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Exergetic performance evaluations of simple & cascade vapour compression refrigeration systems using ecofriendly HFO refrigerants

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Abstract

In this paper thermodynamic analysis of simple and cascaded vapour compression refrigeration systems using several ultra-low GWP ecofriendly HFO refrigerants and it was found that The R1234ze(Z) gives better thermodynamic performances than all HFO and HFC refrigerants. The thermodynamic performance of R1224yd(Z) and HFC-152a and HFC-245fa is nearly similar. The thermodynamic performances of R1234ze(E) and R1243zf are nearly similar and lower than R-1225ye(Z) and HFC-1336mzz(Z). However, R1234yf gives the lowest thermodynamic performances and lower performance than R134a. Numerical computation was carried out and results obtained by using HFO refrigerants were compared with R134a and found that R-1234ze(Z) and R1224yd(Z) can be used up to evaporator temperature of 273K in the high-temperature cycle and R1234ze(E),& R-1243zf used up to -30^{o}C and R1234yf up to evaporator temperature of -50^{o}C in the low-temperature cycle. It was also found that total exergy destruction in the high-temperature cycle in cascaded vapour compression refrigeration system is lower than total exergy destruction in lower temperature cycle. The second law exergetic performances (exergetic efficiency and also rational efficiency) have been computed from simple and cascaded systems. The exergy destruction in vapour compression system and cascaded vapour compression refrigeration systems using R1234ze(Z), R1224yd(Z), R1234ze(E),& R-1243zf in the high-temperature cycle and HFC-1336mzz(Z) in lower temperature cycle is lower than using R1225ye(Z) in lower temperature cycle up to -90^{o}C of evaporator temperature. For ultra-low temperature applications, use of R1234ze(Z), R1234ze(E), R1243zf, R1224yd(Z) in high-temperature cycle up to 0^{o}C and HFO-1336mzz(Z) , R-1225ye(Z) and R1234yf in medium temperature cycle up to -50^{o}C and HFO-1336mzz(Z) or R-1225ye(Z) in low-temperature cycle up to -130^{o}C to -150^{o}C have been proposed for biomedical applications.

Keywords: Thermodynamic performances, exergy destruction in components, HFO refrigerants, Cascaded VCRS.

1. Introduction

Refrigerants are used in a large variety of HVAC&R equipment. The first generation of refrigerants included substances such as hydrocarbons, ammonia, and carbon dioxide. The second generation of refrigerants included chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs), which became widely used because they were efficient, non-flammable, and non-toxic. During the period of 1980s, CFCs and HCFCs were determined to play a vital role in depleting the stratospheric ozone layer. Initially in the 1990s, the industry phased out CFCs and HCFCs in favour of the third generation of refrigerants: hydro-fluorocarbons (HFCs).

HFCs have zero ozone depletion potential; however, when released to the atmosphere, they have important global warming potential (GWP). The growing international emphasis on global warming mitigation has stimulated interest in the fourth generation of low-GWP refrigerants. In 2014, the United States, Canada and Mexico proposed an amendment to the Montreal Protocol to reduce production and consumption of HFCs by 85% during the period 2016–2035, for developed countries. Under the proposal, developing countries would reduce HFC production and consumption by 85% during the later period of 2025–2045.In addition, the European F-gas legislation was issued in 2014. Under the F-gas regulations, HFC consumption will be reduced by 79% over the period 2016–2030, a more aggressive timeline than the North American Montreal Protocol proposal. The F-gas regulations also include application-specific bans covering new

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equipment as well as service and maintenance. In the U.S., reducing the nation's HFC consumption by 85 percent would require in the HVAC&R industry. Therefore, there is an urgent need for searching alternative refrigerants which have low GWP ecofriendly refrigerants [1].

2. Global Warming Potential

Global Warming Potential, or GWP, is a measure of how damaging a climate pollutant is. Refrigerants today are often thousands of times more polluting than carbon dioxide (CO_2). The GWP of a gas refers to the total contribution to global warming resulting from the emission of one unit of that gas relative to one unit of the reference gas, CO_2, which is given a value of 1. GWPs can also be used to define the impact greenhouse gases will have on global warming over different time periods or time horizons.

