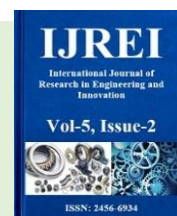




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ORIGINAL ARTICLE

Thermodynamic performances of cascaded vapour compression refrigeration systems using HFO refrigerants for ultra-low temperature applications

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Abstract

This work compares the thermodynamic performances of ultra-low GWP eight HFO refrigerants using mathematical modeling with the input design parameters of evaporator and condenser temperatures variations and variations in temperature overlapping between cascade condenser and cascade evaporator, and computed compressors work input, the coefficient of performance (COP), exergy destruction Ratio and exergetic efficiency, of HFO refrigerants which were examined for comparative performance analysis with R134a taken as the baseline refrigerant. The effect of temperature overlapping in cascaded condenser and subcooling of high temperature condenser was studied in detail. It's found that cascaded (energy&exergy) performances improved by increasing sub cooling in the condenser. The temperature overlapping was also observed and found that when overlapping temperature increases, thermodynamic (Energy-exergy) performances are decreases. Therefore, this research will help in finding alternative HFO refrigerants for the next generation of refrigeration systems that have environmentally friendly characteristics compared to previously used refrigerants for a sustainable environment.

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1. Introduction

Global warming is one of most cruel environmental concerns that our planet is facing today. One of its causes is the previous generation of refrigerant gases and carbon dioxide emissions. Upon release, these gases remain in the atmosphere for longer periods and contribute towards global warming. The severity of these gases' environment impacts is determined by their life cycle analysis (LCA) and the conversion efficiency of refrigeration systems. Due to global warming, Earth's temperature is expected rise over the period of the next 100 years. This will affect agriculture, which will cause in heavy rainfalls, additional heat waves, and sea level can rise of by the next century. Therefore, the member countries of the Montreal

Protocol in 2016, agreed to phase down hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) to reduce net earth warming by 0.5 °C by the year 2100 and to protect the ozone layer. Chlorofluorocarbons (CFCs) and HCFCs were already depleting the ozone layer, so these were wiped out after the Montreal Protocol and the Kyoto Protocol, respectively [1-4]. Presently, the different refrigerants being used for domestic, automotive, commercial refrigeration and air-conditioning systems are mostly HFCs, i.e., R134a, R23, R404A, R407A, R410A, R125 and R507A. Though HFCs have zero ozone depletion potential (ODP), these still possess large global warming potential (GWP) values. R134a has a GWP of 1430, R23 has a GWP of 14800, R404A has a GWP of 3922, R410A has a GWP of 2088, R407A has a GWP of 2107, and R507A has

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a GWP of 3985 [5]. The HCFC refrigerant (R22) was being used in the earlier generation of commercial refrigeration systems, e.g., centrifugal chillers and central air conditioning systems that are used in buildings, and the current generation is using R134a and R123. As per the safety classifications of refrigerants, R22 comes under the category of A1: very low toxicity and no flame propagation, but it has large GWP of 1810. R134a is a globally accepted refrigerant for various types of refrigeration systems. It has a superior safety rating compared with A1, and it has a low toxicity, no flame propagation, and a GWP around 1430. It is also an HFC and will be phased down 100% by 2034. R123 is used in chillers due to its high thermodynamic efficiency and reduced possibility of leakages, but it is HCFC compound with a B1 classification, and it has been a cause of tumors in livers and pancreases due to long term inhalation and hence, it is expected to be phased out by 2025. Due to the large GWP values of the earlier generation of refrigerants, the USA's Environmental Protection Agency (EPA) has decided to systematically phase out HFCs to 50% by 2025, 80% by 2030, and 100% by 2040 [6-11].

Therefore, it is necessary to find substitute refrigerant for the sustainability of the environment that should have a low GWP for minimum environmental impact and was found that as a drop-in replacement of R134a on vapor compression refrigeration (VCRC) with a variable speed compressor and input parameters of evaporator and condenser temperature. As compared to R404a, the HFC-134a gives 3% to 5% higher first law efficiency (COP). Similarly, R410a and R407c also have 1% to 1.5% lower first law efficiency than using R134a [12-16]. The results showed that with the R1234yf decreased to 5 to 10% the first law (energy) efficiency (COP) and by using R1234ze(Z) the energy efficiency (COP) was increased from 3 to 7%. The thermodynamic performances of vapour compression refrigeration systems using R152a are 2 to 6% higher than using R134a. It was observed that the input power of R152a was 7.724%, 7.72% and 7.752% less than that of R134a, the COP of system using R1224yd(Z) showed a 2.35%, 3.15% and 4.95% improvement at compressor speeds of 2000, 2500 and 3000 rpms, respectively, as compared to R134a [17-20].

The HFO-1234yf and HFO-1234ze(E) and R1234ze(Z), R1243zf, R1224yd(Z), R1225ye(Z), R1233zd(E), HFO-1336mzz(Z) were analyzed as potential replacements for R134a and the results showed that R1234ze(E) and R1243zf showed the closest performance to R134a. compared to R1234ze(E) [21-26]. The suitability of eight HFO refrigerants such as HFO-1234yf and HFO-1234ze(E), as potential alternatives to R134a was studied by using the EES software, which showed that these refrigerants improved performance without significantly increasing the GWP [27-30]. The use of R1233zd(E)', R1224yd(Z) and R1234ze(Z) in terms of first law efficiency to be 0.9%, was better than R245fa

The first law (energy) performance in terms of coefficient of

performance (CO) and second law (exergy) performance of ultra-low GWP refrigerants as drop-in replacements was evaluated by varying the value of the evaporating and condensing temperatures of a VCRC-based refrigeration system have been studied in details in simple vapour compression refrigeration systems, cascaded refrigeration systems for ultra-low temperature applications.

2. Results and Discussion

2.1 Performances of vapour compression refrigeration systems using HFO refrigerants

Thermodynamic first law (Energy) performance (i.e. coefficient of performance) of HFO ecofriendly refrigerants using heat exchanger for condenser temperature of 50°C and -10°C, evaporator temperature for 3.5167 kW cooling capacity shown in table-1(a) respectively It was found that the HFO-1234ze(Z) refrigerant gives highest COP. Similarly, HFO R1224yd(Z) refrigerant can be used to evaporator temperature above -10°C. the second best ultra-low refrigerant is R1233zd(E) gives slightly low thermodynamic energy-exergy performances than R1234ze(Z). Although first law energy performance (COP) using HFO-1336mzz(Z) gives nearly same COP as compared to R1224yd(Z). The thermodynamic energy performance using R1243zf is nearly similar as compared to performance R1234ze(E). The thermodynamic energy performance (COP) of R1234ze(Z), R1224yd(Z), R-1233zd(E) and HFO-1336mzz(Z) is higher than HFC-134a. Although energy performance (COP) of R1234ze(E), R1243zf and R1225ye(Z) is slightly lower than HFC-134a. HFO-1234yf gives lowest thermodynamic energy performance (COP). Similarly work required to run compressor using R 1234yf is highest which consumed high electrical energy. While R1234ze(Z) required lower electrical power consumption. It was found that R1234ze(Z), R1234ze(Z) and R1243zf can be only used -30°C above evaporator temperature which can replace HFC refrigerants in coming future. Although R1234yf has low thermodynamic energy performance as compared to HFC-134a, which can be used evaporator temperature above -50°C. The second law (exergy) performance using R1234ze(Z) is highest. The second law (exergetic) efficiency using R1233zd(E) is slightly lower than R1234ze(Z) but higher than HFO-1336mzz(Z). Similarly, exergetic efficiency using R1224yd(Z) is higher than R134a while using R1234yf gives lowest second law (exergetic) performance. Similarly, exergy destruction ratio is highest. The exergy destruction in the various components of vapour compression system are shown in Table-1(b) respectively. It was found that maximum exergy destruction occurred the condenser which can be reduced by changing proper design of condensing heat exchanger. It was found that by using R1234yf, the mass flow rate of refrigerant in the system is increased.

Table-1(a) Effect of ecofriendly refrigerants system performances of simple vapour compression refrigeration systems for ($T_{Cond} = 50^{\circ}C$, and $T_{Evap} = -10^{\circ}C$, isentropic compressors efficiency = 80%.

