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ORIGNAL ARTICLE

Optimization of ultra-low global warming potential refrigerant groups for a three-stages/two stages cascaded vapour compression refrigeration system

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Abstract

Three stage Cascade refrigeration system is an ultra-low temperature refrigeration system and is used for very low temperature range about (-130°C to -150°C). At such ultra-low temperature simple cascaded vapour compression refrigeration cycle and simple cascaded vapour absorption refrigeration cycle is not capable Whereas, cascaded vapour compression refrigeration is much efficient for such conditions. Cascade refrigeration cycle is nothing but simply a combination of two or three VCRS cycles named as low medium and high temperature circuits that are combined together by a two cascade condensers. First cascade condenser unit act as HTC evaporator for high temperature circuit and condenser for medium temperature circuit, the medium temperature circuit uses medium boiling refrigerants such as R1233zd(E), R1225ye(z) , R1336mzz(Z) while second cascade condenser unit act as MTC evaporator for medium temperature circuit and condenser for low temperature circuit, the low temperature circuit uses low boiling refrigerants such as R290, R600a, R1225ye(Z), R-1336mzz(Z) etc. and high temperature uses high boiling point refrigerants such as R717, R152a, R1224yd(Z), R1234ze(E), R1243zf etc. It was found that three stages cascaded vapour compression refrigeration system using R1233zd(E) in HTC, R1336mzz(Z) in MTC and R1225ye(Z) gives best thermodynamic (energetic & exergetic) performances. ©2021 ijrei.com. All rights reserved

1. Introduction

Refrigeration technology plays an important role in human production and life; It is widely used in daily lives commerce and industrial production. The conventional single stage compression refrigeration system and absorption refrigeration system are two basic forms of the refrigeration technology The conventional single stage compression refrigeration system is used in air conditioning, human life, food storage, and transportation. However, for some applications, (e.g., rapid freezing and the storage of frozen food) also required moderately low temperatures in the evaporator (ranging from −40 to −60 °C), high compression ratio, or the high temperature difference in heat exchanger. In addition, the coefficient of performance (COP) and the volumetric efficiency of conventional single stage compression refrigeration system will be reduced by the high output temperature and pressure of the refrigerants. Although conventional single stage compression refrigeration system is commonly used for freezing applications and can effectively convert the low-grade waste heat into high-grade cold energy. However, when the temperature difference between cold energy and heat source increases, both COP and economy of absorption refrigeration system will decrease; thus, the application of refrigeration system at a low evaporation temperature is seriously limited. Therefore, cascade

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refrigeration system has been proposed to achieve lower refrigeration temperatures. cascade refrigeration system has a wide range of applications, for example in the field of hypothermal medicine, cryopreservation for instrument, and cryogenics, e.g. liquefied gas. It is also widely used in the storage and distribution of food, supermarkets, small refrigeration devices, air conditioning, etc. The system can conform to not only a suitable evaporation pressure at a lower evaporation temperature, but also a moderate condensation pressure at ambient temperature [1].

The two-stage cascade absorption refrigeration system is a type of cascade refrigeration system which can operate with two or more different refrigerants. The performance of cascade absorption refrigeration system with R744 and R711 as working has been analyzed by Dopazo J.A, et.al. [2]. to understand the cold energy production at lower temperatures. The results show thatcascade absorption refrigeration system is very suitable for low heat source temperature and low refrigeration temperature system The two-stage vapour compression cascade refrigeration system is another commonly used refrigeration system consisting of two circuits high-temperature cycle (HTC) and low-temperature cycle (LTC). The twocircuits are connected to each other through a heat exchanger, which is simultaneously used as the condenser of the HTC and the evaporator of the LTC [3]. Logesh [4] compared the performance analysis of different refrigerants couples in cascade refrigeration system by considering 70% of the compressor efficiency was assumed to be Refrigerants such as R134a/R23, R410A/R23 and R404A/R170 and found the enhancement in coefficient of performance and flow rate with rise in compressor work and evaporator temperature analyzed in the superheating and sub cooling range of 10 °C and 5 °C respectively. The variation in condenser temperature was from 30°C to 50°C in high temperature circuit while evaporator temperature in low temperature circuit varied in the range of -70°C to -50 °C and concluded that the refrigerant pair R134a/R170 was found to have greater coefficient of performance and lower mass flow rate and the pair R404A/R508B was found to have smaller coefficient of performance and greater mass flow rate. To explore the technical alternatives of refrigerant substitution and analyze the application of low GWP refrigerant in three-stage cascade refrigeration system, the change of operation parameters with the evaporation temperature

Sun[5] studied on thermodynamic analysis three-stage cascade refrigeration systems have been reported. and concluded that R1150 can replace R14 in low-temperature cycle. R41 and R170 can replace R23 in medium-temperature cycle. However in high-temperature cycle, the refrigerants of R717, R152a and R161 are suggested by considering the refrigerant groups of R1150/R41/R717 (system-1), R1150/R41/R152a (system-2),R1150/R41/R161(system-3),R1150/R170/R717 (system-4),R1150/R170/R152a(system-5), R1150/R170/R161(system-6) by taking into account environmental protection and found natural refrigerant of R717 is a good choice in the large refrigeration system. These six cascaded systems provided a basic theoretical analysis of the selection of refrigerants and replacement of refrigerant in three stages cascaded refrigeration systems.

In this papers use of HCFO & HFO refrigerants in high temperature cycle, HCFO & HFO refrigerants in medium temperature cycle (MTC) and HFO refrigerants in low temperature cycle(LTC) for ultra-low temperature have been suggested.

2. The refrigerants selection in three/ two stages cascaded vapour compression refrigeration systems

The selection of working fluids has a great influence on the system performance. In the selection of working fluids, besides thermodynamic properties, physical and chemical properties of working fluids should also be considered, such as toxicity, combustibility, explosivity, interaction with metal materials, interaction with lubricants, low boiling temperature, and atmospheric environmental friendliness. In addition, the critical temperature of refrigerant should be higher and the condensation temperature should be lower. The critical temperature determines whether the refrigerant can liquefy in the range of ordinary low temperature. The boiling point should be as low as possible to produce a lower temperature. Moreover, the evaporation pressure of the refrigerant should be close to or slightly higher than the atmospheric pressure to increase the chance of air mixing into the system. In the earlier period, the traditional CFCs and HCFCs refrigerants, such as R11, R12, R22, R13, R500, and R520, were widely used in cascaded refrigeration system(CRS) However, these refrigerants have higher Ozone Depletion Potential (ODP), leading to ozone layer depletion [4] however, HFCs do not affect the ozone layer and are regarded as a replacement for CFCs and HCFCs. However, HFCs highly contribute to global warming due to its high ODP values and high permanency in the atmosphere. Therefore, these refrigerants have been gradually phased out since 1996. According to Montreal Protocol and its amendments from the United Nations Environment Programme (UNEP), these have been prohibited since 2010 [5]. Therefore, finding new alternative refrigerants is a task of top priority. Environmentally friendly refrigerants, e.g. R744, R717, and hydrocarbons, have been developed [6] few refrigerants such as R717, R152a, R134a, R404a, R410a, R600a, R123, R124, R125, R407c, and R290 are usually used in the HTC of two stages compression cascaded refrigeration system while R744, R170, R23, and N_2O are widely used in the LTC of two stages compression cascaded refrigeration system. However, R744 and R717 are the most widely used refrigerants in two-stage CCRS due to their good characteristics, which have been shown to be the most promising natural refrigerants across a broad spectrum of commercial and industrial refrigeration and air-conditioning systems [6,7,8,9]. R744 [9] is a kind of non-toxic, nonflammable gas with a positive vapor pressure at low temperatures; therefore, it is suitable for the low temperate circuit. Due to the high triple point of R744, the lowest refrigeration temperature is limited above −55ºC. The triple point is a temperature and pressure value in thermodynamics that enables a substance to coexist in three phases (gas phase, liquid phase, and solid phase). It is worth mentioning that, when R744 is applied in ultra-low-temperature CRS, sedimentation of R744 may occur when the flow velocity, condensation temperature, and heating power are low. With the increase of mass flow rate, dry ice particles partly gather on the wall of the expansion tube, which causes the blockage. Therefore, we can add a heater on the inlet tube or increase the opening conditions to solve this problem; increasing the opening condition or the input heat fluxes can also avoid blockages [10-12, 15,16]. R717, as an environmentally friendly refrigerant, has been widely used in cascaded refrigeration systems Moreover, its apparent disadvantages of toxicity and moderate flammability cannot be ignored. R717 with air is flammable when its concentration is about 25% by volume [17,18]. Therefore, the current R717 refrigeration system should strengthen the pipeline welding and air tightness standards to avoid flammability and toxicity issues [19]. It is worth mentioning that R290 and R717 have similar thermodynamic properties in cascaded refrigeration systems, and have no significant difference in economic and exergy efficiency objectives [20]. R290 has 0 ODP and low GWP, but R290 has poor performance against chlorinated solvents and aromatics [21]. Moreover, the level of inherent safety of R717 is higher than R290. In addition to R744 and R717, mixture refrigerants, especially those exhibiting azeotropic phase equilibrium behaviors, have excellent performance in cascaded refrigeration systems. For instance, the binary mixture of R744 and R290 is regarded as a promising alternative to R13 when the evaporation temperature is above 201 K [22]. The ozone-friendly refrigerants pair R507A and R23 is considered as a replacement for CFC refrigerant R13 in low temperature applications. R507A is an azeotropic mixture comprised of R125 (50%) and R143a (50%) on a mass basis. R23 is a single component HFC refrigerant applied as replacement to CFC refrigerant [23]. Moreover, the options of low GWP refrigerant group for a three-stage CRS were developed by Sun et al. [4]. In the middle-temperature cycle, R41 and R170 could replace R23. To obtain a better performance, R170 would be considered first because the optimum condensation temperature of using R41 in MTC is higher than that of using R170 once the refrigerants of HTC and LTC were fixed. In HTC, refrigerants such as R717, R152a, and R161 would be recommended. Out of environmental and safety concern, R717 should be recommended as an environmentally-friendly refrigerant in the larger refrigeration system. The selection of refrigerant facilitates timely conversion from CFC to HCFC, HCFC to HFC or HFO, and HFC or HFO to natural refrigerants [24-27].

3. Results and Discussion

3.1 Comparison of results using HFCs & HC and natural refrigerants with HCFO and HFO refrigerants have ultra-low GWP on the thermodynamic systems performances of cascaded vapour compression systems using for ultra-low temperature of -150ºC

To explore the technical alternatives of refrigerant substitution and analyze the application of low GWP refrigerant in three-stage cascade refrigeration system the change of operation parameters with the evaporation temperatures, temperature overlappings, and high temperature condenser. Sun, Z, et.al. [5]; studied low GWP hydrocarbons(HC) and HFC refrigerants by taking into account environmental protection using, thermodynamic analysis in the three-stage cascade refrigeration systems (TCRS) and concluded that R1150 can replace R14 in low-temperature cycle. R41 and R170 can replace R23 in medium-temperature cycle and R170 is suggested as a priority. However, in high-temperature cycle, the refrigerants of R717, R152a and R161 are suggested. the natural refrigerant of R717 is a good choice in the large refrigeration system. His computed results of six cascaded systems provided a basic theoretical analysis of the selection of refrigerants and replacement of refrigerant in three-stage cascade refrigeration system The computed results of similar systems (refrigerant groups of R1150/R41/R717 (system-1), R1150/R41/R152a (system-2), R1150/R41/R161 (system-3), R1150/R170/R717 (system-4), R1150/R170/R152a (system-5) and R1150/R170/R161 (system-6)) have been compared using developed thermal model [24] using thermodynamic (energy-exergy) analysis for HFO refrigerants introduced in the systems for condenser temperature($T_{\_cond\_HTC}$=50ºC), Evaporator temperatures ($T_{\_Eva\_HTC}$=-20ºC, $_{\_Eva\_MTC}$=-75ºC and$_{_Eva_HTC}$=-135ºC), temperature over lappings (Approach$_{_MTC}$=10 ºC and Approach$_{_LTC}$=10 ºC) with 80% of compressors efficiencies for 35 kW of cooling load conditions.