These are usually 20 years, 100 years, and 500 years. A time horizon of 100 years is used by regulators (e.g., the California Air Resources Board). CARB maintains a list of GWPs for some common refrigerants. The most common refrigerant today, R-22, has a 100-year GWP of 1810, almost 2,000 times the potency of carbon dioxide.

The most common replacement for R-22 in the supermarket systems, R-404A, is more than twice as potent a greenhouse gas than R-22. The shared replacements for R-22, such as R134a, R-404A and R-507A, but the future restrictions is because of their high GWP values and the availability of alternatives that attitude a lower overall risk to human health and/or the environment. In addition, national and international efforts to phase-down the global use of these and other high-GWP refrigerants may affect future price and availability. New low-GWP technologies and solutions are progressing speedily and are available today. Refrigerants regulated under the Refrigerant Management Program (RMP) include any refrigerant that is an ozone-depleting substance (ODS) as defined in the Code of Federal Regulation, Part 82, and any compound with a global warming potential (GWP) value equal to or greater than 150 according to the GWPs quantified in IPCC's fourth Assessment Report of 2007.

3. HFO Refrigerants for replacing R134a

Nowadays most of the energy utilized in cooling and air conditioning in industrial as well as for domestic applications, in addition to energy consumption, using refrigerants in cooling and air conditioning having high GWP and ODP which are responsible for increasing global warming and ozone depletion. The primary requirements of ideal refrigerants are having good physical and chemical properties. Due to good physical and chemical properties such as non-corrosiveness, non-toxicity, non-flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades, but hydro chloro fluoro carbons (HCFCs) and Chlorofluorocarbons (CFCs) having a large amount of chlorine content as well as high global warming potential and ozone depletion potential, Therefore in the 1990s refrigerants under these categories these kinds of refrigerants are almost prohibited and HCFCs and HFC refrigerants were used due to low ODP and medium GWP. After the 1990s, low GWP and zero HFC and few HFO refrigerants such as R1234yf and R1234ze were introduced due to zero global warming potential and ozone depletion potential HFO refrigerants known as Hydrofluro-Olefins, are a new category of refrigerants that have a much lessened global warming potential then it's HFC alternatives. For example being the 134a alternative, 1234yf and 1234ze which is 335 and 225 times lower on the global warming potential scale and only four times and six higher than standard carbon dioxide.

4. Exergy Evaluations in simple and cascaded vapour compression refrigeration systems

The utility of exergy analysis (i.e. second law analysis) on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system. Arora and Kaushik [2] carried out energy and exergy analysis of vapour compression refrigeration system with liquid vapour heat exchanger for a specific temperature range of evaporator and condenser and found that the R502 is the best refrigerant than R404A and R507A,

Padilla et al [3] used energy analysis of domestic vapour compression refrigeration system with R12 and R413a and found that the thermal performances in terms of power consumption and the energy efficiency of R413A is better than R12. Cabello et al.[4] experimentally investigated the effect of condensing pressure, evaporating pressure and degree of superheating on single-stage vapour compression refrigeration system using R22, R134a and R407C and observed that mass flow rate is greatly affected by a change in suction conditions of the compressor and found that higher compression ratio using R407C gives lower first law performance (COP) than R22. Mohanraj et al [5] showed experiments on the domestic refrigerator and determined under different environmental temperatures the first law efficiency in terms of COP of the system using a mixture of R290(45.2%) and R600a (54.8%) by weight and found 3.6% greater thermodynamic performances as compared with the used R134a refrigerant, in the same system, using the same compressor with R134a.

Getu and Bansal [6] had optimized the design operating parameters of R744R717 cascade refrigeration system. Using regression analysis. Most of the study has been carried out for the performance evaluation of vapour compression refrigeration system using energetic analysis, but with the help of first law analysis irreversibility destruction or losses in components of a system unable to determined [2-6], Therefore exergetic analysis is the advanced approach for thermodynamic performances is very essential for finding irreversibility in terms of exergy destruction occurred in the various components of simple and cascaded vapour compression refrigeration systems.