Ecofriendly Refrigerants	First law Efficiency (COP_{VCRS})	Exergy Destruction Ratio (EDR_{system})	VCRS Exergetic Efficiency	Work required to run Compressor W_{Comp} "kW"	Mass flow rate of refrigerant in VCRS(kg/sec)	Exergy Destruction Ratio (EDR_{VCRS})	VCRS Second law Efficiency
R1234ze(Z)	2.851	1.563	0.3902	1.234	0.02248	1.628	0.3806
R1234ze(E)	2.589	1.645	0.3543	1.359	0.03081	1.905	0.3443
R1224yd(Z)	2.762	1.822	0.3780	1.273	0.02982	1.710	0.3690
R1243zf	2.589	1.593	0.3543	1.359	0.02766	1.888	0.3463
R1233zd(E)	2.818	1.863	0.3857	1.248	0.02482	1.657	0.3763
R1225ye(Z)	2.417	1.788	0.3493	1.378	0.03633	1.928	0.3415
HFO-1336mzz(Z)	2.715	1.69	0.3717	1.295	0.02986	1.756	0.3629
R1234yf	2.252	2.023	0.3308	1.455	0.03726	2.088	0.3239
R134a	2.621	1.788	0.3587	1.342	0.02732	1.854	0.3504

Table-1(b) Effect of ecofriendly refrigerants system performances of vapour compression refrigeration systems for ($T_{Cond} = 50^{\circ}C$, and $T_{Evap} = -10^{\circ}C$, isentropic compressors efficiency = 80%.

Ecofriendly Refrigerants	First law Efficiency (COP_{VCRS})	Exergy Destruction Ratio (EDR_{VCRS})	% Exergy Destruction in comp.	% Exergy Destruction in cond.	% Exergy Destruction in valve.	Second law (exergetic) Efficiency	Mass flow rate of refrigerants in VCRS	Work required to run Compressor $W_{CompHTC}$ "kW"
R1234ze(Z)	2.851	1.563	17.92	30.53	13.8	0.3902	0.02248	1.234
R1234ze(E)	2.589	1.645	18.37	28.37	19.54	0.3543	0.03081	1.359
R1224yd(Z)	2.762	1.822	18.39	29.3	15.73	0.3780	0.02982	1.273
R1243zf	2.589	1.593	18.15	28.37	19.2	0.3543	0.02766	1.359
R1233zd(E)	2.818	1.863	18.24	29.88	14.56	0.3857	0.02482	1.248
R1225ye(Z)	2.252	1.788	18.33	27.89	19.99	0.3493	0.03633	1.378
HFO1336mzz(Z)	2.715	1.69	18.44	28.85	16.74	0.3717	0.02986	1.295
R1234yf	2.417	2.023	18.40	26.85	22.74	0.3308	0.03726	1.455
R134a	2.621	1.788	17.82	29.15	18.34	0.3587	0.02732	1.342

Thermodynamic first law (Energy) performance (i.e. coefficient of performance) of HFO ecofriendly refrigerants using heat exchanger for condenser temperature of $50^{\circ}C$ and $-30^{\circ}C$, evaporator temperature for 3.5167 kW cooling capacity shown in table-2(a) respectively. It was found that the HFO-1234ze(Z) refrigerant gives highest COP. The second best ultra-low refrigerant is R1233zd(E) gives slightly low thermodynamic energy-exergy performances than R1234ze(Z). Although first law energy performance (COP) using HFO-1336mzz(Z) gives higher COP as compared to R1225ye(Z). The thermodynamic energy performance using R1243zf is nearly similar as compared to performance R1234ze(E). The thermodynamic energy performance (COP) of R1234ze(Z), R-1233zd(E) and HFO-1336mzz(Z) is higher than HFC-134a. Although energy performance (COP) of R1234ze(E), R1243zf and R1225ye(Z) is slightly lower than HFC-134a. HFO-1234yf gives lowest thermodynamic energy performance (COP). Similarly work required to run compressor using R 1234yf is highest which consumed high electrical energy. While R1234ze(Z) required

lower electrical power consumption. It was found that R1234ze(Z), R1234ze(Z) and R1243zf can be only used $-30^{\circ}C$ above evaporator temperature which can replace HFC refrigerants in coming future. Although R1234yf has low thermodynamic energy performance as compared to HFC-134a, which can be used evaporator temperature above $-50^{\circ}C$.

The second law (exergy) performance using R1234ze(Z) is highest. The second law (exergetic) efficiency using R1233zd(E) is slightly lower than R1234ze(Z) but higher than HFO-1336mzz(Z). Similarly, exergetic efficiency using R1233zd(E) is higher than R134a while using R1234yf gives lowest second law (exergetic) performance. Similarly, exergy destruction ratio is highest. The exergy destruction in the various components of vapour compression system are shown in Table-2(b) respectively. It was found that maximum exergy destruction occurred the condenser which can be reduced by changing proper design of condensing heat exchanger. It was found that by using R1234yf, the mass flow rate of refrigerant in the system is increased.

Table-2(a) Effect of refrigerants system performances of VCRS for ($T_{Cond}=50^{\circ}\text{C}$, and $T_{Evap}=-30^{\circ}\text{C}$, isentropic compressors efficiency =80%.

Ecofriendly Refrigerants	First law Efficiency (COP_{VCRS})	(EDR_{system})	VCRS Exergetic Eff	Work required to run Compressor $\text{W}_{CompHTC}$ “kW”	Mass flow rate of refrigerants in VCRS (kg/sec)	(EDR_{VCRS})	VCRS Second law Eff	Work required to run Comp $\text{W}_{CompHTC}$ “kW”
R1234ze(Z)	1.757	1.414	0.4142	1.957	0.02462	1.457	0.4071	1.957
R1234ze(E)	1.564	1.775	0.3604	2.249	0.03518	1.833	0.3530	2.249
R1243zf	1.585	1.738	0.3653	2.219	0.03098	1.780	0.3597	2.219
R1233zd(E)	1.757	1.470	0.4049	2.002	0.0276	1.512	0.3981	2.022
R1225ye(Z)	1.546	1.806	0.3564	2.274	0.04125	1.848	0.3511	2.274
HFO-1336mzz(Z)	1.650	1.630	0.3802	2.132	0.03424	1.673	0.3741	2.132
R1234yf	1.429	2.037	0.3293	2.461	0.04339	2.088	0.3248	2.461

Table-2(b) Effect of refrigerants system performances of VCRS for ($T_{Cond}=50^{\circ}\text{C}$, and $T_{Evap}=-30^{\circ}\text{C}$, isentropic compressors efficiency =80%.

Ecofriendly Refrigerants	First law Efficiency (COP_{VCRS})	Exergy Destruction Ratio (EDR_{VCRS})	% Exergy Destruction in comp.	% Exergy Destruction in cond.	% Exergy Destruction in valve	Second law Efficiency	Mass flow rate of refrigerants in VCRS	Work required to run Compressor $\text{W}_{CompHTC}$ “kW”
R1234ze(Z)	1.757	1.414	17.47	22.92	19.07	0.4071	0.02462	1.957
R1234ze(E)	1.564	1.775	18.22	20.26	26.53	0.3530	0.03518	2.249
R1243zf	1.585	1.738	17.87	20.85	25.53	0.3597	0.03098	2.219
R1233zd(E)	1.757	1.470	17.9	21.98	20.49	0.3981	0.0276	2.002
R1225ye(Z)	1.546	1.806	18.13	20.22	26.76	0.3511	0.04125	2.274
HFO1336mzz(Z)	1.65	1.630	18.44	20.58	23.77	0.3741	0.03424	2.132
R1234yf	1.429	2.037	18.31	19.81	30.27	0.3248	0.04339	2.461

2.2 Performances of two cascaded vapour compression refrigeration system using HFO refrigerants

The following input data have been used for computing thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly ultra-low GWP refrigerants in lower temperature cycle and high temperature cycles.

S.No	Input Data	Numerical value
1	Condenser temperature in the high temperature cycle	55°C
2	Sub cooling	0.5,10,15,20,25
3	Temperature overlapping	0.5,10,15,20
4	Cooling load on low temperature evaporator (kW)	35.167
5	Isentropic efficiency of high temperature compressor	80%
6	Isentropic efficiency of low temperature compressor	80%
7	HFO refrigerants used in low temperature cycle (LTC)	R1233zd(E), HFO-1336mzz(Z) and R1225ye(Z)

The performance of cascade vapour compression refrigeration system is shown in table-3(a) to 3(b) respectively.

Table-3(a) and Table-3(b), show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using, R1225ye(Z) and HFO1336mzz(Z) in low

temperature cycle evaporator (T_{Evap_LTC}) at -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature (T_{Evap_HTC}) at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature.

