergy of Fuel_HTC	28.94	25.67	22.72	20.05	17.06
Exergy of Product_HTC	7.762	7.762	7.762	7.762	7.762

Table-10(c):Effect of HTC condenser temperature (°C)ondynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (R-1225ye(Z)) in HT cycle andR1336 mzz(Z) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 “kW”, Approach =10°C)

HTC condenser temperature (°C	60	55	50	45	40
COP_Cascade	0.6277	0.6799	0.7319	0.7842	0.8371
Exergy Destruction Ratio (EDR_Cascade)	2.157	1.914	1.707	1.527	1.367
Exergetic Efficiency_Cascade	0.3168	0.3632	0.3694	0.3958	0.4225
Exergy of Fuel_Cascaded “kW”	56.03	51.52	48.05	44.84	42.01
Exergy of Product _ Cascaded“kW”	17.75	17.75	17.75	17.75	17.75
HTC compressor Work“kW”	32.61	28.31	24.63	21.43	18.59
LTC compressor Work“kW”	23.41	23.41	23.41	23.41	23.41
Heat Rejected by HTC Condenser“kW”	91.19	86.89	83.21	80.01	77.18
Heat Rejected by LTC Condenser“kW”	58.58	58.58	58.58	58.58	58.58
HTC_Evaporator Load“kW”	58.58	58.58	58.58	58.58	58.58
LTC_Evaporator Load“kW”	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.7644	0.7015	0.6493	0.6052	0.5674
LTC Mass flow Rate (Kg/sec)	0.2765	0.2765	0.2765	0.2765	0.2765
COP_LTC	1.502	1.502	1.502	1.502	1.502
COP_HTC	1.786	2.069	2.374	2.734	3.15
Total Exergy destruction (EDR_HTC	3.185	2.633	2.162	1.75	1.387
Exergetic Efficiency_HTC	0.2389	0.2752	0.3163	0.3636	0.4190
Exergy of Fuel_HTC	32.61	28.31	24.63	21.43	18.59
Exergy of Product_HTC	7.792	7.792	7.792	7.792	7.792

3.10Effect of HTC Evaporator temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (HCFO-1224yd(Z)) in HT cycle

Effect of HTC *Evaporator* temperature (°C) on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (HCFO-1224yd(Z)) in HT cycle and(HCFO-1233zd(E))in low temperature cycle for low temperature applications have been shown in Table- 9(a) to Table-9(c) respectively and it was found that by the increasing HTC evaporator temperature of the cascaded vapour compression system, the cascaded COP(COP) is increasing and then decreased Similarly exergy efficiency (i.e. exergetic efficiency)is started increasing and then decreasing. and exergy of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is increased. while COP of LTC circuit is decreased and the COPof HTC circuit is increased and mass flow rates in each circuit is also increased

Table-11(a): Effect of HTC Evaporator temperature (°C) on *dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant (R-1224yd(Z)) in HT cycle and(R-1233zd(E))*in *low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 “kW”,* Approach *=10°C)*

HTC Evaporator temperature (°C)	-10	-5	0	5	10
COP_Cascade	0.6965	0.6981	0.6958	6898	6799
Exergy Destruction Ratio (EDR_Cascade)	1.845	1.839	1.848	1.873	1.914
Exergetic Efficiency_Cascade	0.3515	0.3523	0.3512	0.3481	0.3431
Exergy of Fuel_Cascaded “kW”	50.49	50.38	50.54	50.98	51.73
Exergy of Product _ Cascaded“kW”	17.75	17.75	17.75	17.75	17.75
HTC compressor Work“kW”	27.89	25.57	23.37	21.27	19.25