This paper mainly deals with the utility of ultra-low GWP ecofriendly HFO refrigerants by computing thermodynamic performances on vapour compression refrigeration system and cascaded refrigeration systems for replacing high GWP HFC refrigerants(i.e. R134a, R404a, R410a, R507a, R125, R407c, R236fa, R245fa, R32,etc.) and HCFC refrigerants (i.e. R22, R123,R124etc)

The thermodynamic performances evaluation of cascaded vapour compression refrigeration systems using several HFO refrigerants manufactured by Honeywell for replacing the use of HFCs are used in the present investigations.

Mishra [7-10] carried out thermodynamic analysis of vapour compression refrigeration systems using liquid vapour heat exchanger by using ten ecofriendly low GWP HFO refrigerants studies in detail and it was found that The R1234ze(z) gives better thermodynamic performances than R1234ze(E) and R1243zf. The thermodynamic performance of R1224yd(Z) and HFO-1336mzz(Z) is nearly similar and higher than R1234ze(E) but lower than R1224yd(Z).However R1234yf gives lowest thermodynamic performances. The effect of condenser temperature and evaporator temperature of modified vapour compression refrigeration systems were studied in detail and it was found that first law efficiency decreases' with increasing condenser temperature and also increases with evaporator temperature. However by increasing condenser and evaporator temperatures, the exergetic efficiency decreases, It was found that maximum exergy destruction takes place in the compressor which have external irreversibilities and exergy destruction ratio is lower in the throttling valves. However second higher exergy destruction takes place in the evaporator even higher than condenser and throttle valve. Therefore for reducing higher exergy destruction in evaporator, use of nano mixed particles in the secondary evaporator circuit was proposed [11-12].

5. Results and Discussion

Table-1(a) shows the effect of various HFO refrigerants on the thermal performances of vapour compression refrigeration system and it is found that highest performance by using R1233zd(E) and second ecofriendly ultra-low GWP refrigerant is HFO-1336mzz(Z) It is also found that the coefficient of performance using HFO-1234ze(E) is nearly same with HFO-1243zf and slightly higher than using nontoxic HFO-1225ye(Z) .and also higher than R134a. However the lowest COP was observed by using R-1234yf. Similarly power required to run compressor is also lowest by using R1233zd(E) as compared to R134a and also exergy destruction ratio is also lowest.

Table-1(b) shows the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system and it is found that highest exergy destruction in system was found by using R1234yf and lowest by using R-1233zd(E) .It was also observed that for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor. In the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred. Therefore HFO refrigerants can easily replace R134a which has high GWP high GWP

Table-1(a) Thermal Performances of vapour compression refrigeration systems using ultra low GWP following refrigerants (T$_{\_Cond\_HTC}$ =50ºC, T$_{\_EVA\_HTC}$=-30ºC, T$_{\_EVA\_LTC}$=-90ºC, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

Performance Parameters	R1234ze(E)	HFO-1336 mzz(Z)	R-1233zd(E)	R-1225ye(Z)	R1234yf	R-1243zf	R-134a
Over all COP	1.448	1.547	1.669	1.427	1.317	1.446	1.508
EDR_system	2.052	1.856	1.647	2.096	2.354	2.055	1.930
Exergetic Efficiency	0.3277	0.3502	0.3778	0.3230	0.2981	0.3274	0.3413
DOTM(kg/sec)	0.0380	0.0365	0.2904	0.04468	0.04709	0.03294	0.03236
Exergy of Fuel"kW"	2.429	2.273	2.107	2.464	2.67	2.431	2.332
Exergy of Product "kW"	0.796	0.796	0.796	0.796	0.796	0.796	0.796
Exergy_input"kW"	3.195	3.04	2.88	3.225	3.420	3.201	3.103
EDR_Second	3.014	2.819	3.052	3.051	3.307	3.021	2.898
Exergetic Efficiency	0.2491	0.2818	0.2764	0.2468	0.2322	0.2487	0.2585

Table-1(b) Percentages of exergy destruction in various components of vapour compression refrigeration system using ultra low GWP following refrigerants (T$_{\_Cond\_HTC}$ =50ºC, T$_{\_EVA\_HTC}$=-30ºC, T$_{\_EVA\_LTC}$=-90ºC, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