System-1: Cascaded Vapour compression refrigeration systems using R717in HTC & R-41in MTC and R1150 in LTC System-2: Cascaded Vapour compression refrigeration systems using R717in HTC & R-41in MTC and R1150 in LTC

System-2: Cascaded Vapour compression refrigeration systems using R152a in HTC & R-41in MTC and R1150in LTC

System-3: Cascaded Vapour compression refrigeration systems using R161in HTC & R-41in MTC and R1150in LTC in LTC.

System-4: Cascaded Vapour compression refrigeration systems using R717in HTC & R-170 in MTC and R1150in LTC

System-5: Cascaded Vapour compression refrigeration systems using R152a in HTC & R-170) in MTC and R1150in LTC.

System-6: Cascaded Vapour compression refrigeration systems using R161 in HTC & R-170 in MTC and R1150in LTC. The computed results are shown in Table-1(a) respectively and verified the similar statement regarding R717.

Table 1(a): Comparison of two cascaded systems for equal temperature overlapping(°C) on *thermodynamic performances of cascaded vapor compression refrigeration system using ecofriendly low GWP refrigerants for zero approaches (zero temperature overlapping)*

Performance parameters	System1	System2	System3	System4	System5	System6
First Law Efficiency ($COP_{\_Cascade\ three\ stages\ VCRS}$)	0.270	0.2617	0.2676	0.259	0.2654	0.2569
Exergy Destruction Ratio ($EDR_{\_Cascade\ three\ stages\ VCRS}$)	2.196	2.303	2.227	2.334	2.253	2.361
Exergetic Efficiency $_{Cascade\ three\ stages\ VCRS}$	0.3128	0.302	0.3098	0.2998	0.3078	0.2976
Exergy of Fuel$_{_Cascade\ three\ stages\ VCRS}$ "kW"	130.2	134.5	131.4	135.8	132.5	136.9
Exergy of Product$_{_Cascade\ three\ stages\ VCRS}$ "kW"	40.7	40.7	40.7	40.7	40.7	40.7
HTC First Law Efficiency $COP_{\_HTC}$	2.726	2.726	2.652	2.652	2.591	2.591
MTCFirst Law Efficiency $COP_{\_MTC}$	1.382	1.301	1.382	1.301	1.382	1.301
LTC First Law Efficiency $COP_{\_LTC}$	1.004	1.004	1.004	1.004	1.004	1.004

On same cooling load on low temperature evaporator (35.167kW) with same temperature and other conditions using HFO and HCFO refrigerants The numerical computation has been carried out for systems suggested for ultra-low GWP refrigerants as shown in Table-1(b) The systems specifications are given below.

System-1: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC & R1336mzz(Z), in MTC and R-1225ye(Z) in LTC.

System-2: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC & R1225ye(Z) in MTC and R-1336mzz(Z), in LTC.

System-2: Cascaded Vapour compression refrigeration systems using R1224yd(Z) in HTC & R-41in MTC and R1150in LTC.

System-3: Cascaded Vapour compression refrigeration systems using R1224yd(Z)in HTC & R1336mzz(Z), in MTC and R-1225ye(Z) in LTC.

System-4: Cascaded Vapour compression refrigeration systems using R1224yd(Z)in HTC & R1225ye(Z) in MTC and R-1336mzz(Z), in LTC.

System-5: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC & R1336mzz(Z), in MTC and R-1225ye(Z) in LTC.

System-6: Cascaded Vapour compression refrigeration systems using R1234ze(E) in HTC & R1225ye(Z) in MTC and R-1336mzz(Z), in LTC.

The computed results using HFO & HCFO refrigerants and compared the results of table-1(a)of same six systems using and found that HFO refrigerants.as shown in Table-1(b) gives better thermodynamic performances as compared with refrigerants suggested [sun]. The results show that HFO-R1225ye(Z) and R1336mzz(Z) can replace R14 and R1150 in low-temperature cycle.R1233zd(E), HFO-R1225ye(Z) and R1336mzz(Z) can replace R23 and R41, R170 in medium-temperature cycle and R-1224yd(Z), R1234ze(Z), R1243zf, R1234ze(Z) R1233zd(E), HFO-R1225ye(Z) and R1336mzz(Z) and R1234yf will be recommended will replace R717, R152a and R161in high-temperature cycle, However the HC &HFC refrigerants gives lower first law efficiency ($COP_{\_Cascade}$) and second law performance (exergetic efficiency) as compared to the HFO suggested as shown in Table-1(b).

Table 1(b): Comparison of six cascaded systems for equal temperature overlapping(°C) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants equal approaches (10°C of temperature overlapping)*

Performance parameters	System7	System8	System9	System10	System11	System12
First Law Efficiency ($COP_{\_Cascade\ three\ stages\ VCRS}$)	0.2992	0.2913	0.2965	0.2887	0.2878	0.2803
Exergy Destruction Ratio ($EDR_{\_Cascade\ three\ stages\ VCRS}$)	1.886	1.964	1.913	1.999	2.0	2.08
Exergetic Efficiency $_{Cascade\ three\ stages\ VCRS}$	0.3465	0.33702	0.343	0.3340	0.330	0.324
Exergy of Fuel$_{_Cascade\ three\ stages\ VCRS}$ "kW"	117.5	120.7	118.6	121.8	122.2	125.4
Exergy of Product$_{_Cascade\ three\ stages\ VCRS}$ "kW"	40.7	40.7	40.7	40.7	40.7	40.7
HTC First Law Efficiency $COP_{\_HTC}$	2.691	2.691	2.622	2.622	2.42	2.42
MTCFirst Law Efficiency $COP_{\_MTC}$	1.502	1.516	1.502	1.516	1.502	1.516
LTC First Law Efficiency $COP_{\_LTC}$	1.110	1.055	1.110	1.055	1.110	1.055

3.2 Effect of varying MTC&LTC approaches (temperature overlapping) on the thermodynamic systems performances cascaded vapour compression systems using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -135°C.

Following systems have been selected for comparison of cascaded vapour compression systems performances using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -135°C.

System-1: Cascaded Vapour compression refrigeration systems using R1233zd(E), in HTC & R1336mzz(Z), in MTC and R-1225ye(Z) in LTC.

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

Table 1(c): Numerical Input data used in the cascaded vapour compression refrigeration systems.

Component	Data
Low temperature evaporator cooling load capacity	35.167 kW
High temperature condenser temperature	50°C
Ambient temperature	25°C
High temperature evaporator temperature	- 20°C
High temperature Compressor efficiency	80%
Medium temperature Compressor efficiency	80%
Low temperature Compressor efficiency	80%
Medium temperature evaporator temperature	- 95(°C)
Low temperature evaporator temperature	- 135 (°C)
Temperature overlapping *Approach*_MTC	10 (°C)
Temperature overlapping_*Approach*_LTC)	10 (°C)

Table 2(a): Comparison of two cascaded systems for equal temperature overlapping(°C) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants for zero approaches (zero temperature overlapping)*

Both Temperature Overlapping (MTC *Approach* =LTC *Approach*)= 0(°C)	System 1	System 2
(COP_ Cascade three stages VCRS)	0.3649	0.3671
(EDR_ Cascade three stages VCRS)	1.366	1.352
Exergetic Efficiency Cascade three stages VCRS	0.4226	0.4385
Exergy of Fuel_ Cascade three stages VCRS "kW"	96.37	95.80
Exergy of Product_ Cascade three stages VCRS "kW"	40.73	40.73
HTC Mass flow Rate (Kg/sec)	0.6954	0.6924
MTC Mass flow Rate (Kg/sec)	0.3693	0.4115
LTC Mass flow Rate (Kg/sec)	0.1989	0.170
Q_Cond_HTC"kW"	131.5	131.0
Q_Cond_MTC"kW"	89.15	88.77
Q_ Cond__LTC"kW"	51.25	51.64
Q_ EVA _LTC"kW"	35.167	35.167
First Law Efficiency (COP_MTCascade)	0.6384	0.6510
Exergy Destruction Ratio (EDRMTCascade)	1.325	1.281
MTCascade Exergetic Efficiency_MTC	0.430	0.4385
MTCascade Exergy of Fuel _MTC"kW"	80.28	79.33
MTCascade Exergy of Product _HTC"kW"	34.52	34.78
First Law Efficiency COP_HTC	2.104	2.104
Exergy Destruction Ratio (EDR)	1.674	1.674
Exergetic Efficiency_HTC	0.3739	0.3739
Exergy of Fuel _HTC"kW"	42.38	42.20
Exergy of Product _HTC"kW"	15.85	15.78
First Law Efficiency COP_HTC	2.104	2.104
First Law Efficiency COP_MTC	1.352	1.391
First Law Efficiency COP_LTC	2.186	2.135

Table 2(b): Comparison of two case cascaded systems for equal Temperature Overlapping(°C) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants for 5°C approaches (i.e.5°C temperature overlapping)*

Both Temperature Overlapping (MTC *Approach* =LTC *Approach*)= 5(°C)	System1	System 2
First Law Efficiency (COP_ Cascade three stages VCRS)	0.3249	0.3259
(EDR_ Cascade three stages VCRS)	1.659	1.65
Exergetic Efficiency Cascade three stages VCRS	0.3760	0.3774
Exergy of Fuel_ Cascade three stages VCRS "kW"	108.3	107.9
Exergy of Product_ Cascade three stages VCRS "kW"	40.73	40.73
HTC Mass flow Rate (Kg/sec)	0.7586	0.7565
MTC Mass flow Rate (Kg/sec)	0.4041	0.4504
LTC Mass flow Rate (Kg/sec)	0.2036	0.1752
HTC compressor Work "kW"	46.23	46.10
MTC compressor Work "kW"	43.63	42.83
LTC compressor Work "kW"	18.46	18.99
Q_Cond_HTC"kW"	143.5	143.1
Q_Cond_LTC"kW"	97.25	96.99
Q_EVA_HTC"kW"	53.63	54.15
Q_ EVA _LTC"kW"	35.167	35.167
MTCascade First Law Efficiency	0.5968	0.6089
MTC Exergy Destruction Ratio (EDR)	1.488	1.438
MTC Exergetic Efficiency	0.4020	0.4102
MTCascade Exergy of Fuel _MTC"kW"	89.86	88.93
MTCascade Exergy of Product "kW"	36.12	36.48
First Law Efficiency COP_HTC	2.104	2.104
Exergy Destruction Ratio (EDR)	1.674	1.674
Exergetic Efficiency_HTC	0.3739	0.3739
Exergy of Fuel _HTC"kW"	46.23	46.11
Exergy of Product _HTC"kW"	17.29	17.24
First Law Efficiency COP_HTC	2.104	2.104
First Law Efficiency COP_MTC	1.229	1.261
First Law Efficiency COP_LTC	1.905	1.852

3.3 Effect of Varying MTC &LTC approaches (temperature overlapping) on the thermodynamic performances cascaded vapour compression systems using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -150°C.