LTC compressor Work"kW"	22.60	24.81	27.17	29.72	32.47
Heat Rejected by HTC Condenser"kW"	85.66	85.54	85.71	86.15	86.89
Heat Rejected by LTC Condenser"kW"	57.77	59.97	62.34	64.88	67.64
HTC_Evaporator Load"kW"	57.77	59.97	62.34	64.88	67.64
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5782	0.5814	0.5859	0.5917	0.5990
LTC Mass flow Rate (Kg/sec)	0.2309	0.2606	0.2512	0.2628	0.2756
COP_LTC	1.556	1.418	1.294	1.183	1.083
COP_HTC	2.071	2.345	2.667	3.051	3.513
Total Exergy destruction (EDR_HTC	2.63	2.811	3.096	3.051	3.513
Exergetic Efficiency_HTC	0.2755	0.2624	0.2441	0.2194	0.1861
Exergy of Fuel_HTC	27.89	25.57	23.37	21.27	19.25
Exergy of Product_HTC	7.683	6.710	5.705	4.665	3.583

Table-11(b): Effect of HTC Evaporator temperature (°C)on dynamic thermodynamic Performances of cascaded VCR Systems using ultra low GWP refrigerant R1336 mzz(Z) in HT cycle and(R-1225ye(Z))in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Evaporator temperature (°C)	-10	-5	0	5	10
COP_Cascade	0.6745	0.6738	0.6677	6562	6393
Exergy Destruction Ratio (EDR_Cascade)	1.938	1.941	1.968	2.019	2.099
Exergetic Efficiency_Cascade	0.3404	0.340	0.3370	0.3312	0.3226
Exergy of Fuel_Cascaded "kW"	52.13	52.19	52.67	53.59	55.01
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
HTC compressor Work"kW"	28.94	26.52	24.26	22.14	20.13
LTC compressor Work"kW"	23.19	25.67	28.41	31.45	34.87
Heat Rejected by HTC Condenser"kW"	87.3	87.36	87.83	88.76	90.18
Heat Rejected by LTC Condenser"kW"	58.36	60.84	63.58	66.62	70.04
HTC_Eva. Load"kW"	58.36	60.84	63.58	66.62	70.04
LTC_Eva. Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.5930	0.7676	0.7734	0.7821	0.794
LTC Mass flow Rate (Kg/sec)	0.3080	0.3239	0.3419	0.3624	0.3860
COP_LTC	1.516	1.37	1.238	1.118	1.008
COP_HTC	2.106	2.294	2.621	3.010	3.479
Total Exergy destruction (EDR_HTC	2.729	2.896	3.169	3.621	4.426
Exergetic Efficiency_HTC	0.2682	0.2567	0.2399	0.2164	0.1843
Exergy of Fuel_HTC	28.94	26.52	24.26	22.14	20.13
Exergy of Product_HTC	7.762	6.807	5.819	4.790	3.710

Table-11(c):Effect of HTC Evaporator temperature (°C)ondynamic thermodynamic Performances of cascaded VCR systems using ultra low GWP refrigerant (R-1225ye(Z)) in HT cycle andR1336 mzz(Z) in low temperature cycle for low temperature applications ($T_{\_Cond\_HTC}$=60°C, 30°C, $T_{\_Eva\_LTC}$=-75°C, Comp. Efficiency$_{_HTC}$=0.80, Comp. Efficiency$_{LTC}$=0.80, LTC Evaporator Load=35.167 "kW", Approach =10°C)

HTC Evaporator temperature (°C)	-10	-5	0	5	10
COP_Cascade	0.6277	0.6321	0.6319	6269	6171
Exergy Destruction Ratio (EDR_Cascade)	2.157	2.135	2.136	2.161	2.211
Exergetic Efficiency_Cascade	0.3168	0.319	0.3189	0.3164	0.3114
Exergy of Fuel_Cascaded "kW"	56.03	55.64	55.65	56.10	56.99
Exergy of Product _ Cascaded"kW"	17.75	17.75	17.75	17.75	17.75
HTC compressor Work"kW"	32.61	29.77	27.13	24.64	22.29
LTC compressor Work"kW"	23.41	25.86	28.53	31.46	34.70
Heat Rejected by HTC Condenser"kW"	91.19	90.80	90.82	91.26	92.16
Heat Rejected by LTC Condenser"kW"	58.58	67.03	63.70	66.63	69.87
HTC_Evaporator Load"kW"	58.58	67.03	63.70	66.63	69.87
LTC_Evaporator Load"kW"	35.167	35.167	35.167	35.167	35.167
HTC Mass flow Rate (Kg/sec)	0.7644	0.7676	0.7734	0.7821	0.794
LTC Mass flow Rate_ (Kg/sec)	0.2765	0.2905	0.3060	0.3233	0.3428
COP_LTC	1.502	1.36	1.233	1.118	1.013