Table-4(a) and Table-4(b), show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using, R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature (T_{Evap_HTC}) at -10°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature. Table-5(a) to Table-5(c), show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using, R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature (T_{Evap_HTC}) at

10°C, and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C) it was found that best

thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower temperature.

Table-3(a) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at = -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C, ($T_{Cond}=50°C$), and subcooling of condenser at 45°C and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Ecofriendly Refrigerants	First law Efficiency (COP_{HTC})	HTC Exergetic Efficiency	HTC EDR	Cascade COP	Cascade Exergetic Efficiency	Cascade EDR	First law Efficiency (COP_{LTC})	Cascade COP	Second law Efficiency
R1234ze(Z)	1.634	2.119	0.3764	0.5645	0.3838	1.606	1.391	0.6944	0.3207
R1234ze(E)	1.386	2.642	0.3193	0.5103	0.3469	1.883	1.391	0.6584	0.2747
R1243zf	1.408	2.572	0.3244	0.5154	0.3503	1.854	1.391	0.6619	0.2799
R1233zd(E)	1.593	2.192	0.3672	0.5562	0.3781	1.645	1.391	0.6891	0.3133
HFO1336mzz(Z)	1.481	2.414	0.3412	0.5319	0.3616	1.766	1.391	0.6731	0.2929
R1234yf	1.242	3.009	0.2863	0.4755	0.3232	2.094	1.391	0.6334	0.2494

Table-3(b) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using HFO-1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at = -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C, ($T_{Cond}=50°C$), and isentropic HTC<C compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Ecofriendly Refrigerants	First law Efficiency (COP_{HTC})	HTC Exergetic Efficiency	HTC EDR	Cascade COP	Cascade Exergetic Efficiency	Cascade EDR	First law Efficiency (COP_{LTC})	Cascade COP	Second law Efficiency
R1234ze(Z)	1.634	0.3764	2.119	0.5542	0.6884	1.654	1.352	0.6884	0.3207
R1234ze(E)	1.386	0.3193	2.62	0.5013	0.6520	1.935	1.352	0.6520	0.2746
R1243zf	1.408	0.3244	2.572	0.5062	0.6556	1.906	1.352	0.6556	0.2799
R1233zd(E)	1.593	0.2973	2.192	0.5461	0.6830	1.694	1.352	0.6830	0.3133
R1225ye(Z)	1.366	0.3148	2.673	0.4968	0.6488	1.951	1.352	0.6488	0.2723
R1234yf	1.242	0.2863	3.009	0.4673	0.6268	2.148	1.352	0.6268	0.2494
R134a	1.441	0.3320	2.494	0.5136	0.6608	1.864	1.352	0.6608	0.2862

Table-4(a) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at = -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C, ($T_{Cond}=50°C$), and subcooling of condenser at 45°C and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Ecofriendly Refrigerants	HTC First Law Efficiency (COP_{HTC})	HTC EDR	LTC First law Efficiency	Second law Efficiency	Cascade COP	Cascade Exergetic Efficiency	Cascade Exergy Destruction Ratio	HTC mc(t)	LTC mc(t)
R1234ze(Z)	1.713	1.534	1.352	0.3947	0.6984	0.3873	1.582	0.4495	0.2534
R1234ze(E)	1.448	1.997	1.352	0.3336	0.6619	0.3502	1.856	0.6611	0.2534
R1243zf	1.472	1.941	1.352	0.3392	0.6656	0.3538	1.827	0.5802	0.2534
R-1225ye(Z)	1.669	2.041	1.352	0.3289	0.6587	0.3471	1.881	0.7775	0.2534
R1233zd(E)	1.427	1.60	1.352	0.3847	0.693	0.3815	1.621	0.5052	0.2534
R1234yf	1.295	2.350	1.352	0.2985	0.6366	0.3265	2.063	0.8325	0.2534
R134a	1.508	1.878	1.352	0.3475	0.6709	0.3591	1.785	0.5628	0.2534

Table-4(b) Effect of refrigerants on the system performances of cascaded VCRS using HFO-1336mzz(Z) in low temperature cycle evaporator at -95°C and following ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C, ($T_{Cond}=50°C$), and subcooling of condenser at 45°C and isentropic HTC<C compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Ecofriendly Refrigerants	HTC First Law Efficiency (COP_{HTC})	HTC EDR	LTC First law Efficiency	Second law Efficiency	Cascade COP	Cascade Exergetic Efficiency	Cascade EDR	HTC mc(t)	LTC mc(t)
R1234ze(Z)	1.713	1.534	1.391	0.3947	0.7043	0.3946	1.534	0.4442	0.2802
R1234ze(E)	1.448	1.997	1.391	0.3336	0.6681	0.3566	1.805	0.6533	0.2802
R1243zf	1.472	1.941	1.391	0.3392	0.6718	0.3602	1.776	0.5732	0.2802
R1233zd(E)	1.669	2.041	1.391	0.3847	0.6989	0.3887	1.573	0.4993	0.2802
HFO1336mzz(Z)	1.547	1.60	1.391	0.3565	0.6827	0.3714	1.692	0.6276	0.2802
R1234yf	1.295	2.350	1.391	0.2985	0.6431	0.3322	2.010	0.8227	0.2802
R134a	1.508	1.878	1.391	0.3475	0.6771	0.3656	1.735	0.5562	0.2802

Table-5(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1233ze(E) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -75°C and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for $T_{\text{Evap_HTC}}$ at -10°C , ($T_{\text{Cond}}=50^{\circ}\text{C}$), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC First Law Efficiency (COP_{HTC})	HTC EDR	LTC First law Efficiency	Second law Efficiency	Cascade COP	Cascade Exergetic Efficiency	Cascade EDR	HTC mc(t)	LTC mc(t)
R1234ze(Z)	2.728	1.678	1.556	0.3735	0.8093	0.4098	1.440	0.3859	0.2309
R1234ze(E)	2.420	2.019	1.556	0.3313	0.7902	0.3860	1.591	0.5414	0.2309
R1243zf	2.424	2.014	1.556	0.3317	0.7904	0.3863	1.589	0.4852	0.2309
R-1224yd(Z)	2.622	1.786	1.556	0.3589	0.8032	0.4019	1.488	0.5159	0.2309
R-1225ye(Z)	2.378	2.072	1.556	0.3255	0.7872	0.3825	1.614	0.6403	0.2309
HFO1336mzz(Z)	2.568	1.845	1.556	0.3515	0.7998	0.3978	1.514	0.5185	0.2309
R1234yf	2.223	2.286	1.556	0.3043	0.7757	0.3692	1.709	0.6656	0.2309
R134a	2.464	1.964	1.556	0.3373	0.7932	0.3896	1.567	0.4773	0.2309

Table-5(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -75°C and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for $T_{\text{Evap_HTC}}$ at -10°C , ($T_{\text{Cond}}=50^{\circ}\text{C}$), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC First Law Efficiency (COP_{HTC})	HTC EDR	LTC First law Efficiency	Second law Efficiency	Cascade COP	Cascade Exergetic Efficiency	Cascade EDR	HTC mc(t)	LTC mc(t)
R1234ze(Z)	2.728	1.678	1.516	0.3735	0.8059	0.4024	1.485	0.3899	0.3080
R1234ze(E)	2.420	2.019	1.516	0.3313	0.7859	0.3792	1.637	0.5469	0.3080
R1243zf	2.424	2.014	1.516	0.3317	0.7861	0.3795	1.635	0.4902	0.3080
R1224yd(Z)	2.622	1.786	1.516	0.3589	0.7991	0.3947	1.533	0.5211	0.3080
R1233zd(E)	2.691	1.715	1.516	0.3684	0.8032	0.3997	1.502	0.4312	0.3080
HFO-1336mzz(Z)	2.568	1.845	1.516	0.3515	0.7957	0.3907	1.560	0.5242	0.3080
R1234yf	2.223	2.286	1.516	0.3043	0.7712	0.3628	1.756	0.6724	0.3080
R134a	2.464	1.964	1.516	0.3373	0.7889	0.3827	1.613	0.4822	0.3080