Performance Parameters	R1234ze(E)	HFO-1336 mzz(Z)	R-1233zd(E)	R-1225ye(Z)	R1234yf	R-1243zf	R-134a
(%) EXD$_{\_Total}$	75.09	73.82	72.36	75.32	76.78	75.13	74.35
(%) EXD$_{\_Comp}$	13.85	13.79	13.1	13.86	14.24	13.45	13.11
(%) EXD$_{\_Cond}$	14.86	14.82	15.59	14.67	14.86	15.10	15.69
(%) EXD$_{\_Eva}$	23.68	25.84	26.75	23.50	21.8	24.75	24.73
(%) EXD$_{\_Valve}$	22.9	20.06	16.92	23.29	25.86	21.84	20.81
(%) Exergetic Efficiency	24.91	28.18	27.64	24.68	23.22	24.87	25.85

5.1 Thermodynamic performance evaluation of cascade vapour compression refrigeration systems

Table-2(a) shows the effect of high temperature ecofriendly HFO refrigerants on the thermal performances of cascade vapour compression refrigeration system using ultra low GWP R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle and it is found that highest overall system first law performance in terms of coefficient of performance(COP_Overall) is highest by using R1233zd(E). It is also fund that first law efficiency in terms of coefficient of performance by using performance was found by using HFO1336mzz(Z) refrigerant is nearly similar thermodynamic performances as using R1234ze(E) refrigerant .Similarly power consumption to run whole system is also nearly same by using HFO1336mzz(Z) or R1234ze(E) refrigerant . but mass flow rate of refrigerant in high temperature cycle is different which significantly effecting the size of the system with same cooling capacity.Similarly power required to run high temperature compressor is also lowest by using R1233zd(E) as comparison to R1234ze(E) and HFO-1336mzz(Z). Also, heat rejection from condensers is also lowest by using R1233zd (E). The power required to run high temperature cycle compressor is nearly same by using R1234ze (E) and HFO-1336mzz (Z). Table-2(b) shows the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system using ultra low GWP R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle ultra-low GWP R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle and it is found that highest exergy destruction in lower temperature cycle (LTC) is around 80% than the exergy destruction in high temperature cycle .It was also found that exergy destruction in LTC cycle is highest as using R1233zd(E) in high temperature cycle and lowest in high temperature cycle as compared to other HFO refrigerants used in high temperature cycle. The total exergy destruction in compressors was found highest by using R1234ze(E) and lowest by using HFO-1336mzz(Z) and exergy destruction in compressors using R1233zd(E) is slightly higher than using HFO-1336mzz(Z) and lowest than using R1234ze(E). Similarly for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor and throttle valves for all HFO refrigerants used in high temperature cycle. To comparison, it was also found that the exergy destruction in evaporators are highest by using HFO1336mzz (Z) in high temperature cycle and using R-1234ze(E) is lowest. Similarly in the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred in the throttle valves. Therefore HFO refrigerants of ultra-low GWP can easily replace R134a which has high GWP in near future.