The effect of MTC Temperature Overlapping(°C) on the thermodynamic performances have been shown in Table-3(a) to 3(b) respectively. It was found that when the MTC Temperature Overlapping(oC) is increasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is decreasing while first law efficiency of medium temperature cycle is decreasing. The effect of LTC Temperature Overlapping(oC) on the thermodynamic performances have been shown in Table-3(c) to 3(d) respectively. It was found that when the MTC Temperature Overlapping(oC) is increasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is decreasing while first law efficiency of LTC temperature cycle is decreasing.

Table 2(c): Comparison of two case cascaded vapour compression refrigeration systems for equal Temperature Overlapping (ºC) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants for 10ºC approaches (zero temperature overlapping)*

Both Temperature Overlapping (MTC *Approach* =LTC *Approach)*= 10 (ºC)	System 1	System 2
First Law Efficiency ($COP_{\_Cascade\ three\ stages\ VCRS}$)	0.2895	0.2897
($EDR_{\_Cascade\ three\ stages\ VCRS}$)	1.983	1.980
Exergetic Efficiency $_{Cascade\ three\ stages\ VCRS}$	0.3353	0.3356
Exergy of Fuel$_{_Cascade\ three\ stages\ VCRS}$ “kW”	121.6	121.4
Exergy of Product$_{_Cascade\ three\ stages\ VCRS}$ “kW”	40.73	40.73
HTC Mass flow Rate (Kg/sec)	0.8282	0.8276
MTC Mass flow Rate (Kg/sec)	0.4429	0.4943
LTC Mass flow Rate (Kg/sec)	0.2086	0.1807
HTC Comp Work “kW”	50.47	50.44
MTC Comp Work “kW”	50.10	49.33
LTC Comp Work “kW”	20.91	21.61
Q_Cond_$_{HTC}$“kW”	156.6	156.5
Q_Cond_$_{MTC}$“kW”	106.2	106.1
Q_ Cond_$_{LTC}$ “kW”	56.06	56.78
Q_ EVA _$_{LTC}$“kW”	35.167	35.167
First Law Efficiency (COP_$_{MTCascade}$)	0.5578	0.5691
Exergy Destruction Ratio (EDR $_{MTCascade}$)	1.662	1.609
MTCascade Exergetic Efficiency_$_{MTC}$	0.3756	0.3356
MTCascade Exergy of Fuel _$_{MTC}$“kW”	100.6	99.76
MTCascade Exergy of Product _$_{HTC}$“kW”	37.77	38.24
First Law Efficiency COP_$_{HTC}$	2.104	2.104
Exergy Destruction Ratio (EDR)	1.674	1.674
Exergetic Efficiency_$_{HTC}$	0.3739	0.3739
Exergy of Fuel _$_{HTC}$“kW”	50.47	50.44
Exergy of Product _$_{HTC}$“kW”	18.87	18.86
First Law Efficiency COP_$_{HTC}$	2.104	2.104
First Law Efficiency COP_$_{MTC}$	1.119	1.119
First Law Efficiency COP_$_{LTC}$	1.682	1.627

3.4 Effect of HTC Condenser Temperature (ºC) on the thermodynamic performances cascaded vapour compression systems performances using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -150ºC

The effect of HTC Condenser Temperature (ºC) on the thermodynamic performances have been shown in Table-4(a) to 4(b) respectively. It was found that when the HTC Condenser temperature (ºC) is decreasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is increasing while first law efficiency of high temperature cycle is increasing while exergy of fuel (means power required to run whole system) is decreasing. Similarly, heat losses from HTC condenser is decreasing and cascaded first law efficiency ($COP_{\_Cascaded\_MTC}$) and cascaded MTC exergetic efficiency of two stage cascaded efficiency is increasing. as condenser temperature is decreasing.

3.5 Effect of HTC evaporator temperature (oC) on cascaded vapour compression systems performances using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -150ºC

The effect of HTC Evaporator Temperature (oC) on the thermodynamic performances have been shown in Table-4(a) to 4(b) respectively. It was found that when the HTC evaporator temperature (ºC) is increasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is decreasing while first law efficiency of high temperature cycle is increasing The effect of HTC Condenser Temperature (ºC) on the thermodynamic performances have been shown in Table-5(a) to 5(b) respectively. It was found that when the HTC Condenser temperature (ºC) is decreasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is increasing while first law efficiency of high temperature cycle is increasing while exergy of fuel (means power required to run whole system) is decreasing. Similarly, heat losses from HTC condenser is decreasing and cascaded first law efficiency (COP_Cascaded_MTC) and cascaded MTC exergetic efficiency of two stage cascaded efficiency is increasing. as condenser temperature is decreasing.

3.6 Effect of MTC evaporator temperature (oC) on thermodynamic performances of cascaded vapour compression systems performances using HCFO-1233zd(E) refrigerant in HTC and HFO-1336mzz(Z) in MTC and HFO-1225ye(Z) in LTC have ultra-low GWP for ultra-low temperature of -150oC

The effect of MTC Evaporator Temperature (ºC) on the thermodynamic performances have been shown in Table-6 to Table-7 respectively. It was found that when the MTC evaporator temperature (ºC) is increasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is decreasing while first law efficiency of high temperature cycle is increasing

Table 3(a): Effect of MTC *Approach (*MTC Temperature Overlapping(ºC)) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly HCFO-1233zd(E) ultra-low GWP refrigerants in high temperature cycle (T_Cond=50ºC, $T_{\_ambient}$=25ºC, $T_{\_Eva\_HTC}$= - 20ºC& Compressor efficiency$_{_HTC}$=80%,) and HFO-1225ye(Z) in medium temperature cycle at $T_{\_Eva\_MTC}$= - 95ºC& Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in ultra-low temperature cycle at Q_Eva=35.167 kW using , Compressor efficiency$_{_LTC}$=80%, $T_{\_Eva\_LTC}$= - 150ºC,* LTC *Approach=10(ºC)*

MTC Temperature Overlapping(ºC)	0	5	10	15
First Law Efficiency (COP$_{_\text{Cascade three stages VCRS}}$)	0.2385	0.2268	0.2153	0.204
Exergy Destruction Ratio (EDR$_{_\text{Cascade three stages VCRS}}$)	1.95	2.103	2.268	2.449
Exergetic Efficiency$_{\text{Cascade three stages VCRS}}$	0.3390	0.3223	0.3833	0.3578
Exergy of Fuel$_{_\text{Cascade three stages VCRS}}$ "kW"	147.4	155.1	163.3	172.4
Exergy of Product$_{_\text{Cascade three stages VCRS}}$ "kW"	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	0.9642	0.8290	0.8655	0.9051
MTC Mass flow Rate (Kg/sec)	0.5737	0.5988	0.6267	0.6579
LTC Mass flow Rate (Kg/sec)	0.1882	0.1882	0.1882	0.1882
Q_Cond$_{_HTC}$"kW"	182.6	190.2	198.5	207.5
Q_Cond$_{_LTC}$"kW"	123.8	128.99	134.5	140.7
Q_EVA$_{_HTC}$"kW"	71.99	71.99	71.99	71.99
Q_ EVA $_{\_LTC}$"kW"	35.167	35.167	35.167	35.167
First Law Efficiency (COP$_{_MTCascade}$)	0.651	0.6089	0.5691	0.5312
MTCascade Exergy Destruction Ratio (EDR)	1.281	1.438	1.609	1.795
MTCascade Exergetic Efficiency$_{_MTC}$	0.4385	0.4102	0.3833	0.3578
MTCascade Exergy of Fuel $_{\_MTC}$"kW"	110.6	118.2	126.5	135.5
MTCascade Exergy of Product $_{\_HTC}$"kW"	47.25	47.25	47.25	47.25
First Law Efficiency COP$_{_HTC}$	2.104	2.104	2.104	2.104
Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674
Exergetic Efficiency$_{_HTC}$	0.3739	0.3739	0.3739	0.3739
Exergy of Fuel $_{\_HTC}$"kW"	58.83	61.29	63.96	66.86
Exergy of Product $_{\_HTC}$"kW"	22.0	22.92	23.92	24.69
First Law Efficiency COP$_{_HTC}$	2.104	2.104	2.104	2.104
First Law Efficiency COP$_{_MTC}$	1.352	1.264	1.151	1.048
First Law Efficiency COP$_{_LTC}$	0.955	0.955	0.955	0.955

Table 3(b): Effect of MTC *Approach (*MTC Temperature Overlapping(ºC)) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly HCFO-1233zd(E) ultra-low GWP refrigerants in high temperature cycle (T_Cond=50ºC, $T_{\_ambient}$=25ºC, $T_{\_Eva\_HTC}$= - 20ºC& Compressor efficiency$_{_HTC}$=80%,) and HFO-1336mzz(Z) in medium temperature cycle at $T_{\_Eva\_MTC}$= - 95ºC& Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in ultra-low temperature cycle at Q_Eva=35.167 kW using , Compressor efficiency$_{_LTC}$=80%, $T_{\_Eva\_LTC}$= - 150ºC,* LTC *Approach=10(ºC)*

MTC Temperature Overlapping(ºC)	0	5	10	15
First Law Efficiency (COP$_{_\text{Cascade three stages VCRS}}$)	0.2428	0.2306	0.2187	0.2072
Exergy Destruction Ratio (EDR$_{_\text{Cascade three stages VCRS}}$)	1.898	2.052	2.217	2.396
Exergetic Efficiency$_{\text{Cascade three stages VCRS}}$	0.345	0.3270	0.3108	0.2944
Exergy of Fuel$_{_\text{Cascade three stages VCRS}}$ "kW"	144.8	152.5	160.8	169.7
Exergy of Product$_{_\text{Cascade three stages VCRS}}$ "kW"	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	0.9517	0.9923	1.306	1.083
MTC Mass flow Rate (Kg/sec)	0.5055	0.5286	0.5539	0.5819
LTC Mass flow Rate (Kg/sec)	0.2157	0.2157	0.2157	0.2157
HTC Compressor Work (W$_{_Comp_HTC}$)"kW"	58.0	60.47	63.13	66.02
MTC Compressor Work (W$_{_Comp_MTC}$)"kW"	51.87	57.06	62.66	68.73
LTC Compressor Work (W$_{_Comp_LTC}$)"kW"	34.97	34.97	34.97	34.97
Q_Cond_HTC"kW"	180.0	187.7	195.9	204.9
Q_Cond_MTC"kW"	122.0	127.2	132.8	138.9
Q_ Cond__LTC"kW"	70.14	70.14	70.14	70.14
Q_EVA_LTC"kW"	35.167	35.167	35.167	35.167
First Law Efficiency COP_MTCascade	0.6384	0.5969	0.5576	0.5205
MTCascade Exergy Destruction Ratio (EDR)	1.325	1.488	1.662	1.852
MTCascade Exergetic Efficiency_HTC	0.430	0.3739	0.375	0.354
MTCascade Exergy of Fuel	109.9	117.5	125.8	134.7
MTCascade Exergy of Product	47.25	47.25	47.25	47.25
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104