Table-5(c) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using HFO-1336mzz(Z) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\text{Evap_HTC}}$ at -10°C , ($T_{\text{Cond}}=50^{\circ}\text{C}$), and isentropic HTC<C compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC First law Efficiency (COP_{HTC})	HTC EDR	LTC First law Eff	Second law Efficiency	Cascade COP	Cascade EDR	Cascade EDR	HTC mc(t)	LTC mc(t)
R1234ze(Z)	2.728	1.678	1.516	0.3735	0.8059	0.4024	1.485	0.3913	0.2765
R1234ze(E)	2.420	2.019	1.516	0.3313	0.7859	0.3792	1.637	0.549	0.2765
R1243zf	2.424	2.014	1.516	0.3317	0.7861	0.3795	1.635	0.4920	0.2765
R1224yd(Z)	2.622	1.786	1.516	0.3589	0.7991	0.3947	1.533	0.5231	0.2765
R1233zd(E)	2.691	1.715	1.516	0.3684	0.8032	0.3997	1.502	0.4328	0.2765
R1225ye(Z)	2.378	2.072	1.516	0.3255	0.7813	0.3734	1.678	0.6493	0.2765
R1234yf	2.223	2.286	1.516	0.3043	0.7712	0.3628	1.756	0.6749	0.2765
R134a	2.464	1.964	1.516	0.3373	0.7889	0.3827	1.613	0.4840	0.2765

Table-6(a-c) , show the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -75°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T_{\text{Evap_HTC}}$) at -30°C ,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C) it was found that best thermodynamic performances occurred by using R1233zd(E) in LTC and R1234ze(Z) but performances are nearly similar at this lower

temperature. Table-7(a-b) ,shows the effect of ecofriendly refrigerants in high temperature circuit on the system performances of cascaded vapour compression refrigeration system using , R1225ye(Z) and HFO1336mzz(Z) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for evaporator temperature ($T_{\text{Evap_HTC}}$) at -30°C ,and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80% , Cooling load =35.167 kW, temperature overlapping= 10°C) it was found best thermodynamic performances using HFO-1336mzz(Z)in LTC and R1234ze(Z).

Table-6(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1233yd(E) in low temperature cycle evaporator (T_{Evap_LTC}) at -75°C and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -20°C , ($T_{Cond}=55^{\circ}\text{C}$), and subcooling of condenser at 50°C , isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC First Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Efficiency	LTC 1 st law Eff	HTC work kW	LTC work "kW"	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	HTC Q _{Cond} "kW"	LTC Q _{Cond} = HTC Q _{EVA}
R1234ze(Z)	2.029	1.771	0.3609	1.892	26.49	18.59	0.7801	1.538	0.3940	80.25	53.76
R1234ze(E)	1.767	2.183	0.3142	1.892	30.43	18.59	0.7174	1.760	0.3623	84.18	53.76
R1243zf	1.779	2.160	0.3165	1.892	30.21	18.59	0.7206	1.748	0.3639	83.97	53.76
HFO1336mzz(Z)	1.88	1.99	0.3343	1.892	28.59	18.59	0.7454	1.656	0.3765	82.34	53.76
R-1225ye(Z)	1.738	2.235	0.3091	1.892	30.93	18.59	0.7102	1.788	0.3587	84.69	53.76
R1234yf	1.606	2.501	0.2856	1.892	33.47	18.59	0.6755	1.931	0.3411	87.23	53.76
R134a	1.841	2.099	0.3227	1.892	29.63	18.59	0.7293	1.715	0.3683	83.39	53.76
R245fa	1.944	1.892	0.3458	1.892	27.65	18.59	0.7605	1.604	0.3841	81.43	53.76

Table-6(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using HFO-1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -20°C , ($T_{Cond}=55^{\circ}\text{C}$), and sub cooling at 50°C isentropic HTC<C compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC First Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Efficiency	LTC 1 st law Eff	HTC work kW	LTC work kW	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	HTC Q _{Cond} "kW"	LTC Q _{Cond} = Q _{EVA,HTC} "kW"
R1234ze(Z)	2.029	1.771	0.3609	1.845	26.72	19.06	0.7681	1.578	0.3879	80.95	54.23
R1234ze(E)	1.767	2.183	0.3142	1.845	30.70	19.06	0.7068	1.801	0.3570	83.97	54.23
R1243zf	1.779	2.160	0.3165	1.845	30.48	19.06	0.7099	1.789	0.3585	84.70	54.23
R1233zd(E)	1.88	1.822	0.3543	1.845	27.22	19.06	0.7599	1.608	0.3838	81.45	54.23
R1225ye(Z)	1.738	2.235	0.3091	1.845	31.20	19.06	0.7352	1.693	0.3713	83.0	54.23
R1234yf	1.606	2.501	0.2856	1.845	33.77	19.06	0.6657	1.974	0.3362	88.0	54.23
R134a	1.841	2.099	0.3227	1.845	29.89	19.06	0.7184	1.715	0.3628	84.12	54.23
R245fa	1.944	1.892	0.3458	1.845	27.90	19.06	0.7489	1.715	0.3782	82.12	54.23

Table-6(c) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -75°C and following ecofriendly ultra low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -20°C , ($T_{Cond}=55^{\circ}\text{C}$), and sub cooling at -50°C , isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C).

Ecofriendly Refrigerants	HTC 1 st Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Efficiency	LTC 1 st law Eff	HTC work kW	LTC work "kW"	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	HTC Q _{Cond} "kW"	LTC Q _{Cond} = Q _{EVA,HTC} "kW"
R1234ze(Z)	2.029	1.771	0.3609	1.868	26.61	18.83	0.7741	0.3909	1.558	80.6	53.43
R1234ze(E)	1.767	2.183	0.3142	1.868	30.56	18.83	0.7121	0.3595	1.781	84.56	53.43
R1243zf	1.779	2.160	0.3165	1.868	30.35	18.83	0.7152	0.3612	1.768	84.34	53.43
R-1233yd(E)	1.992	1.822	0.3543	1.868	27.1	18.83	0.7657	0.3867	1.822	81.09	53.43
HFO1336mzz(Z)	1.88	1.99	0.3343	1.868	28.71	18.83	0.7398	0.3736	1.677	82.71	53.43
R1234yf	1.606	2.501	0.2856	1.868	33.82	18.83	0.6705	0.3387	1.953	87.61	53.43
R134a	1.814	2.099	0.3227	1.868	29.76	18.83	0.7238	0.3656	1.736	83.75	53.43
R245fa	1.944	1.892	0.3458	1.868	27.77	18.83	0.7547	0.3811	1.624	81.77	53.43

Table-8, shows the effect of subcooling at condenser outlet on the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in HTC for T_{Evap_HTC} at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors

efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C) it was found that sub cooling temperature increases, the overall cascaded COP is increases and also HTC Energy Efficiency (COP) and exergetic efficiency is increases because high temperature compressor work and mass flow rate in HTC is decreases. Also heat rejected by HTC condenser and EDR of HTC and whole system is decreases.

Table-7(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R-1225ye(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -20°C , ($T_{Cond}=50^{\circ}\text{C}$), and isentropic compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C .

Ecofriendly Refrigerants	HTC 1 st Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Efficiency	LTC 1 st law Eff	HTC work kW	LTC work "kW"	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	HTC Q _{Cond} "kW"	LTC Q _{Cond} =Q _{EVA_{HTC}} "kW"	HTC Mass flow rate Kg/sec	LTC Mass flow rate Kg/sec
R1234ze(Z)	2.029	1.771	0.3609	1.119	32.81	31.42	0.5475	0.3691	1.709	99.39	66.58	0.4660	0.2777
R1234ze(E)	1.767	2.183	0.3142	1.119	37.69	31.42	0.5089	0.3431	1.915	104.3	66.58	0.6681	0.2777
R1243zf	1.779	2.16	0.3165	1.119	37.42	31.42	0.5109	0.3444	1.904	104.0	66.58	0.5933	0.2777
R1233zd(E)	1.992	1.822	0.3543	1.119	33.42	31.42	0.5424	0.3656	1.735	100.0	66.58	0.5194	0.2777
R1225ye(Z)	1.738	2.235	0.309	1.119	38.31	31.42	0.5044	0.340	1.941	104.9	66.58	0.7883	0.2777
R1234yf	1.606	2.501	0.2856	1.119	41.46	31.42	0.4825	0.3253	2.074	108.0	66.58	0.8305	0.2777

Table-7(b) Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R-1225ye(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -20°C , ($T_{Cond}=50^{\circ}\text{C}$), and isentropic HTC<C compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C .