COP(COP_HTC)	1.796	2.05	2.348	2.704	3.135
Total Exergy destruction (EDR_HTC)	3.185	3.361	3.653	4.143	5.021
Exergetic Efficiency_HTC	0.2389	0.2293	0.2149	0.1944	0.1661
Exergy of Fuel_HTC	32.61	29.77	27.13	24.64	22.29
Exergy of Product_HTC	7.792	6.828	5.83	4.791	3.301

4. Conclusions

The thermodynamic performances of the cascade VCR system operated by different refrigerant couples in the designs of cascade VCR systems have been carried out by taking into account the environmental impact issues, and some conclusions were drawn by analyzing exergy-energy analysis.

- The optimum (i.e. best reasonable) solution for refrigerant couple in cascade VCR system increases overall COP. the HCFO1233zd(E) in HT cycle (at evaporator temperature (-30°C) and HFO1225ye(Z) in LT cycle at ultra-low evaporator temperature(-100°C). The best thermodynamic performance with zero ODP and low GWP value in the cascade VCR system gives the best thermodynamic performance. HCFO1233zd(E) in HT cycle (at evaporator temperature (-30 °C) and HFO1336mzz(Z) in low temperature cycle at ultra-low evaporator temperature(-100°C). The cascade vapour refrigeration system gives a better thermodynamic performance with zero ODP and a low GWP value.
- The cascaded VCR system, the cascaded COP(COP) & second law (exergy) efficiency is highest using HFO1234ze(Z) in HT cycle (at evaporator temperature (0°C) and HCFO1233zd(E) in LTcycle at lower evaporator temperature(-75oC) however cascaded vapour compression system, the cascaded COP efficiency is slightly lower (means second highest) using HCFO1224yd(Z) in HT cycle (at evaporator temperature (0°C) and HCFO1233zd(E) in LT cycle at lower evaporator temperature(-75oC).
- The optimum performance was observed in the cascaded VCR Systems using HCFO1233zd(E) in HT cycle (at evaporator temperature (-30°C) and HFO1225ye(Z) in the low-temperature cycle at ultra-low evaporator temperature(-100°C).
- By the increasing HTC evaporator temperature of the cascaded VCR system, the cascaded COP(COP) is increasing and then decreases. Similarly, exergy efficiency (i.e., exergy efficiency (i.e. exergetic efficiency) is started increasing and then decreasing. and exergy of fuel in terms of electrical energy consumption (i.e., total power required by both compressors) is increased. While the COP of the LTC circuit is decreased and the COP of the HTC circuit is increased and mass flow rates in each circuit is also increased.
- By the increasing HTC evaporator temperature of the cascaded VCR system, the cascaded COP(COP) is decreased similarly, exergy efficiency (i.e. exergetic efficiency) is started increasing and then decreasing. and exergy of fuel in terms of electrical energy consumption (i.e., total power required by both compressors) is increased. While the COP of the HTC circuit is decreased and mass flow rates in each circuit is also increased.
- By the increasing LTC evaporator temperature of the cascaded vapour compression system, the cascaded COP(COP) is increased while exergy efficiency (i.e. exergetic efficiency) is started to increase. The energy efficiency of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is decreased. while the COP of the LTC circuit is increased and mass flow rates in each circuit is also decreased.
- Increasing the Approach of the cascaded VCR system, the cascaded COP(COP) & exergetic efficiency(both) are decreased and the exergy of fuel in terms of electrical energy consumption (i.e. total power required by both compressors) is increased. while COP of LTC circuit is decreased, mass flow rates in each circuit are also increased.

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