HTC Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674
HTC Exergetic Efficiency_HTC	0.3739	0.3739	0.3739	0.3739
Exergy of Fuel _HTC"kW"	58.0	60.47	63.13	66.02
Exergy of Product _HTC"kW"	21.69	22.61	23.61	24.67
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104
First Law Efficiency COP_MTC	1.352	1.229	1.119	1.021
First Law Efficiency COP_LTC	1.005	1.005	1.005	1.005

Table 3(c): Effect of LTC *Approach (*MLTC Temperature Overlapping(^oC)) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly HCFO-1233zd(E) ultra-low GWP refrigerants in high temperature cycle (T_Cond=50°C, $T_{\_ambient}$=25°C, $T_{\_Eva\_HTC}$= - 20°C& Compressor efficiency$_{_HTC}$=80%,) and HFO-1225ye(Z) in medium temperature cycle at $T_{\_Eva\_MTC}$= - 95°C& Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in ultra-low temperature cycle at Q_Eva=35.167 kW using , Compressor efficiency$_{_LTC}$=80%, $T_{\_Eva\_LTC}$= - 150°C,* MTC *Approach=10(°C)*

LTC Temperature Overlapping(^oC)	0	5	10	15
First Law Efficiency (COP_ Cascade three stages VCRS)	0.245	0.2295	0.2153	0.2023
Exergy Destruction Ratio (EDR_ Cascade three stages VCRS)	1.873	2.066	2.268	2.479
Exergetic Efficiency Cascade three stages VCRS	0.3481	0.3261	0.3060	0.2874
Exergy of Fuel_ Cascade three stages VCRS "kW"	143.6	153.2	163.3	173.9
Exergy of Product_ Cascade three stages VCRS "kW"	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	0.945	0.9961	1.049	1.105
MTC Mass flow Rate (Kg/sec)	0.5643	0.5949	0.6267	0.660
LTC Mass flow Rate (Kg/sec)	0.1766	0.1822	0.1882	0.1945
Q_Cond_HTC"kW"	178.7	188.4	198.5	209.0
Q_Cond_LTC"kW"	121.1	127.7	134.5	141.7
Q_EVA_HTC"kW"	64.82	68.33	71.99	75.81
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167
First Law Efficiency (COP_MTCascade)	0.5691	0.5691	0.5691	0.5691
MTCascade Exergy Destruction Ratio (EDR)	1.609	1.609	1.609	1.609
MTCascade Exergetic Efficiency_MTC	0.3833	0.3833	0.3833	0.3833
MTCascade Exergy of Fuel _MTC"kW"	126.5	126.5	126.5	126.5
MTCascade Exergy of Product _HTC"kW"	43.67	43.67	43.67	43.67
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104
Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674
Exergetic Efficiency_HTC	0.3739	0.3739	0.3739	0.3739
Exergy of Fuel _HTC"kW"	57.59	60.71	63.96	67.35
Exergy of Product _HTC"kW"	21.53	22.7	23.92	25.19
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104
First Law Efficiency COP_MTC	1.151	1.151	1.151	1.151
First Law Efficiency COP_LTC	1.186	1.06	0.955	0.8652

Table 3(d): Effect of LTC *Approach (*LTC Temperature Overlapping(^oC)) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly HCFO-1233zd(E) ultra-low GWP refrigerants in high temperature cycle (T_Cond=50°C, $T_{\_ambient}$=25°C, $T_{\_Eva\_HTC}$= - 20°C& Compressor efficiency$_{_HTC}$=80%,) and HFO-1336mzz(Z) in medium temperature cycle at $T_{\_Eva\_MTC}$= - 95°C& Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in ultra-low+ temperature cycle at Q_Eva=35.167 kW using , Compressor efficiency$_{_LTC}$=80%, $T_{\_Eva\_LTC}$= - 150°C,* MTC *Approach=10(°C)*

LTC Temperature Overlapping(^oC)	0	5	10	15
First Law Efficiency (COP_ Cascade three stages VCRS)	0.2465	0.2320	0.2187	0.2065
Exergy Destruction Ratio (EDR_ Cascade three stages VCRS)	1.855	2.033	2.217	2.408
Exergetic Efficiency Cascade three stages VCRS	0.3503	0.3297	0.3108	0.2935
Exergy of Fuel_ Cascade three stages VCRS "kW"	142.7	151.6	160.8	170.3
Exergy of Product_ Cascade three stages VCRS "kW"	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	0.9402	0.9873	1.036	1.086
MTC Mass flow Rate (Kg/sec)	0.5027	0.5279	0.5539	0.5809
LTC Mass flow Rate (Kg/sec)	0.2053	0.2104	0.2157	0.2215
HTC compressor Work (W_comp_HTC) "kW"	57.29	60.16	63.13	66.2
MTC compressor Work (W_comp_MTC) "kW"	56.87	59.72	62.66	65.71
LTC compressor Work (W_comp_LTC) "kW"	28.45	31.68	34.97	38.39
Q_Cond_HTC"kW"	177.8	186.7	195.9	205.5
Q_Cond_MTC"kW"	120.5	126.6	132.8	139.3

Q_ Cond _LTC“kW”	63.66	66.85	70.14	73.55
Q_EVA_LTC“kW”	35.167	35.167	35.167	35.167
First Law Efficiency COP_MTCascade	0.5576	0.5576	0.5576	0.5576
MTCascade Exergy Destruction Ratio (EDR)	1.662	1.662	1.662	1.662
MTCascade Exergetic Efficiency_HTC	0.3756	0.3756	0.3756	0.3756
MTCascade Exergy of Fuel	114.2	119.9	125.8	131.9
MTCascade Exergy of Product	42.88	45.03	47.25	49.54
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104
HTC Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674
HTC Exergetic Efficiency_HTC	0.5916	0.5916	0.5916	0.5916
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104
First Law Efficiency COP_MTC	1.119	1.119	1.119	1.119
First Law Efficiency COP_LTC	1.234	1.11	1.005	0.9161

Table 4(a): Effect of HTC condenser temperature (^oC) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at $T_{\_Cond\_HTC}=50^oC$ & Compressor efficiency$_{_HTC}$=80%,and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%,and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}=25^oC$, $T_{\_Cond}=50^oC$,$T_{\_Eva\_HTC}= - 20^oC$, $T_{\_Eva\_MTC=}$ - 95^oC , $T_{\_Eva\_LTC}= - 150^oC$, Approach_ $_{MTC}$_=10(^{o}C), Approach_ $_{LTC}$ =10(^{o}C),)*

HTC Condenser Temperature (^{o}C)	55	50	45	40	35	30
(COP_ $_{\text{Cascade three stages VCRS}}$)	0.2063	0.2153	0.2243	0.2333	0.2424	0.2515
(EDR_ $_{\text{Cascade three stages VCRS}}$)	2.411	2.268	2.137	2.016	1.903	1.798
Exergetic Efficiency $_{\text{Cascade three stages VCRS}}$	0.2932	0.3060	0.3187	0.3316	0.3444	0.3574
Exergy of Fuel_ $_{\text{Cascade three stages VCRS}}$ “kW”	170.5	163.3	156.8	150.7	145.1	139.8
Exergy of Product_ $_{\text{Cascade three stages VCRS}}$ “kW”	49.97	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	1.105	1.049	0.9999	0.9550	0.9141	0.8768
MTC Mass flow Rate (Kg/sec)	0.6267	0.6267	0.6267	0.6267	0.6267	0.6267
LTC Mass flow Rate (Kg/sec)	0.1882	0.1882	0.1882	0.1882	0.1882	0.1882
Q_Cond$_{_HTC}$“kW”	205.6	198.5	191.9	185.9	180.2	175.0
Q_Cond$_{_LTC}$“kW”	134.5.0	134.5.0	134.5.0	134.5.0	134.5.0	134.5.0
Q_EVA$_{_HTC}$“kW”	71.99	71.99	71.99	71.99	71.99	71.99
Q_ EVA $_{\_LTC}$“kW”	35.167	35.167	35.167	35.167	35.167	35.167
First Law Efficiency (COP$_{_MTCascade}$)	0.5387	0.5691	0.6002	0.6321	0.6650	0.6991
MTCascade Exergy Destruction Ratio (EDR)	1.756	1.609	1.474	1.349	1.232	1.124
MTCascade Exergetic Efficiency$_{_MTC}$	0.3625	0.3833	0.40640	0.4258	0.4484	0.4709
MTCascade Exergy of Fuel $_{\_MTC}$“kW”	133.6	126.5	120.0	113.9	108.3	103.0
MTCascade Exergy of Product $_{\_HTC}$“kW”	48.49	48.49	48.49	48.49	48.49	48.49
First Law Efficiency COP$_{_HTC}$	1.893	2.104	2.344	2.62	2.943	3.327
Exergy Destruction Ratio (EDR)	1.972	1.674	1.40	1.147	0.9112	0.6907
Exergetic Efficiency$_{_HTC}$	0.3365	0.3739	0.4166	0.4656	0.5232	0.5915
Exergy of Fuel $_{\_HTC}$“kW”	71.08	63.96	57.41	51.35	45.71	40.43
Exergy of Product $_{\_HTC}$“kW”	23.92	23.92	23.92	23.92	23.92	23.92
First Law Efficiency COP$_{_HTC}$	1.893	2.104	2.344	2.62	2.943	3.327
First Law Efficiency COP$_{_MTC}$	1.151	1.151	1.151	1.151	1.151	1.151
First Law Efficiency COP$_{_LTC}$	0.955	0.955	0.955	0.955	0.955	0.955

Table 4(b): Effect of HTC condenser temperature (^{o}C) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%,and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%,and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}=25^oC$,$T_{\_Eva\_HTC}= - 20^oC$, $T_{\_Eva\_MTC=}$ - 95^oC , $T_{\_Eva\_LTC}= - 150^oC$, Approach_ $_{MTC}$_=10(^{o}C), Approach_ $_{LTC}$ =10(^{o}C),)*

HTC condenser temperature (^{o}C)	50	45	40	35	30
First Law Efficiency (COP_ $_{\text{Cascade three stages VCRS}}$)	0.2187	0.2279	0.2371	0.2463	0.2557
Exergy Destruction Ratio (EDR_ $_{\text{Cascade three stages VCRS}}$)	2.217	2.088	1.968	1.857	1.752
Exergetic Efficiency $_{\text{Cascade three stages VCRS}}$	0.3108	0.3239	0.3369	0.3501	0.3633
Exergy of Fuel_ $_{\text{Cascade three stages VCRS}}$ “kW”	160.8	154.3	148.3	142.8	1375
Exergy of Product_ $_{\text{Cascade three stages VCRS}}$ “kW”	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	1.036	0.9870	0.9426	0.9023	0.8655
MTC Mass flow Rate (Kg/sec)	0.5539	0.5539	0.5539	0.5539	0.5539