Ecofriendly Refrigerants	HTC 1 st Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Efficiency	LTC 1 st law Eff	HTC work kW	LTC work "kW"	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	HTC Q _{Cond} "kW"	LTC Q _{Cond} =Q _{EVA_{HTC}} "kW"	HTC Mass flow rate Kg/sec	LTC Mass flow rate Kg/sec
R1234ze(Z)	2.029	1.771	0.3609	1.151	32.81	30.55	0.5475	0.369	1.70	99.3	66.58	0.4660	0.2777
R1234ze(E)	1.767	2.183	0.3142	1.151	37.69	30.55	0.5089	0.343	1.91	104.	66.58	0.6681	0.2777
R1243zf	1.779	2.16	0.3165	1.151	37.42	30.55	0.5109	0.344	1.90	104.	66.58	0.5933	0.2777
R1233zd(E)	1.992	1.822	0.3543	1.151	33.42	30.55	0.5424	0.365	1.73	100	66.58	0.5194	0.2777
HFO1336mzz(Z)	1.88	1.99	0.3345	1.151	34.95	30.55	0.5369	0.361	1.76	100	66.58	0.6334	0.2777
R1234yf	1.606	2.501	0.2856	1.151	41.46	30.55	0.4825	0.325	2.07	108	66.58	0.8305	0.2777

Table-8 Effect of ecofriendly refrigerants on the system performances of cascaded VCRS using R1234ze(Z) in HTC and HFO1336mzz(Z) in LTC evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping= 10°C .

Sub cooling temp at cond outlet $^{\circ}\text{C}$	HTC 1 st Law Eff (COP _{HTC})	HTC EDR	HTC 2 nd law (Exergetic) Eff	LTC 1 st law Eff	HTC work kW	LTC work "kW"	Cascade 1 st law eff Cascade COP _{Cas}	Cascade Exergetic Eff	Cascade EDR	Heat Rejected by HTC cond "kW"	LTC Q _{Cond} =Q _{EVA_{HTC}} "kW"	HTC Mass flow rate Kg/sec	LTC Mass flow rate Kg/sec
0	1.552	1.847	0.3512	1.351	39.42	26.01	0.5375	0.3623	1.760	100.6	66.58	0.4732	0.2534
5	1.634	1.705	0.3697	1.351	37.45	26.01	0.5542	0.3737	1.677	98.62	66.58	0.4495	0.2534
10	1.714	1.577	0.3880	1.351	35.68	26.01	0.5701	0.3843	1.602	96.86	66.58	0.4283	0.2534
15	1.794	1.463	0.4061	1.351	34.10	26.01	0.5851	0.3945	1.535	95.27	66.58	0.4093	0.2534
20	1.873	1.359	0.4239	1.351	32.65	26.01	0.5995	0.4040	1.415	93.84	66.58	0.3920	0.2534
25	1.951	1.265	0.4415	1.351	31.36	26.01	0.6130	0.4133	1.420	92.53	66.58	0.3764	0.2534
30	2.028	1.179	0.4590	1.351	30.70	26.01	0.6260	0.4220	1.369	91.34	66.58	0.3621	0.2534

Table-9(a) and Table-9(b), show the effect of temperature overlapping in cascaded condenser at condenser of the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator (T_{Evap_LTC}) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for T_{Evap_HTC} at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW,

temperature overlapping= 10°C) it was found that temperature overlapping is increases, the overall cascaded COP is decreases and HTC Energy Efficiency (COP) and exergetic efficiency do not affect because high and low temperature compressors work is increases and both mass flow rate in the HTC and LTC circuit are increases mass flow rate in HTC is decreases. Also heat rejected by HTC condenser and exergy destruction ratio of HTC and whole system is increases creases is decreases

Table-9(a) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R1234ze(Z) in high temperature circuit and HFO1336mzz(Z) in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\text{Evap_HTC}}$ at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Temperature Overlapping ($^{\circ}\text{C}$)	HTC First Law Efficiency (COP_{HTC})	HTC EDR	HTC Second law (Exergetic) Efficiency	LTC First law Eff	HTC) work “kW”	LTC) work “kW”	Cascade first law efficiency Cascade COP_{Cas}	Cascade Exergetic Efficiency	Cascade EDR	Heat Rejected by HTC condenser “kW”	LTC $\text{Q}_{\text{Cond}} = \text{Q}_{\text{EVA_HTC}}$ “kW”	HTC Mass flow rate Kg/sec	LTC Mass flow rate Kg/sec
0	1.714	1.577	0.3880	1.651	32.94	21.30	0.6483	0.4370	1.288	89.41	56.47	0.3954	0.2331
5	1.714	1.577	0.3880	1.491	34.27	23.58	0.6079	0.4098	1.440	93.01	58.75	0.4113	0.2428
10	1.714	1.577	0.3880	1.352	35.68	26.01	0.5701	0.3843	1.602	96.86	61.17	0.4283	0.2534
15	1.714	1.577	0.3880	1.229	37.20	28.61	0.5344	0.3602	1.776	101.0	63.76	0.4465	0.2650
20	1.714	1.577	0.3880	1.119	38.84	31.42	0.5006	0.3375	1.963	105.4	66.58	0.4662	0.2777

Table-9(b) Effect of ecofriendly refrigerants on the system performances of cascaded vapour compression refrigeration system using R152a in high temperature circuit and HFC134a in low temperature cycle evaporator ($T_{\text{Evap_LTC}}$) at -95°C and following ecofriendly ultra-low GWP refrigerants in higher temperature cycle for $T_{\text{Evap_HTC}}$ at -30°C , and isentropic HTC compressors efficiency =80%, LTC compressors efficiency =80%, Cooling load =35.167 kW, temperature overlapping=10°C).

Temperature Overlapping ($^{\circ}\text{C}$)	HTC First Law Efficiency (COP_{HTC})	HTC EDR	HTC Second law (Exergetic) Eff	LTC First law Efficiency	HTC) work “kW”	LTC) work “kW”	Cascade first law efficiency Cascade COP_{Cas}	Cascade Exergetic Efficiency	Cascade EDR	Heat Rejected by HTC cond “kW”	LTC $\text{Q}_{\text{Cond}} = \text{Q}_{\text{EVA_HTC}}$ “kW”	HTC Mass flow rate Kg/sec	LTC Mass flow rate Kg/sec
0	1.669	1.647	0.3778	1.667	33.70	21.09	0.4327	0.3623	1.669	89.96	56.26	0.2759	0.1965
5	1.669	1.647	0.3778	1.509	35.03	23.30	0.6029	0.4054	1.460	93.5	58.47	0.2868	0.2039
10	1.669	1.647	0.3778	1.371	36.44	25.65	0.5664	0.3818	1.619	97.25	60.82	0.2983	0.2118
15	1.669	1.647	0.3778	1.249	37.94	28.16	0.5321	0.3587	1.788	101.3	63.33	0.3104	0.2204
20	1.669	1.647	0.3778	1.140	39.55	30.85	0.4996	0.3368	1.969	105.6	66.01	0.3238	0.2299

2.3 Thermal performances of three cascaded vapour compression refrigeration systems for ultra-low temperature applications

The following systems have been considered for thermodynamic performance at ultralow evaporator temperature (-155°C) of three cascaded vapour compression refrigeration system using HFO refrigerants.

System-1

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -30°C and R-1225ye (Z) in MTC at evaporator temperature of -95°C and HFO-1336mzz (Z) in LTC at evaporator temperature at -155°C .

System-2

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -30°C and 1336mzz (Z) in MTC at evaporator temperature of -95°C and R-1225ye (Z) in LTC at evaporator temperature at -155°C .

System-3

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -30°C and 1225ye (Z) in MTC at evaporator temperature of -95°C and HFO-1336mzz (Z) in LTC at evaporator temperature at -155°C .

System-4

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -95°C and R1225ye (Z) in LTC at evaporator temperature at -155°C .

System-5

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and R-1225ye (Z) in MTC at evaporator temperature of -95°C and HFO-1336mzz (Z) in LTC at evaporator temperature at -155°C .

System-6

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -95°C and R-1225ye (Z) in LTC at evaporator temperature at -155°C.

System-7

Cascaded vapour compression refrigeration system using R1233zd(E) in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -95°C and R1225ye (Z) in LTC at evaporator temperature at -155°C.

System-8

Cascaded vapour compression refrigeration system using R1233zd(E) in HTC at evaporator temperature of -30°C and 1225ye (Z) in MTC at evaporator temperature of -95°C and HFO-1336mzz (Z) in LTC at evaporator temperature at -155°C.

System-9

Cascaded vapour compression refrigeration system using

R1234yf in HTC at evaporator temperature of -30°C and R1233zd (E) in MTC at evaporator temperature of -95°C and R-1225ye (Z) in LTC at evaporator temperature at -155°C.