Table-3(a) shows the effect of high temperature ecofriendly HFO refrigerants on the thermal performances of cascade vapour compression refrigeration system using ultra low GWP ecofriendly HFO-1336mzz (Z) refrigerant in low temperature and following refrigerants in high temperature cycle and it is found that highest overall system first law performance in terms of coefficient of performance (COP_Overall) is highest by using R1233zd (E). It is also fund that first law efficiency in terms of coefficient of performance by using performance was found by using HFO1336mzz(Z) refrigerant is nearly similar thermodynamic performances as using R1234ze(E) refrigerant .Similarly power consumption to run whole system is also nearly same by using HFO1336mzz(Z) or R1234ze(E) refrigerant . But mass flow rate of refrigerant in high temperature cycle is different which significantly effecting the size of the system with same cooling capacity. Similarly power required to run high temperature compressor is also lowest by using R1233zd(E) as comparison to R1234ze(E) and HFO-1336mzz(Z). Also, heat rejection from condensers is also lowest by using R1233zd(E). The power required to run high temperature cycle compressor is nearly same by using R1234ze(E) and HFO-1336mzz(Z). The thermodynamic performances using R152a is best as compared to HFO refrigerants but HFO refrigerants has ultra-low GWP as compared to R152a up to high temperature evaporator temperature of -20ºC. For high temperature application of evaporator temperature above 0ºC, the HFO refrigerant R1234ze(z) has best thermodynamic performance as compared to R152a and R245fa. Similarly the thermodynamic performances using R-1224yd(Z) is similar than using R152a in high temperature cycle for HTC evaporator temperature of 0ºC. Table-3(b) shows the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system using ultra low GWP ecofriendly HFO-1336mzz(Z) refrigerant in low temperature and following refrigerants in high temperature cycle and following refrigerants in high temperature cycle and it is found that highest exergy destruction in lower temperature cycle (LTC) is around 22.4% than the exergy destruction in high temperature cycle .It was also found that exergy destruction in LTC cycle is highest as using R1233zd(E) in high temperature cycle and lowest in high temperature cycle as compared to other HFO refrigerants used in high temperature cycle. The total exergy destruction in compressors was found highest by using R1234ze(E) and lowest by using HFO-1336mzz(Z) and exergy destruction in compressors using R1233zd(E) is slightly higher than using HFO-1336mzz(Z) and lowest than using R1234ze(E). Similarly for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor and throttle valves for all HFO refrigerants used in high temperature cycle. To comparison, it was also found that the exergy destruction in evaporators are highest by using HFO1336mzz (Z) in high temperature cycle and using R-1234ze(E) is lowest. Similarly in the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred in the throttle valves. Therefore HFO refrigerants of ultra-low GWP can easily replace R152a , R245fa, R32 and R134a which has high GWP in near future.

Table-2 (a) Thermal Performances of cascade vapour compression refrigeration systems using ultra low GWP R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{EVA\_HTC}$=-20^{o}C, T_$_{EVA\_LTC}$=-90^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

Performance Parameters	R-1234ze(E)	HFO1336mzz(Z)	R-1233zd(E)	R-1243zf
Overall cascaded First law efficiency (COP)	0.5796	0.5773	0.5997	0.5792
Cascaded Exergy Destruction Ratio (EDR)	1.745	1.756	1.653	1.760
Cascaded Exergetic Efficiency	0.3643	0.3626	0.3679	0.3691
Power required to run system & Exergy of Fuel"kW"	60.67	60.91	58.64	60.79
Cascaded Exergy of Product "kW"	22.1	22.1	22.1	22.1
High temperature cycle first law Efficiency (COP_$_{HTC}$)	1.860	1.847	1.98	2.104
Low temperature cycle first law Efficiency COP_$_{LTC}$)	1.295	1.295	1.295	1.295
Mass flow rate in high temperature cycle (DOTM_$_{HTC}$) Kg/s	0.6255	0.5492	0.6007	0.4862
Mass flow rate in low temperature cycle (DOTM_$_{LTC}$) Kg/s	0.2997	0.2997	0.2997	0.2997
Power required to run high temperature cycle compressor (W$_{\_Comp\_HTC}$) "kW"	33.51	33.75	31.48	29.63
Power required to run low temperature cycle compressor (W$_{\_Comp\_LTC}$) "kW"	27.16	27.16	27.16	27.16
Heat rejected by high temperature condenser (Q$_{\_Cond\_HTC}$) "kW"	95.84	96.08	93.8	91.96
Heat rejected by low temperature condenser (Q$_{\_Cond\_LTC}$) "kW"	62.33	62.33	62.33	62.33
Cooling load on low temperature evaporator (Q$_{\_Eva\_LTC}$) "kW"	35.167	35.167	35.167	35.167

Table-2(b) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{EVA\_HTC}$=-20^{o}C, T_$_{EVA\_LTC}$=-90^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