LTC Mass flow Rate (Kg/sec)	0.2157	0.2157	0.2157	0.2157	0.2157
Q_Cond_HTC"kW"	195.9	189.5	183.5	177.9	172.7
Q_Cond_LTC"kW"	132.8	132.8	132.8	132.8	132.8
Q_EVA_HTC"kW"	70.14	70.14	70.14	70.14	70.14
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167
First Law Efficiency COP _MTCascade	0.5576	0.5876	0.6188	0.6508	0.6508
Cascaded_MTC Exergy Destruction Ratio (EDR)	1.662	1.526	1.399	1.281	1.171
Cascaded_MTC Exergetic Efficiency_MTC	0.3756	0.3959	0.4168	0.4384	0.4608
Cascaded_MTC Exergy of Fuel _HTC"kW"	125.8	119.3	113.3	107.8	102.6
Cascaded_MTC Exergy of Product _HTC"kW"	47.25	47.25	47.25	47.25	47.25
First Law Efficiency COP _HTC	2.104	2.340	2.62	2.943	3.327
HTC Exergy Destruction Ratio (EDR)	1.674	1.40	1.147	0.9112	0.6907
HTC Exergetic Efficiency_HTC	0.373	0.4160	0.4650	0.5230	0.5510
HTC Exergy of Fuel _HTC"kW"	63.13	56.66	50.68	45.12	39.91
HTC Exergy of Product _HTC"kW"	23.61	23.61	23.61	23.61	23.61
First Law Efficiency COP_MTC	1.119	1.119	1.119	1.119	1.119
First Law Efficiency COP_LTC	1.005	1.005	1.005	1.005	1.005

Table 5(a): Effect of HTC Evaporator *temperature* (ºC) on *thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency*$_{HTC}$*=80%,and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency*$_{MTC}$*=80%,and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency*$_{LTC}$*=80%,and Q*$_{Eva}$*=35.167 kW, T*$_{Cond}$*=50ºC ,T*$_{ambient}$*=25ºC,T*$_{Eva\_HTC}$*= - 30ºC, T*$_{Eva\_MTC}$*= - 95ºC , T*$_{Eva\_LTC}$*= - 150ºC, Approach_* $_{MTC}$*_=10(ºC), Approach_* $_{LTC}$ *=10(ºC),)*

HTC Evaporator Temp(ºC)	-20	-15	-10	-5	0	+5	+10
First Law Efficiency (COP_ $_{\text{Cascade three stages VCRS}}$)	0.2153	0.2135	0.2106	0.2067	0.2017	0.1956	0.1884
(EDR_ $_{\text{Cascade three stages VCRS}}$)	2.268	2.294	2.341	2.405	2.489	2.598	2.736
Exergetic Efficiency $_{\text{Cascade three stages VCRS}}$	0.3060	0.3033	0.2993	0.2936	0.2866	0.278	0.2677
Exergy of Fuel_ $_{\text{Cascade three stages VCRS}}$ "kW"	163.3	164.7.7	167.0	170.1	174.3	179.8	186.7
Exergy of Product_ $_{\text{Cascade three stages VCRS}}$ "kW"	49.97	49.97	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	1.049	1.067	1.089	1.115	1.145	1.182	1.226
MTC Mass flow Rate (Kg/sec)	0.6267	0.6579	0.693	0.7327	0.778	0.8302	0.891
LTC Mass flow Rate (Kg/sec)	0.1882	0.1882	0.1882	0.1882	0.1882	0.1882	0.1882
Q_Cond_HTC"kW"	198.5	199.9	202.1	205.3	209.5	214.9	221.8
Q_Cond_MTC"kW"	134.5	140.7	147.4	154.8	163.2	172.6	183.5
Q_ Cond _LTC"kW"	71.99	71.99	71.99	71.99	71.99	71.99	71.99
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
HTC Compressor Work ($W_{\_Comp\_HTC}$) 'kW"	63.96	59.25	54.77	50.47	46.33	42.31	38.38
MTC Compressor Work ($W_{\_Comp\_MTC}$) 'kW"	62.55	68.66	75.39	82.85	91.20	100.6	111.5
LTC Compressor Work ($W_{\_Comp\_LTC}$) 'kW"	36.83	36.83	36.83	36.83	36.83	36.83	36.83
First Law Efficiency COP_MTCascade	0.5691	0.5628	0.5531	0.540	0.5235	0.5036	0.4804
Cascade Exergy Destruction Ratio ($EDR_{\_Cascade}$)	1.609	1.638	1.684	1.749	1.836	1.948	2.09
Cascade Exergetic Efficiency$_{_MTCascade}$	0.3833	0.3791	0.3726	0.3638	0.3526	0.3392	0.3236
Cascade Exergy of Fuel _HTC"kW"	126.5	127.9	130.2	133.3	137.5	143.0	149.9
Cascade Exergy of Product "kW"	48.49	48.49	48.49	48.49	48.49	48.49	48.49
First Law Efficiency (COP_HTC)	2.104	2.374	2.691	3.068	3.523	4.08	4.78
Exergy Destruction Ratio ($EDR_{\_HTC}$)	1.674	1.719	1.794	1.794	2.102	2.408	2.949
Exergetic Efficiency_HTC	0.3739	0.3678	0.3579	0.3132	0.3224	0.2934	0.2532
Exergy of Fuel _HTC	63.96	59.25	54.77	50.47	46.33	42.31	38.38
HTC Exergy of Product	23.92	21.79	19.60	17.32	14.94	12.41	9.719
First Law Efficiency COP_HTC	2.104	2.374	2.691	3.068	3.523	4.08	4.78
First Law Efficiency COP_MTC	1.151	1.048	0.955	0.869	0.7894	0.7153	0.6458
First Law Efficiency COP_LTC	0.955	0.955	0.955	0.955	0.955	0.955	0.955

Table 5(b): Effect of HTC Evaporator *temperature* (°C) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency_HTC=80%,and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency_MTC=80%,and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency_LTC=80%,and Q_Eva=35.167 kW, T_Cond=50°C ,T_ambient=25°C,T_Eva_HTC= - 20°C, T_Eva_MTC= - 95°C , T_Eva_LTC= - 150°C, Approach_ MTC_=10(°C), Approach_ LTC =10(°C),)*

HTC Evaporator Temp(°C)	-30	-25	-20	-15	-10	-5	-0	+5	+10	+15	+20
(COP_ Cascade three stages VCRS)	0.2608	0.2587	0.2557	0.2517	0.2467	0.2407	0.2338	0.2289	0.2171	0.2073	0.1966
(EDR_ Cascade three stages VCRS)	1.698	1.72	1.752	1.796	1.853	1.923	2.01	2.115	2.241	2.395	2.58
Exergetic Efficiency Cascade three stages VCRS	0.3706	0.3676	0.3633	0.3576	0.3505	0.3421	0.3323	0.3211	0.3085	0.2946	0.2793
Fuel Exergy_ Cascade three stages VCRS "kW"	134.8	135.9	137.5	139.7	142.6	146.1	150.4	155.7	162.0	169.6	178.9
Exergy of Product_ Cascade three stages VCRS	49.97	49.97	49.97	49.97	49.97	49.97	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339	0.8339
MTC Mass flow Rate (Kg/sec)	0.5055	0.5286	0.5539	0.5819	0.6129	0.6475	0.6864	0.7304	0.7807	0.8386	0.9062
LTC Mass flow Rate (Kg/sec)	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157	0.2157
Q_Cond_HTC"kW"	170.0	171.1	172.7	174.9	177.7	181.2	185.6	190.8	197.2	204.8	214.1
Q_Cond_MTC"kW"	122.0	127.2	132.8	138.9	145.5	152.8	160.8	169.9	180.0	191.6	205.0
Q_ Cond _LTC"kW"	70.14	70.14	70.14	70.14	70.14	70.14	70.14	70.14	70.14	70.14	70.14
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167
Comp Work (W_Comp_HTC) 'kW"	48.0	43.89	39.91	36.03	32.23	28.47	24.72	20.96	17.14	13.2	9.098
Compressor Work _MTC) 'kW"	51.87	57.06	62.66	68.73	75.36	82.64	90.7	99.71	109.9	121.5	134.8
Comp Work (W_Comp_LTC) 'kW"	34.97	34.97	34.97	34.97	34.97	34.97	34.97	34.97	34.97	34.97	34.97
COP_MTCascade	0.7023	0.6948	0.6838	0.6695	0.652	0.6313	0.6077	0.5812	0.5522	0.5209	0.4873
(EDRCascade_MTC)	1.114	1.137	1.171	1.217	1.853	1.352	1.443	1.554	1.688	1.850	2.045
Cascade Exergetic Efficiency_MTCascade	0.4731	0.4680	0.4606	0.4510	0.4392	0.4252	0.4093	0.3915	0.3720	0.3508	0.3283
Cascade Exergy of Fuel _HTC "kW"	99.87	101.0	102.6	104.8	107.6	111.10	115.4	120.7	127.0	134.7	143.9
Cascade Exergy of Product "kW"	47.25	47.25	47.25	47.25	47.25	47.25	47.25	47.25	47.25	47.25	47.25
First Law Efficiency (COP_HTC)	2.542	2.894	3.327	3.854	4.515	5.367	6.506	8.103	10.5	14.51	22.53
(EDR_HTC)	0.7392	0.7125	0.6907	0.6745	0.6653	0.6655	0.6795	0.7163	0.7971	0.9859	1.602
Exergetic Efficiency_HTC	0.5750	0.5839	0.5915	0.5972	0.6005	0.6004	0.5954	0.5827	0.5564	0.5036	0.3843
Exergy of Fuel _HTC	48.0	43.89	39.91	36.03	32.23	28.47	24.72	20.96	17.14	13.2	9.098
HTC Exergy of Product	27.6	25.63	23.61	21.52	19.35	17.09	14.72	12.21	9.536	6.649	3.496
First Law Efficiency COP_HTC	2.542	2.894	3.327	3.854	4.515	5.367	6.506	8.103	10.50	14.51	22.53
First Law Efficiency COP_MTC	1.352	1.229	1.119	1.021	0.9308	0.8488	0.7733	0.7034	0.6384	0.5775	0.5202
First Law Efficiency COP_LTC	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005

Table 6: Effect of MTC Evaporator temperature (°C) on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency_HTC=80%,and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency_MTC=80%,and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency_LTC=80%,and Q_Eva=35.167 kW,T_ambient=25°C,T_Eva_HTC= - 20°C, T_Eva_MTC= - 95°C , T_Eva_LTC= - 150°C, Approach_ MTC_=10(°C), Approach_ LTC =10(°C),)