System-10

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30°C and R1233zd (E) in MTC at evaporator temperature of -95°C and HFO-1336mzz (Z) in LTC at evaporator temperature at -155°C. To find out the effect of system performances using R1234ze(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{Cond} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -30°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -95°C and following four cascaded systems (system-1 to system-4) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -155°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $= 80\%$. it was observed that First law (energy) and second law (Exergy) performances of system-2 are highest and system-9 is lowest is shown in Table-10(a) & Table-10(b) respectively.

Table-10(a) Effect of system performances using R1234ze(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{Cond} = 50^\circ\text{C}$ and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -135°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $= 80\%$.

Performance Parameters	System-1	System-2	System-3	System-4	System-5	System-6
HTC First law Efficiency (COP _{HTC})	1.714	1.714	1.497	1.497	1.516	1.516
MTC First law Efficiency (COP _{MTC})	1.391	1.352	1.391	1.352	1.391	1.352
LTC First law Efficiency (COP _{LTC})	0.6181	0.6209	0.6181	0.6209	0.6181	0.6209
Cascade First law Efficiency (COP _{Cascade})	0.5808	0.5701	0.5355	0.5259	0.5396	0.5292
Cascade First law Efficiency (COP _{Cascade})	0.1951	0.20	0.1834	0.188	0.1805	0.1831
Exergetic Efficiency _{HTC}	0.3880	0.3388	0.3388	0.3880	0.3431	0.3431
Exergy Destruction Ratio (EDR _{HTC})	1.577	1.577	1.951	1.951	1.915	1.694
Exergetic Efficiency _{MTC}	0.3937	0.3992	0.3690	0.3683	0.3658	0.3711
System Exergy Destruction Ratio _{Two Stages}	1.391	1.506	1.755	1.715	1.734	1.694
Exergetic Efficiency _{Three Stages}	0.2927	0.3052	0.2798	0.2868	0.2814	0.2814
Exergy Destruction Ratio (EDR _{Three Stages})	2.359	2.277	2.574	2.487	2.553	2.467
Work required to run Compressor $W_{Comp\ HTC}$ "kW"	79.35	77.72	90.87	89.0	89.74	87.9
Work required to run Compressor $W_{Comp\ MTC}$ "kW"	56.90	56.64	56.90	56.64	56.90	56.64
Work required to run Compressor W_{Comp} "kW"	43.96	41.43	43.96	41.43	43.96	41.46
Exergy of Fuel _{Two Stages} "kW"	136.2	134.4	147.8	145.6	146.6	146.6
Exergy Product _{Two Stages} "kW"	53.36	51.64	53.36	51.64	53.36	51.64
Exergy of Fuel _{Three Stages} "kW"	180.2	175.81	191.7	187.10	190.6	190.6
Exergy Product _{Three Stages} "kW"	53.64	53.64	53.64	53.64	53.64	53.64
Condenser Heat _{HTC} "kW"	215.4	211.0	226.9	222.2	225.8	221.1
HTC Evaporator load = Condenser Heat _{MTC} "kW"	136.0	133.2	136.0	133.2	136	133.2
MTC Evaporator load = Condenser Heat _{LTC} "kW"	79.13	76.59	79.13	76.59	79.13	76.59
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.9524	0.9329	1.361	1.33	1.198	1.176
MTC Mass flow rate (kg/sec)	0.6305	0.5520	0.6305	0.552	0.6305	0.552
LTC Mass flow rate (kg/sec)	0.1907	0.2180	0.1907	0.218	0.1907	0.1915

Table-10(b) Effect of system performances using R1234ze(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 50^\circ\text{C}$ and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -135°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $= 80\%$.

Performance Parameters	System-7	System-8	System-9	System-10
HTC First law Efficiency (COP_{HTC})	1.677	1.677	1.37	1.37
MTC First law Efficiency (COP_{MTC})	1.391	1.352	1.391	1.352
LTC First law Efficiency (COP_{LTC})	0.6181	0.6209	0.6181	0.6209
Cascade First law Efficiency ($\text{COP}_{\text{Cascade}}$)	0.5628	0.5734	0.4977	0.5067
Cascade First law Efficiency ($\text{COP}_{\text{Cascade}}$)	0.1961	0.1933	0.1801	0.1757
Exergetic Efficiency $_{\text{HTC}}$	0.3796	0.3796	0.3101	0.3101
Exergy Destruction Ratio (EDR_{HTC})	1.634	1.634	2.225	2.225
Exergetic Efficiency $_{\text{MTC}}$	0.3942	0.3837	0.3486	0.3435
System Exergy Destruction Ratio $_{\text{Two Stages}}$	1.537	1.573	1.869	1.911
Exergetic Efficiency $_{\text{Three Stages}}$	0.3022	0.2948	0.2747	0.2680
Exergy Destruction Ratio ($\text{EDR}_{\text{Three Stages}}$)	2.309	2.392	2.641	2.731
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	79.45	81.11	79.24	99.28
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	56.90	56.64	56.90	56.64
Work required to run Compressor $W_{\text{Comp LTC}}$ "kW"	41.93	41.43	43.43	41.43
Exergy of Fuel $_{\text{Two Stages}}$ "kW"	136.1	138.0	153.9	155.2
Exergy Product $_{\text{Two Stages}}$ "kW"	53.35	51.64	53.35	51.64
Exergy of Fuel $_{\text{Three Stages}}$ "kW"	177.5	182.0	195.3	200.1
Exergy Product $_{\text{Three Stages}}$ "kW"	53.64	53.64	53.64	53.64
Condenser Heat $_{\text{HTC}}$ "kW"	212.7	217.1	230.5	235.3
HTC Evaporator load = Condenser Heat $_{\text{MTC}}$ "kW"	136.0	133.2	136.0	133.2
MTC Evaporator load = Condenser Heat $_{\text{LTC}}$ "kW"	79.13	76.59	79.13	76.59
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	1.046	1.067	1.644	1.678
MTC Mass flow rate (kg/sec)	0.6305	0.5520	0.6305	0.552
LTC Mass flow rate (kg/sec)	0.1907	0.2180	0.1907	0.218

2.4 Thermal performances of three cascaded vapour compression refrigeration systems for low temperature applications

The following systems mentioned in table-11(a) to Table-11(f) have been considered for thermodynamic performance at low evaporator temperature (-115°C) of three cascaded vapour compression refrigeration system using HFO refrigerants

System-1

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -10°C and R1233zd (E) at evaporator temperature of -75°C in MTC and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C

System-2

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -10°C and R1233zd (E) at evaporator temperature of -75°C in MTC and R1225ye (Z) in LTC at evaporator temperature of -115°C

System-3

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -30°C and R1225ye (Z) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C

System-4

Cascaded vapour compression refrigeration system using R1234ze(Z) in HTC at evaporator temperature of -10°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -115°C .

To find out the effect of system performances using R1234ze(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-1 to system-4) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $= 80\%$. it was observed that First law (energy) and second law (Exergy) performances of system-1 are highest and system- 3 is lowest is shown in table-11(a).

Table-11(a) Effect of system performances using R1234ze(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$.

Performance Parameters	System-1	System-2	System-3	System-4
HTC First law Efficiency (COP _{HTC})	2.669	2.669	2.669	2.669
MTC First law Efficiency (COP _{MTC})	1.516	1.516	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.045	1.035	1.009	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7948	0.7948	0.7805	0.7752
Cascade First law Efficiency (COP _{Cascade})	0.4234	0.4176	0.4116	0.4150
Exergetic Efficiency _{HTC}	0.3552	0.3552	0.3552	0.3552
Exergy Destruction Ratio (EDR _{HTC})	1.815	1.815	1.815	1.815
Exergetic Efficiency _{MTC}	0.4730	0.4685	0.460	0.4614
System Exergy Destruction Ratio _{Two Stages}	1.114	1.135	1.174	1.165
Exergetic Efficiency _{Three Stages}	0.3751	0.370	0.3647	0.3678
Exergy Destruction Ratio (EDR _{Three Stages})	1.666	1.703	1.742	1.719
Work required to run Compressor W _{Comp HTC} "kW"	32.23	32.54	32.87	32.68
Work required to run Compressor W _{Comp MTC} "kW"	33.65	33.98	34.86	34.86
Work required to run Compressor W _{Comp} "kW"	17.19	17.70	17.70	17.19
Exergy of Fuel _{Two Stages} "kW"	65.88	66.52	67.74	65.54
Exergy Product _{Two Stages} "kW"	26.44	26.70	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	83.07	84.22	85.44	84.73
Exergy Product _{Three Stages} "kW"	31.16	31.15	31.13	31.15
Condenser Heat _{HTC} "kW"	118.2	119.4	120.6	119.9
HTC Evaporator load = Condenser Heat _{MTC} "kW"	86.01	86.85	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.36	52.87	52.87	52.36
LTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.5498	0.5552	0.5609	0.5576
MTC Mass flow rate (kg/sec)	0.3438	0.3472	0.4630	0.4117
LTC Mass flow rate (kg/sec)	0.2203	0.1939	0.1939	0.2203

To find out the effect of system performances using R1234ze(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-5 to system-8) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$ is shown in table-11(b) respectively.

System-5

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -10°C and R1233zd (E) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C .

System-6

Cascaded vapour compression refrigeration system

using R1234ze(E) in HTC at evaporator temperature of -30°C and R1233zd (E) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -115°C

System-7

Cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -10°C and R1225ye (Z) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -115°C . System-8 cascaded vapour compression refrigeration system using R1234ze(E) in HTC at evaporator temperature of -10°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -115°C .

Table-11(b) shows the comparisons of thermodynamic performances of system-5 to system-8 using R1234ze(E) in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-5 are highest and system-7 is lowest as shown in Table-11(b).

Table-11(b) Effect of system performances using R1234ze(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$.

Performance Parameters	System-5	System-6	System-7	System-8
HTC First law Efficiency (COP _{HTC})	2.433	2.433	2.433	2.433
MTC First law Efficiency (COP _{MTC})	1.556	1.556	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.045	1.035	1.009	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7588	0.7588	0.7454	0.7404
Cascade First law Efficiency (COP _{Cascade})	0.4080	0.4025	0.3968	0.4001
Exergetic Efficiency _{HTC}	0.3237	0.3237	0.3237	0.3237
Exergy Destruction Ratio (EDR _{HTC})	2.089	2.089	2.089	2.089
Exergetic Efficiency _{MTC}	0.4516	0.4472	0.4393	0.4407
System Exergy Destruction Ratio _{Two Stages}	1.214	1.236	1.276	1.269
Exergetic Efficiency _{Three Stages}	0.3615	0.3566	0.3516	0.3545
Exergy Destruction Ratio (EDR _{Three Stages})	1.766	1.804	1.844	1.821
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	35.36	35.70	36.06	35.85
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	33.65	33.98	34.86	34.86
Work required to run Compressor $W_{\text{Comp LTC}}$ "kW"	17.19	17.70	17.70	17.19
Exergy of Fuel _{Two Stages} "kW"	69.0	69.68	70.93	70.71
Exergy _{Product Two Stages} "kW"	26.44	26.70	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	86.20	87.38	88.63	87.9
Exergy _{Product Three Stages} "kW"	31.16	31.15	31.13	31.15
Condenser Heat _{HTC} "kW"	121.4	122.6	123.8	123.1
HTC Evaporator load = Condenser Heat _{MTC} "kW"	86.01	86.85	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.36	52.87	52.87	52.36
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.7535	0.7608	0.7686	0.7641
MTC Mass flow rate (kg/sec)	0.3436	0.3472	0.4630	0.4117
LTC Mass flow rate (kg/sec)	0.2203	0.1939	0.1939	0.2203

To find out the effect of system performances using R1224yd(Z) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-9 to system-12) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$ is shown in Table-11(c) respectively.

System-9

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10°C and R1233zd (E) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -135°C .

System-10

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10°C and

R1233zd (E) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -135°C

System-11

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10°C and HFO-1336mzz (Z) in MTC at evaporator temperature of -75°C and R1225ye (Z) in LTC at evaporator temperature of -135°C

System-12

Cascaded vapour compression refrigeration system using R1224yd(Z) in HTC at evaporator temperature of -10°C and R1225ye (Z) in MTC at evaporator temperature of -75°C and HFO-1336mzz (Z) in LTC at evaporator temperature of -135°C .

Table-11(c) shows the comparisons of thermodynamic performances of system-9 to system-12 using R1224yd(Z) in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-9 are highest and system-12 is lowest.

Table-11(c) Effect of system performances using R1224yd(Z)ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^{\circ}\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$.

Performance Parameters	System-9	System-10	System-11	System-12
HTC First law Efficiency (COP _{HTC})	2.59	2.59	2.59	2.59
MTC First law Efficiency (COP _{MTC})	1.556	1.556	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.045	1.035	1.009	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7832	0.7832	0.7692	0.7640
Cascade First law Efficiency (COP _{Cascade})	0.4184	0.4127	0.4069	0.4102
Exergetic Efficiency _{HTC}	0.3447	0.3447	0.3447	0.3447
Exergy Destruction Ratio (EDR _{HTC})	1.901	1.901	1.901	1.901
Exergetic Efficiency _{MTC}	0.4661	0.4616	0.4534	0.4547
System Exergy Destruction Ratio _{Two Stages}	1.145	1.166	1.206	1.199
Exergetic Efficiency _{Three Stages}	0.3708	0.3657	0.3605	0.3535
Exergy Destruction Ratio (EDR _{Three Stages})	1.696	1.734	1.774	1.751
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	33.2	33.53	33.87	33.67
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	33.65	33.98	34.86	34.86
Work required to run Compressor $W_{\text{Comp LTC}}$ "kW"	17.19	17.70	17.70	17.19
Exergy of Fuel _{Two Stages} "kW"	66.85	67.5	68.73	68.53
Exergy Product _{Two Stages} "kW"	26.44	26.70	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	84.04	85.2	86.43	85.72
Exergy Product _{Three Stages} "kW"	31.16	31.15	31.13	31.15
Condenser Heat _{HTC} "kW"	119.2	120.4	121.6	120.9
HTC Evaporator load = Condenser Heat _{MTC} "kW"	86.01	86.85	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.36	52.87	52.87	52.36
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.7293	0.7364	0.7440	0.7396
MTC Mass flow rate (kg/sec)	0.3438	0.3472	0.4630	0.4117
LTC Mass flow rate (kg/sec)	0.2203	0.1939	0.1939	0.2203

To find out the effect of system performances using R1243zfecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^{\circ}\text{C}$ and sub cooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-13 to system-16) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$ is shown in Table-11(d) respectively.

System-13

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and R1233zd(E) in MTC and R1225ye (Z) in LTC.

System-14

Cascaded vapour compression refrigeration system

using R1243zf in HTC at evaporator temperature of -30°C and R1233zd(E) in MTC and R1225ye (Z) in LTC

System-15

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC and R1225ye (Z) in LTC

System-16

Cascaded vapour compression refrigeration system using R1243zf in HTC at evaporator temperature of -30°C and HFO-1336mzz (Z) in MTC and R1225ye (Z) in LTC

Table-11(d) shows the comparisons of thermodynamic performances of system-13 to system-16 using R1243zf in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-13 are highest and system-15 is lowest.

Table-11(d) Effect of system performances using R124yf ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^{\circ}\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies = 80%.

Performance Parameters	System-13	System-14	System-15	System-16
HTC First law Efficiency (COP _{HTC})	2.431	2.431	2.431	2.431
MTC First law Efficiency (COP _{MTC})	1.556	1.556	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.045	1.035	1.035	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7585	0.7586	0.7451	0.7401
Cascade First law Efficiency (COP _{Cascade})	0.4079	0.4023	0.3967	0.3999
Exergetic Efficiency _{HTC}	0.3235	0.3235	0.3235	0.3235
Exergy Destruction Ratio (EDR _{HTC})	2.091	2.091	2.091	2.091
Exergetic Efficiency _{MTC}	0.4514	0.4470	0.4392	0.4405
System Exergy Destruction Ratio _Two Stages	1.215	1.237	1.277	1.270
Exergetic Efficiency _{Three Stages}	0.3614	0.3565	0.3515	0.3544
Exergy Destruction Ratio (EDR _{Three Stages})	1.767	1.805	1.845	1.822
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	35.38	35.73	36.09	35.88
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	33.65	33.98	34.86	34.86
Work required to run Compressor W_{Comp} "kW"	17.19	17.70	17.70	17.19
Exergy of Fuel _{Two Stages} "kW"	69.03	69.70	70.96	70.74
Exergy _{Product} _{Two Stages} "kW"	26.44	26.70	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	86.22	87.41	88.66	87.93
Exergy _{Product} _{Three Stages} "kW"	31.16	31.15	31.13	31.15
Condenser Heat _{HTC} "kW"	121.4	122.6	123.8	123.1
HTC Evaporator load = Condenser Heat _{MTC} "kW"	86.01	86.85	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.36	52.87	52.87	52.36
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.6764	0.7830	0.7899	0.7859
MTC Mass flow rate (kg/sec)	0.3436	0.3472	0.4630	0.4117
LTC Mass flow rate (kg/sec)	0.2203	0.1939	0.1939	0.2203

To find out the effect of system performances using R1234yf ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^{\circ}\text{C}$ and sub cooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following four cascaded systems (system-17 to system-20) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies = 80% is shown in Table-11(e) respectively.