MTC Evaporator Temperature (°C)	-95	-90	-85	-80	-75
First Law Efficiency (COP_ Cascade three stages VCRS)	0.2153	0.2156	0.2154	0.2145	0.213
Exergy Destruction Ratio (EDR_ Cascade three stages VCRS)	2.268	2.263	2.268	2.281	2.304
Exergetic Efficiency Cascade three stages VCRS	0.3060	0.3064	0.3060	0.3048	0.3027
Exergy of Fuel_ Cascade three stages VCRS "kW"	163.3	163.1	163.3	164.0	165.1
Exergy of Product_ Cascade three stages VCRS "kW"	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	1.049	1.048	1.459	1.053	1.059
MTC Mass flow Rate (Kg/sec)	0.6267	0.6459	0.6655	0.6856	0.7063
LTC Mass flow Rate (Kg/sec)	0.1882	0.1882	0.1882	0.1882	0.1882
Q_Cond_HTC"kW"	198.5	198.2	198.5	199.1	200.3
Q_Cond_LTC"kW"	134.5	134.4	134.5	135.0	135.7
Q_EVA_HTC"kW"	71.99	75.81	79.81	84.01	88.42
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167
First Law Efficiency (COP_MTCascade)	0.5691	0.6192	0.6727	0.7297	0.7904
MTCascade Exergy Destruction Ratio (EDR)	1.609	1.572	1.543	1.521	1.507
MTCascade Exergetic Efficiency_MTC	0.3833	0.3888	0.3933	0.3967	0.3989
MTCascade Exergy of Fuel _MTC"kW"	126.5	122.40	118.6	115.1	111.9
MTCascade Exergy of Product _HTC"kW"	48.49	47.60	46.66	45.67	44.62
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104	2.104

Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674	1.674
Exergetic Efficiency_HTC	0.3739	0.3739	0.3739	0.3739	0.3739
Exergy of Fuel _HTC"kW"	63.96	63.87	63.94	64.16	64.53
Exergy of Product _HTC"kW"	23.92	23.89	23.91	23.99	24.13
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104	2.104
First Law Efficiency COP_MTC	1.151	1.295	1.459	1.648	1.864
First Law Efficiency COP_LTC	0.955	0.8652	0.7877	0.7201	0.6604

Table 7: Effect of MTC Evaporator *temperature* (ºC) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%,and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%,and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 20ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach$_{_MTC_}$=10(ºC), Approach$_{_LTC}$ =10(ºC),)*

MTC Evaporator Temp(ºC)	-100	-95	-90	-85	-80	-75	-70
First Law Efficiency (COP_ Cascade three stages VCRS)	0.2522	0.2557	0.2583	0.2602	0.2612	0.2613	0.2606
Exergy Destruction Ratio (EDR_ Cascade three stages VCRS)	1.791	1.752	1.724	1.705	1.695	1.693	1.701
Exergetic Efficiency Cascade three stages VCRS	0.3583	0.3633	0.3671	0.3697	0.3711	0.3713	0.3703
Exergy of Fuel_ Cascade three stages VCRS "kW"	139.5	137.5	136.1	135.2	134.7	134.6	135.0
Exergy of Product_ Cascade three stages VCRS "kW"	49.97	49.97	49.97	49.97	49.97	49.97	49.97
HTC compressor Work (W_Comp_HTC)"kW"	40.35	39.91	39.58	39.36	39.24	39.23	39.31
Wompressor Work (W_Comp_MTC)"kW"	67.43	62.66	58.15	53.87	49.79	45.88	42.12
LTC compressor Work (W_Comp_LTC)"kW"	31.68	34.97	38.39	41.93	45.62	49.48	53.53
HTC Mass flow Rate (Kg/sec)	0.8753	0.8584	0.8584	0.8536	0.851	0.8507	0.8526
MTC Mass flow Rate (Kg/sec)	0.5410	0.5669	0.5669	0.5801	0.5935	0.6073	0.6216
LTC Mass flow Rate (Kg/sec)	0.2104	0.2215	0.2215	0.2276	0.2342	0.2414	0.2491
Q_Cond_HTC"kW"	174.6	172.7	171.3	170.3	169.8	169.8	170.1
Q_Cond_MTC"kW"	134.3	132.8	131.7	131.0	130.6	130.5	130.8
Q_ Cond _LTC"kW"	66.85	70.14	70.14	70.14	70.14	70.14	70.14
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law Efficiency COP_MTCascade	0.6202	0.6838	0.7526	0.7526	0.9074	0.9946	1.089
Cascaded Exergy Destruction Ratio (EDR_MTC)	1.233	1.171	1.116	1.068	1.027	0.9922	0.9631
Cascaded Exergetic Efficiency_MTC	0.4477	0.4606	0.4725	0.4834	0.4933	0.5019	0.5094
Cascaded Exergy of Fuel _MTC"kW"	107.8	102.6	97.74	93.24	89.03	85.11	81.43
Cascaded Exergy of Product _MTC"kW"	48.26	47.25	46.18	45.07	43.92	42.72	41.48
First Law Efficiency COP_HTC	3.327	3.327	3.327	3.327	3.327	3.327	3.327
Exergy Destruction Ratio (EDR)	0.6907	0.6907	0.6907	0.6907	0.6907	0.6907	0.6907
Exergetic Efficiency_HTC	0.5915	0.5915	0.5915	0.5915	0.5915	0.5915	0.5915
Exergy of Fuel _HTC"kW"	40.35	39.91	39.58	39.36	39.24	39.23	39.31
Exergy of Product _HTC"kW"	23.67	23.61	23.41	23.26	23.21	23.20	23.25
First Law Efficiency COP _HTC	3.327	3.327	3.327	3.327	3.327	3.327	3.327
First Law Efficiency COP_LTC	0.9914	1.119	1.265	1.431	1.623	1.845	2.106
First Law Efficiency COP _HTC	1.11	1.005	0.9161	0.8387	0.7708	0.7107	0.6569

3.7 Effect of LTC Evaporator temperature (ºC) on thermodynamic performances of cascaded vapour compression systems performances using HCFO and HFO refrigerants in have ultra-low GWP for ultra-low temperature of -150ºC

The effect of LTC evaporator temperature (ºC) on the thermodynamic performances (in terms of COP$_{_Cascaded_VCRS_Three_Stages}$ and Exergetic Efficiency$_{_Cascaded_VCRS_Three_Stages}$) have been shown in Table-8 respectively. It was found that when the LTC evaporator temperature (ºC) is increasing, thermodynamic performance of three stages cascaded vapour compression refrigeration is increasing while first law efficiency of ultra-low temperature cycle is increasing

Table 8: Effect of LTC Evaporator *temperature* (ºC) *on thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%,and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%,and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and Q$_{_Eva}$=35.167 kW,T$_{_Cond}$=50ºC, T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 20ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach_ $_{MTC\_}$=10(ºC), Approach_ $_{LTC}$ =10(ºC),)*

LTC Evaporator Temp(ºC)	-155	-150	-145	-140	-135	-130	-125	-120
First Law Efficiency (COP_ $_{Cascade\ three\ stages\ VCRS}$)	0.1967	0.2187	0.2416	0.2652	0.2895	0.3143	0.3397	0.3655
Exergy Destruction Ratio (EDR_ $_{Cascade\ three\ stages\ VCRS}$)	2.337	2.217	2.12	2.042	1.983	1.938	1.908	1.890
Exergetic Efficiency $_{Cascade\ three\ stages\ VCRS}$	0.2927	0.3108	0.3205	0.3287	0.3353	0.3403	0.3439	0.3460
Exergy of Fuel_ $_{Cascade\ three\ stages\ VCRS}$ "kW"	178.8	160.8	145.5	132.6	121.5	111.9	103.5	96.22
Exergy of Product_ $_{Cascade\ three\ stages\ VCRS}$ "kW"	53.58	49.97	46.65	3.584	40.73	38.08	35.61	33.3
HTC Mass flow Rate (Kg/sec)	1.131	1.036	0.9554	0.8869	0.8282	0.7775	0.7333	0.6947
MTC Mass flow Rate (Kg/sec)	0.6069	0.5539	0.5109	0.4743	0.4429	0.4157	0.3921	0.3714
LTC Mass flow Rate (Kg/sec)	0.2180	0.2157	0.2134	0.2110	0.2086	0.2062	0.2037	0.2012
HTC Compressor Work "kW"	68.94	63.13	58.23	54.05	50.47	47.38	44.69	42.33
MTC Compressor Work "kW"	68.43	62.66	57.79	53..65	50.10	47.03	44.36	42.02
LTC Compressor Work "kW"	41.43	34.97	29.53	24.89	20.91	17.47	14.49	11.87
Q_Cond_HTC"kW"	214.0	195.9	180.7	167.8	156.6	147.0	138.7	131.4
Q_Cond_MTC"kW"	145.0	132.8	122.5	113.7	106.2	99.67	94.01	89.05
Q_EVA_LTC"kW"	76.59	70.14	64.69	60.05	56.08	52.64	49.65	47.04
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167
Cascade First Law Efficiency COP_$_{MTC}$	0.5576	0.5576	0.5576	0.5576	0.5576	0.5576	0.5576	0.5576
Cascade Exergy Destruction Ratio (EDR)	1.652	1.662	1.652	1.652	1.652	1.652	1.652	1.652
Cascade Exergetic Efficiency_HTC	0.3756	0.3756	0.3756	0.3756	0.3756	0.3756	0.3756	0.3756
Cascade Exergy of Fuel _HTC"kW"	137.4	137.4	116.0	107.7	100.6	94.41	89.05	84.35
Cascade Exergy of Product _HTC"kW"	51.59	49.97	43.58	40.45	37.77	35.46	33.45	31.68
HTC First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104	2.104	2.104	2.104	2.104
HTC Exergy Destruction Ratio (EDR)	1.674	1.674	1.674	1.674	1.674	1.674	1.674	1.674
HTC Exergetic Efficiency_HTC	0.3739	0.3739	0.3739	0.3739	0.3739	0.3739	0.3739	0.3739
HTC Exergy of Fuel _HTC"kW"	68.94	63.13	58.23	54.05	50.47	47.38	44.69	42.33
HTC Exergy of Product _HTC"kW"	25.78	23.61	21.77	20.21	18.87	17.12	17.12	15.83
First Law Efficiency COP_HTC	2.104	2.104	2.104	2.104	2.104	2.104	2.104	2.104
First Law Efficiency COP_MTC	1.119	1.119	1.119	1.119	1.119	1.119	1.119	1.119
First Law Efficiency COP_LTC	0.8489	1.005	1.191	1.413	1.682	2.012	2.428	2.963

3.8 Comparison of systems performances by changing different HCFO & HCFO refrigerants in high temperature cycle of cascaded three staged vapour compression systems performances using HCFO and HFO refrigerants have ultra-low GWP for ultra-low temperature of -135ºC

The following three stages cascaded vapour compression refrigeration systems have been evaluated using HCFO and HFO refrigerants for ultra-low temperature applications

System-1: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$= 80%, and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$ = 80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC, T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach_ $_{MTC\_}$=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-2: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1243zf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%,and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach_ $_{MTC\_}$=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-3: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234ze(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach_ $_{MTC\_}$=10(ºC), Approach_ $_{LTC}$ =10(ºC),).

System-4: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1224yd(Z) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach$_{_MTC_}$=10(ºC), Approach$_{_LTC}$ =10(ºC),)

System-5: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234yf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1336mzz(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%,and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach$_{_MTC_}$=10(ºC), Approach$_{_LTC}$ =10(ºC),)

The effect of HFO & HCFO refrigerants on the thermodynamic performances have been shown in Table-9(a) respectively. It was found that the thermodynamic performances (energy performance (COP$_{_cascaded\ three\ stages}$) of three stages cascaded vapour compression refrigeration is is highest while first law energy efficiency (COP$_{_Cascade\ three\ stages}$) is lowest Similarly Exergetic efficiency of cascaded three stage system is highest and lowest for system-5.

Table 9(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, T_Cond=50ºC, T_ambient=25ºC,T$_{_Eva_HTC}$= - 10ºC, Compressor efficiency$_{_HTC}$=80%, T$_{_Eva_MTC}$= - 95ºC, Compressor efficiency$_{_MTC}$=80% ,T$_{_Eva_LTC}$= - 135ºC, Compressor efficiency$_{_LTC}$=80%)

Performance Parameters	System-1	System-2	System-3	System-4	System-5
First Law Efficiency (COP$_{_ Cascade\ three\ stages\ VCRS}$)	0.2992	0.2880	0.2878	0.2965	0.2785
Exergy Destruction Ratio (EDR$_{_ Cascade\ three\ stages\ VCRS}$)	1.886	1.998	2.0	1.913	2.10
Exergetic Efficiency$_{Cascade\ three\ stages\ VCRS}$	0.3465	0.3335	0.3334	0.3433	0.3226
Exergy of Fuel$_{_ Cascade\ three\ stages\ VCRS}$ "kW"	117.5	122.1	122.2	118.6	126.3
Exergy of Product$_{_ Cascade\ three\ stages\ VCRS}$ "kW"	40.73	40.73	40.73	40.73	40.73
HTC Mass flow Rate (Kg/sec)	0.8226	0.9351	1.043	0.9942	1.283
MTC Mass flow Rate (Kg/sec)	0.5255	0.5255	0.5255	0.5255	0.5255
LTC Mass flow Rate (Kg/sec)	0.2325	0.2325	0.2325	0.2325	0.2325
HTC compressor work (kW)	41.37	45.94	46.01	42.46	50.08
MTC compressor work (kW)	44.5	44.5	44.5	44.5	44.5
LTC compressor work (kW)	31.67	31.67	31.67	31.67	31.67
Q_Cond_HTC"kW"	152.7	157.3	157.3	153.8	161.4
Q_Cond_LTC"kW"	113.3	113.3	113.3	113.3	113.3
Q_EVA_HTC"kW"	66.84	66.84	66.84	66.84	66.84
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167
First Law Efficiency COP_LTC	1.11	1.11	1.11	1.11	1.11
First Law Efficiency COP_MTC	1.502	1.502	1.502	1.502	1.502
First Law Efficiency COP_HTC	2.691	2.424	2.42	2.622	2.223
Exergy Destruction Ratio (EDR)	1.794	2.102	2.107	1.867	2.382
Exergetic Efficiency_HTC	0.3579	0.3223	0.3219	0.3488	0.2957
Exergy of Fuel _HTC"kW"	41.37	45.94	46.01	42.46	50.08
Exergy of Product _HTC"kW"	14.81	14.81	14.81	14.81	14.81
First Law Efficiency COP$_{_ MTCascade}$	0.7783	0.7390	0.7385	0.7686	0.7066
Exergy Destruction Ratio (EDR)	1.546	1.681	1.683	1.578	1.804
Exergetic Efficiency_ MTCascade	0.3928	0.3730	0.3727	0.3879	0.3566
Exergy of Fuel _ MTCascade "kW"	85.67	90.44	90.51	86.96	94.58
Exergy of Product _ MTCascade "kW"	33.73	33.73	33.73	33.73	33.73

3.9 Comparison of systems performances by changing different HCFO & HCFO refrigerants in high temperature cycle of cascaded three staged vapour compression systems using different HCFO and HFO refrigerants in HFO refrigerants in lower temperature cycle (LTC) have ultra-low GWP for ultra-low temperature of -135ºC

The following three stages cascaded vapour compression refrigeration systems have been evaluated using HCFO and HFO refrigerants for ultra-low temperature applications

System-6: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HCFO-1233zd(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25ºC,T$_{_Eva_HTC}$= - 30ºC, T$_{_Eva_MTC=}$ - 95ºC , T$_{_Eva_LTC}$= - 150ºC, Approach$_{_MTC_}$=10(ºC), Approach$_{_LTC}$ =10(ºC),) *System-7:* cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1243zf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$ =80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25^{o}C, T$_{_Eva_HTC}$= - 30^{o}C, T$_{_Eva_MTC=}$ - 95^{o}C , T$_{_Eva_LTC}$= - 150^{o}C, Approach$_{_MTC_}$=10(^{o}C), Approach$_{_LTC}$ =10(^{o}C),)

System-8: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234ze(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25^{o}C, T$_{_Eva_HTC}$= - 30^{o}C, T$_{_Eva_MTC=}$ - 95^{o}C , T$_{_Eva_LTC}$= - 135^{o}C, Approach$_{_MTC_}$=10(^{o}C), Approach$_{_LTC}$ =10(^{o}C),)

System-9: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1224yd(Z) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25^{o}C, T$_{_Eva_HTC}$= - 30^{o}C, T$_{_Eva_MTC=}$ - 95^{o}C , T$_{_Eva_LTC}$= - 150^{o}C, Approach$_{_MTC_}$=10(^{o}C), Approach$_{_LTC}$ =10(^{o}C),)

System-10: Cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234yf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HFO-1225ye(Z) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z)in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and Q$_{_Eva}$=35.167 kW,T$_{_ambient}$=25^{o}C,T$_{_Eva_HTC}$= - 30^{o}C, T$_{_Eva_MTC=}$ - 95^{o}C , T$_{_Eva_LTC}$= - 150^{o}C, Approach$_{_MTC_}$=10(^{o}C), Approach$_{_LTC}$ =10(^{o}C),)

The effect of HFO & HCFO refrigerants on the thermodynamic performances have been shown in Table-9(b) respectively. It was found that the thermodynamic performances (energy performance (COP$_{_cascaded\ three\ stages}$) of three stages cascaded vapour compression refrigerationsystem-6 is highest while first law energy efficiency (COP$_{_Cascade\ three\ stages}$) is lowest Similarly Exergetic efficiency of cascaded three stage system is highest and lowest for system-10.

Table 9(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, T_Cond=50^{o}C, T_ambient=25^{o}C, , T_Cond=50^{o}CT_ambient=25^{o}C,T$_{_Eva_HTC}$= - 10^{o}C, Compressor efficiency$_{_HTC}$=80%, T$_{_Eva_MTC}$= - 95^{o}C, Compressor efficiency$_{_MTC}$=80% ,T$_{_Eva_LTC}$= - 135^{o}C, Compressor efficiency$_{_LTC}$=80%)

Performance Parameters	System6	System7	System-8	System9	System10
First Law Efficiency (COP$_{_\ Cascade\ three\ stages\ VCRS}$)	0.2913	0.2805	0.2803	0.2887	0.2713
Exergy Destruction Ratio (EDR$_{_\ Cascade\ three\ stages\ VCRS}$)	1.964	2.078	2.080	1.991	2.182
Exergetic Efficiency$_{Cascade\ three\ stages\ VCRS}$	0.3374	0.3249	0.3247	0.3343	0.3142
Exergy of Fuel$_{_\ Cascade\ three\ stages\ VCRS}$ “kW”	120.7	125.4	125.4	121.8	129.6
Exergy of Product$_{_\ Cascade\ three\ stages\ VCRS}$ “kW”	40.73	40.73	40.73	40.73	40.73
HTC Mass flow Rate (Kg/sec)	0.8397	0.8397	0.8397	0.8397	0.8397
MTC Mass flow Rate (Kg/sec)	0.5997	0.5997	0.5997	0.5997	0.5997
LTC Mass flow Rate (Kg/sec)	0.2065	0.2065	0.2065	0.2065	0.2065
HTC compressor work (kW)	41.37	45.94	46.01	42.46	50.08
MTC compressor work (kW)	44.5	44.5	44.5	44.5	44.5
LTC compressor work (kW)	31.67	31.67	31.67	31.67	31.67
Q_Cond_HTC“kW”	155.9	160.5	160.6	157.0	164.8
Q_Cond_LTC“kW”	113.7	113.7	113.7	113.7	113.7
Q_EVA_HTC“kW”	68.49	68.49	68.49	68.49	68.49
Q_ EVA _LTC“kW”	35.167	35.167	35.167	35.167	35.167
First Law Efficiency COP_LTC	1.055	1.055	1.055	1.055	1.055
First Law Efficiency COP_MTC	1.516	1.516	1.516	1.516	1.516
First Law Efficiency COP_HTC	2.691	2.424	2.42	2.622	2.223
Exergy Destruction Ratio (EDR)	1.794	2.102	2.107	1.867	2.382
Exergetic Efficiency_HTC	0.3579	0.3223	0.3219	0.3488	0.2957
Exergy of Fuel _HTC“kW”	42.23	42.23	42.23	42.23	42.23
Exergy of Product _HTC“kW”	15.12	15.12	15.12	15.12	15.12
First Law Efficiency COP$_{_\ MTCascade}$	0.7856	0.7439	0.7434	0.7738	0.7112
Exergy Destruction Ratio (EDR)	1.529	1.664	1.665	1.561	1.786
Exergetic Efficiency_ MTCascade	0.3955	0.3754	0.3752	0.3905	0.3589
Exergy of Fuel _ MTCascade “kW”	87.4	92.06	92.13	88.50	96.29
Exergy of Product _ MTCascade “kW”	34.56	34.56	34.56	34.56	34.56

3.10 Comparison of systems performances by changing different HCFO & HCFO refrigerants in high temperature cascaded three staged vapour compression systems using different HCFO and HFO refrigerants in HFO refrigerants in lower temperature cycle (LTC) have ultra-low GWP for ultra-low temperature of -150ºC

The following three stages cascaded vapour compression refrigeration systems have been evaluated using HCFO and HFO refrigerants for ultra-low temperature applications

System-11: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1225ye(Z) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-12: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1336mzz(Z) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-13: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234ze(E) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-14: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1243zf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC, $T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-15: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1224yd(Z) in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z) in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC, $T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-16: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234yf in high temperature circuit (HTC) at Compressor efficiency$_{_HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency$_{_MTC}$=80%, and HFO-1336mzz(Z)in low temperature circuit (LTC) at Compressor efficiency$_{_LTC}$=80%, and $Q_{\_Eva}$=35.167 kW,$T_{\_ambient}$=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, $T_{\_Eva\_MTC=}$ - 75ºC , $T_{\_Eva\_LTC}$= - 135ºC, Approach_$_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

The effect of HFO & HCFO refrigerants on the thermodynamic performances have been shown in Table-10(a) respectively. It was found that the thermodynamic performances (energy performance ($COP_{\_cascaded\ three\ stages}$) of three stages cascaded vapour compression refrigeration system-12 is highest while first law energy efficiency ($COP_{\_Cascade\ three\ stages}$) is lowest Similarly Exergetic efficiency of cascaded three stage system is highest and lowest for system-16.