System-17

Cascaded vapour compression refrigeration system using R1234yf in HTC and R1233zd (E) in MTC and R-1225ye (Z) in LTC.

System-18

Cascaded vapour compression refrigeration system using

R1234yf in HTC and R1233zd (E) in MTC and HFO-1336mzz (Z) in LTC

System-19

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30°C and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

System-20

Cascaded vapour compression refrigeration system using R1234yf in HTC at evaporator temperature of -30°C and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

Table-11(e) shows the comparisons of thermodynamic performances of system-17 to system-20 using R1234yf in the high temperature cycle and it was observed that First law (energy) and second law (Exergy) performances of system-17 are highest and system-19 is lowest.

Table-11(e) Effect of system performances using R1234yf ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies = 80%.

Performance Parameters	System-17	System-18	System-19	System-20
HTC First law Efficiency (COP _{HTC})	2.276	2.276	2.276	2.276
MTC First law Efficiency (COP _{MTC})	1.556	1.556	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.035	1.045	1.009	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7329	0.7329	0.7202	0.7154
Cascade First law Efficiency (COP _{Cascade})	0.3925	0.3968	0.386	0.3891
Exergetic Efficiency _{HTC}	0.3029	0.3029	0.3029	0.3029
Exergy Destruction Ratio (EDR _{HTC})	2.302	2.302	2.302	2.302
Exergetic Efficiency _{MTC}	0.4320	0.4362	0.4245	0.4258
System Exergy Destruction Ratio _{Two Stages}	1.315	1.293	1.356	1.349
Exergetic Efficiency _{Three Stages}	0.3469	0.3516	0.3420	0.3448
Exergy Destruction Ratio (EDR _{Three Stages})	1.883	1.844	1.924	1.90
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	38.16	37.79	38.55	38.32
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	33.98	33.65	34.86	34.86
Work required to run Compressor $W_{\text{Comp LTC}}$ "kW"	17.7	17.19	17.70	17.19
Exergy of Fuel _{Two Stages} "kW"	72.14	71.44	73.41	73.18
Exergy Product _{Two Stages} "kW"	26.44	26.70	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	89.84	88.63	91.11	90.37
Exergy Product _{Three Stages} "kW"	31.16	31.15	31.13	31.15
Condenser Heat _{HTC} "kW"	125.0	123.8	126.3	125.5
HTC Evaporator load = Condenser Heat _{MTC} "kW"	86.85	86.01	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.87	52.37	52.87	52.36
MTC Evaporator load "kW"	35.167	35.167	35.167	35.167
HTC Mass flow rate (kg/sec)	0.9203	0.9114	0.9297	0.9242
MTC Mass flow rate (kg/sec)	0.3436	0.3472	0.4630	0.4117
LTC Mass flow rate (kg/sec)	0.2203	0.1939	0.1939	0.2203

To find out the effect of system performances using R1233zd(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^\circ\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following two cascaded systems (system-21 & system-22) using ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies = 80%. Is shown in table-11(f) respectively.

System-21

Cascaded vapour compression refrigeration system using

R1233zd (E) in HTC at evaporator temperature of -10°C and 1225ye (Z) in MTC and HFO-1336mzz (Z) in LTC

System-22

Cascaded vapour compression refrigeration system using R1233zd (E) in HTC at evaporator temperature of -10°C and HFO-1336mzz (Z) in MTC and and R1225ye (Z) in LTC

Table-11(f) shows the comparisons of thermodynamic performances of system-21 & system-22 using R1233zd(E) in the high temperature cycle and it was observed that second law (Exergy) performances of system-22 are higher than system-21. Although system-22 is less energy efficient than system-21 in terms of first law efficiency (COP).

Table-11(f) Effect of system performances using R1233zd(E) ecofriendly refrigerant in high temperature cycle at condenser temperature $T_{\text{Cond}} = 55^{\circ}\text{C}$ and subcooling at 45°C and evaporator temperature -10°C , and ecofriendly refrigerant in intermediate temperature cycle at evaporator temperature -75°C and following ecofriendly refrigerant in low temperature cycle at evaporator temperature -115°C on the performance of cascade vapour compression refrigeration systems for isentropic compressors efficiencies $=80\%$.

Performance Parameters	System 21	System 22
HTC First law Efficiency (COP _{HTC})	2.640	2.640
MTC First law Efficiency (COP _{MTC})	1.516	1.502
LTC First law Efficiency (COP _{LTC})	1.009	1.009
Cascade First law Efficiency (COP _{Cascade})	0.7764	0.7711
Cascade First law Efficiency (COP _{Cascade})	0.4099	0.4133
Exergetic Efficiency _{HTC}	0.3513	0.3513
Exergy Destruction Ratio (EDR _{HTC})	1.846	1.846
Exergetic Efficiency _{MTC}	0.4576	0.4589
System Exergy Destruction Ratio _{Two Stages}	1.145	1.179
Exergetic Efficiency _{Three Stages}	0.3632	0.3662
Exergy Destruction Ratio (EDR _{Three Stages})	1.753	1.731
Work required to run Compressor $W_{\text{Comp HTC}}$ "kW"	33.23	33.04
Work required to run Compressor $W_{\text{Comp MTC}}$ "kW"	34.86	1.846
Work required to run Compressor W_{Comp} "kW"	17.7	17.19
Exergy of Fuel _{Two Stages} "kW"	68.10	67.9
Exergy _{Product} Two Stages "kW"	26.70	26.44
Exergy of Fuel _{Three Stages} "kW"	85.80	85.09
Exergy _{Product} Three Stages "kW"	31.16	31.15
Condenser Heat _{HTC} "kW"	121.0	120.3
HTC Evaporator load = Condenser Heat _{MTC} "kW"	87.73	87.22
MTC Evaporator load = Condenser Heat _{LTC} "kW"	52.87	52.36
LTC Evaporator load "kW"	35.167	35.167
HTC Mass flow rate (kg/sec)	0.6191	0.6155
MTC Mass flow rate (kg/sec)	0.463	0.4117
LTC Mass flow rate (kg/sec)	0.1939	0.2203

3. Conclusions

To see the suitability of using HFO refrigerants, the numerical computations for simple vapour compression refrigeration systems (VCRC) in the two & three stages cascaded vapour compression refrigeration system (CVCRC) have been carried out to investigate the thermodynamic (energy-exergy) performances of ultra-low GWP hydrofluoroolefens (HFO) refrigerants working on vapour compression refrigeration cycle. The effect of varying temperature overlapping between cascaded condenser-evaporator (approach), and sub cooling in high temperature condenser on thermodynamic performances also been investigated for cascaded vapour compression refrigeration systems.

The output parameters computed are compressors work as exergy input ($W_{\text{Comp HTC}}$ and $W_{\text{Comp LTC}}$), and Compressor and the coefficient of performance (COP) of HTC cycle and energy performance of cascaded vapour compression refrigeration systems (COP_{Cascade System}) have been carried out. The second law performances (exergetic efficiency and exergy destruction ratios) of simple and cascaded vapour compression refrigeration systems have been computed. Results showed that R1234ze (Z) and R1233zd(E) gives better thermodynamic performances. Than using HFC -134a. However, R1224yd (Z) of seven GWP

overcome favorable thermodynamic (energy and exergy) performances, above -10°C of evaporator can suitably replace R134a. Similarly, HFO-1336mzz(Z) also gives better energy-exergy performances as compared to HFC-134a. However, R1234yf although gives 4% to 10% lesser thermodynamic (energy and exergy) performances than using high GWP ecofriendly HFC-134a refrigerant. Therefore, these ultra-low GWP ecofriendly HFO refrigerants can serve as new alternative refrigerants for replacing HFC-134a in the vapour compression refrigeration systems for a sustainable environment.

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