Table 10(a): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, T_Cond=50ºC,T_ambient=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, Compressor efficiency$_{_HTC}$=80%, $T_{\_Eva\_MTC}$= - 95ºC, Compressor efficiency$_{_MTC}$=80% ,$T_{\_Eva\_LTC}$= - 135ºC, Compressor efficiency$_{_LTC}$=80%)

Performance Parameters	System11	System12	System-13	System14	System15	System16
First Law Efficiency ($COP_{\_Cascade\ three\ stages\ VCRS}$)	0.2821	0.2996	0.2840	0.2842	0.2925	0.2749
Exergy Destruction Ratio ($EDR_{\_Cascade\ three\ stages\ VCRS}$)	2.060	1.882	2.040	2.038	1.952	2.141
Exergetic Efficiency $_{Cascade\ three\ stages\ VCRS}$	0.3268	0.3470	0.3289	0.3291	0.3387	0.3183
Exergy of Fuel$_{_Cascade\ three\ stages\ VCRS}$ "kW"	124.6.5	117.4	123.8	123.8	120.2	127.9
Exergy of Product$_{_Cascade\ three\ stages\ VCRS}$ "kW"	40.73	40.73	40.73	40.73	40.73	40.73
HTC Mass flow Rate (Kg/sec)	1.247	0.9862	1.057	0.9449	1.0005	1.296
MTC Mass flow Rate (Kg/sec)	0.4497	0.4389	0.4497	0.4497	0.4497	0.4497
LTC Mass flow Rate (Kg/sec)	0.2065	0.2325	0.2065	0.2065	0.2065	0.2065
HTC compressor work (kW)	41.31	42.75	46.49	46.42	42.9	50.61

MTC compressor work (kW)	44.02	42.95	44.02	44.02	44.02	44.02
LTC compressor work (kW)	31.32	31.67	33.32	33.32	33.32	33.32
Q_Cond_HTC“kW”	159.8	152.5	159.0	158.9	155.4	163.1
Q_Cond_LTC“kW”	112.5	109.8	112.5	112.5	112.5	112.5
Q_EVA_HTC“kW”	68.49	68.49	68.49	68.49	68.49	68.49
Q_ EVA _LTC“kW”	35.167	35.167	35.167	35.167	35.167	35.167
First Law Efficiency COP_LTC	1.055	1.11	1.055	1.055	1.055	1.055
First Law Efficiency COP_MTC	1.556	1.556	1.556	1.556	1.556	1.556
First Law Efficiency COP_HTC	2.378	2.568	2.42	2.424	2.622	2.223
Exergy Destruction Ratio (EDR)	2.162	1.928	2.107	2.102	1.867	2.382
Exergetic Efficiency_HTC	0.3268	0.3416	0.3219	0.3223	0.3488	0.2957
Exergy of Fuel _HTC“kW”	47.3	42.75	46.49	46.42	42.9	50.61
Exergy of Product _HTC“kW”	14.96	14.60	14.96	14.96	14.96	14.96
First Law Efficiency COP_ $_{MTCascade}$	0.7499	0.7798	0.7567	0.7573	0.788	0.7238
Exergy Destruction Ratio (EDR)	1.642	1.541	1.618	1.617	1.515	1.738
Exergetic Efficiency_ MTCascade	0.3785	0.3936	0.3819	0.3822	0.3977	0.3653
Exergy of Fuel _ MTCascade “kW”	91.32	85.71	90.5	90.44	86.92	94.62
Exergy of Product _ MTCascade “kW”	34.56	33.73	34.56	34.56	34.56	34.56

3.11 Comparison of systems performances by changing different HCFO & HCFO refrigerants in high temperature cascaded three staged vapour compression systems using different HCFO and HFO refrigerants in HFO refrigerants in lower temperature cycle (LTC) have ultra-low GWP for ultra-low temperature of -135ºC.

The following three stages cascaded vapour compression refrigeration systems have been evaluated using HCFO and HFO refrigerants for ultra-low temperature applications

System-17: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234ze(E) in high temperature circuit (HTC) at Compressor efficiency_$_{HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency_$_{MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency_$_{LTC}$=80%, and Q_$_{Eva}$=35.167 kW,T_$_{ambient}$=25ºC, T_$_{Eva_HTC}$= - 10ºC, T_$_{Eva_MTC=}$ - 75ºC , T_$_{Eva_LTC}$= - 135ºC, Approach_ $_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-18: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1243zf in high temperature circuit (HTC) at Compressor efficiency_$_{HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency_$_{MTC}$=80%, and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency_$_{LTC}$=80%, and Q_$_{Eva}$=35.167 kW,T_$_{ambient}$=25ºC,T_$_{Eva_HTC}$= - 10ºC, T_$_{Eva_MTC=}$ - 75ºC , T_$_{Eva_LTC}$= - 135ºC, Approach_ $_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-19: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1224yd(Z) in high temperature circuit (HTC) at Compressor efficiency_$_{HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency_$_{MTC}$=80%, and) HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency_$_{LTC}$=80%,and Q_$_{Eva}$=35.167 kW,T_$_{ambient}$=25ºC, T_$_{Eva_HTC}$= - 10ºC, T_$_{Eva_MTC=}$ - 75ºC , T_$_{Eva_LTC}$= - 135ºC, Approach_ $_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)

System-20: cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants HFO-1234yf in high temperature circuit (HTC) at Compressor efficiency_$_{HTC}$=80%, and HCFO-1233zd(E) in medium temperature circuit (MTC) at Compressor efficiency_$_{MTC}$=80% and HFO-1225ye(Z) in low temperature circuit (LTC) at Compressor efficiency_$_{LTC}$=80%, and Q_$_{Eva}$=35.167 kW,T_$_{ambient}$=25ºC,T_$_{Eva_HTC}$= -10ºC, T_$_{Eva_MTC}$ $_{=}$+++-75ºC, T_$_{Eva_LTC}$= -135ºC, Approach_ $_{MTC}$_=10(ºC), Approach_ $_{LTC}$ =10(ºC),)
The effect of HFO & HCFO refrigerants on the thermodynamic performances have been shown in Table-10(b) respectively. It was found that the thermodynamic performances (energy performance (COP_$_{cascaded\ three\ stages}$) of three stages cascaded vapour compression refrigeration system-19 is highest while first law energy efficiency (COP_$_{Cascade\ three\ stages}$) is lowest Similarly Exergetic efficiency of cascaded three stage system is highest and lowest for system-20.

Table 10(b): Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva=35.167 kW, , T_Cond=50ºC,T_ambient=25ºC,$T_{\_Eva\_HTC}$= - 10ºC, Compressor efficiency$_{_HTC}$=80%, $T_{\_Eva\_MTC}$= - 95ºC, Compressor efficiency$_{_MTC}$=80% ,$T_{\_Eva\_LTC}$= - 135ºC, Compressor efficiency$_{_LTC}$=80%)

Performance Parameters	System17	System18	System-19	System20
First Law Efficiency (COP$_{_ \text{Cascade three stages VCRS}}$)	0.2931	0.2932	0.3019	0.2836
Exergy Destruction Ratio (EDR$_{_ \text{Cascade three stages VCRS}}$)	1.946	1.944	1.86	2.245
Exergetic Efficiency $_{\text{Cascade three stages VCRS}}$	0.3394	0.3396	0.3496	0.3284
Exergy of Fuel$_{_ \text{Cascade three stages VCRS}}$ "kW"	120.0	119.9	116.5	124.0
Exergy of Product$_{_ \text{Cascade three stages VCRS}}$ "kW"	40.73	40.73	40.73	40.73
HTC Mass flow Rate (Kg/sec)	1.029	0.9222	0.9804	1.265
MTC Mass flow Rate (Kg/sec)	0.4389	0.4389	0.4389	0.4389
LTC Mass flow Rate (Kg/sec)	0.2325	0.2325	0.2325	0.2325
HTC compressor work (kW)	45.37	45.3	41.87	49.39
MTC compressor work (kW)	42.95	42.95	42.95	42.95
LTC compressor work (kW)	31.67	31.67	31.67	31.67
Q_Cond_HTC"kW"	155.2	155.1	151.7	159.2
Q_Cond_LTC"kW"	109.8	109.8	109.8	109.8
Q_EVA_HTC"kW"	66.84	66.84	66.84	66.84
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167
First Law Efficiency COP_LTC	1.11	1.11	1.11	1.11
First Law Efficiency COP_MTC	1.556	1.556	1.556	1.556
First Law Efficiency COP_HTC	2.42	2.424	2.622	2.223
Exergy Destruction Ratio (EDR)	2.107	2.102	1.867	2.382
Exergetic Efficiency_HTC	0.3219	0.3223	0.3488	0.2957
Exergy of Fuel _HTC"kW"	45.37	45.3	41.87	49.39
Exergy of Product _HTC"kW"	14.6	14.60	14.6	14.6
First Law Efficiency COP$_{_ \text{MTCascade}}$	0.7567	0.7573	0.788	0.7238
Exergy Destruction Ratio (EDR)	1.618	1.617	1.515	1.738
Exergetic Efficiency_ MTCascade	0.3819	0.3822	0.3977	0.3653
Exergy of Fuel _ MTCascade "kW"	88.32	88.26	84.82	92.34
Exergy of Product _ MTCascade "kW"	33.73	33.73	33.73	33.73

4. Conclusions

Following Conclusions were drawn from present investigations.

- In six three stages cascaded vapour compression refrigeration systems the refrigerants suggested(R717, R-152a & R161) by sun [4] in the HTC and R-41 & R-170 suggested in MTC and R1150 in LTC and gives inferior first law energy efficiency(COP$_{\text{Cacaded _VCRS_Three_Stages}}$) and exergetic efficiency $_{\text{Cacaded \_VCRS\_Three\_Stages}}$ than using ultra low GWP of HCFO & HFO (R-1233zd(E), R1224yd(Z), R1234ze(E), R1243zf, R1234yf, R1225ye(Z) & R1336mzz(Z)) in HTC and ultra-low GWP of HCFO & HFO (R-1233zd(E), R1225ye(Z) & R1336mzz(Z) in MTC and ultra-low GWP of HCFO & HFO (R-1233zd(E), R1225ye(Z) & R1336mzz(Z) in LTC up to T_Eva_LTC=-135ºC with same input conditions.
- Three stages vapour compression refrigeration system using R1233zd(E) in HTC, R1336mzz(Z) in MTC and R1225ye(Z) in LTC (System-2) gives best (optimum) first law energy performance(COP$_{\text{Cascade}}$) and exergetic efficiency $_{\text{Cascade}}$. As compared to all cascaded vapour compression refrigeration systems.
- In all three stages & two stages vapour compression refrigeration system using HFO &HCFO refrigerants, the energy and exergy performances decreases as temperature overlapping increasing.
- In all three stages & two stages vapour compression refrigeration system using HFO &HCFO refrigerants, HTC condenser Temperature (ºC) is increasing, thermodynamic energy-exergy performances in terms of and exergetic efficiency of three stages cascaded vapour compression refrigeration is decreasing while first law efficiency of high temperature cycle is also decreasing. Similarly, for two stages cascaded systems COP_ and Exergetic Efficiency also decreasing.
- In all three stages & two stages vapour compression refrigeration system using HFO & HCFO refrigerants, MTC evaporator temperature (ºC) is increasing, thermodynamic energy-exergy performances in terms of and exergetic efficiency of three stages cascaded vapour compression refrigeration is increasing while first law efficiency of high temperature cycle is also decreasing. Similarly, for two stages cascaded systems COP_ and Exergetic Efficiency also increasing.
- In all three stages & two stages vapour compression refrigeration system using HFO &HCFO refrigerants, LTC evaporator temperature (ºC) is increasing, thermodynamic energy-exergy performances in terms of and exergetic efficiency of three stages cascaded vapour

compression refrigeration is increasing while first law efficiency of low temperature cycle is also increasing. Similarly, for two stages cascaded systems COP_ and Exergetic Efficiency also increasing.

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