% Exergy Destruction in Components	R-1234ze(E)	HFO1336mzz(Z)	R-1233zd(E)	R-1243zf
High temperature Compressor_$_{HTC}$	7.425	7.214	7.716	6.679
Low temperature Compressor Comp_$_{LTC}$	6.312	6.23	6.45	6.496
Total Exergy destruction in Compressors_$_{Total}$	13.74	13.44	13.63	13.17
High temperature Condenser_$_{HTC}$	9.079	8.163	9.026	9.034
Low temperature Condenser Cond_$_{LTC}$	8.126	8.023	8.305	8.365
Total Exergy destruction in Condenser_$_{Total}$	17.210	17.19	17.33	17.140
High temperature Evaporator_$_{HTC}$	4.855	6.308	5.418	7.04
Low temperature Evaporator_$_{LTC}$	18.67	18.43	19.08	19.21
Total Exergy destruction in Eva_$_{Total}$	23.52	24.73	24.49	26.25
High temperature Valve_$_{HTC}$	10.79	10.35	9.057	7.427
Low temperature Valve_$_{LTC}$	7.999	7.895	8.173	8.231
Total Exergy destruction in Valves_$_{Total}$	18.79	18.24	17.23	15.66
% Total Exergy Destruction in HTC	32.15	33.03	30.78	30.18
% Total Exergy Destruction in LTC	41.11	40.58	42.0	42.3
EDR_Rational and Total Exergy Destruction	0.7326	0.7361	0.7278	0.7248
Rational Exergetic_Efficiency	0.2674	0.2639	0.2732	0.2752
EDR_system	2.7397	2.7893	2.664	2.6332

Table-3(a) Thermal Performances of cascade vapour compression refrigeration systems using low GWP HFO-1336mzz(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{EVA\_HTC}$=-20^{o}C, T_$_{EVA\_LTC}$=-90^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

Performance Parameters	R1234ze(E)	R1243zf	R1225ye(Z)	R1233zd(E)	R-152a
Overall cascaded First law efficiency (COP)	0.5704	0.5681	0.5652	0.6091	0.6066
Cascaded Exergy Destruction Ratio (EDR)	1.790	1.801	1.816	1.613	1.623
Cascaded Exergetic Efficiency	0.3584	0.3570	0.3552	0.3827	0.3812
Power required to run system & Exergy of Fuel"kW"	61.86	61.9	62.22	57.74	57.97
Cascaded Exergy of Product "kW"	22.1	22.1	22.1	22.1	22.1
High temperature cycle first law Efficiency (COP_$_{HTC}$)	1.86	1.847	1.83	2.104	2.047
Low temperature cycle first law Efficiency COP_$_{LTC}$)	1.265	1.265	1.265	1.265	1.265
Mass flow rate in high temperature cycle (DOTM_$_{HTC}$) Kg/s	0.6319	0.5548	0.7456	0.4912	0.3125
Mass flow rate in low temperature cycle (DOTM_$_{LTC}$) Kg/s	0.2711	0.2711	0.2711	0.2711	0.2711
Power required to run high temp cycle compressor (W$_{\_Comp\_HTC}$) "kW"	33.85	34.1	34.42	29.93	30.17
Power required to run low temp cycle compressor (W$_{\_Comp\_LTC}$) "kW"	27.8	27.8	27.8	27.8	27.8
Heat rejected by high temperature condenser (Q$_{\_Cond\_HTC}$) "kW"	96.82	97.07	97.39	92.91	93.14
Heat rejected by low temperature condenser (Q$_{\_Cond\_LTC}$) "kW"	62.97	62.97	62.97	62.97	62.97

Table-3(b) Percentage exergy Destruction in various components of cascade vapour compression refrigeration systems using low GWP HFO-1336mzz(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50°C, T_$_{EVA\_HTC}$=-20°C, T_$_{EVA\_LTC}$=-90°C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

% Exergy Destruction in Components	R-1234ze(E)	R-1243zf	R1225ye(Z)	R1233zd(E)	R-152a
Comp_$_{HTC}$	7.320	7.112	7.479	6.580	6.021
Comp_$_{LTC}$	6.386	6.304	6.44	6.568	6.395
Comp_$_{Total}$	13.71	13.42	13.92	13.15	12.42
Cond_$_{HTC}$	8.951	9.035	9.108	9.902	9.516
Cond_$_{LTC}$	8.269	8.163	8.339	8.505	8.28
Cond_$_{Total}$	17.22	17.20	17.44	17.41	17.8
Eva_$_{HTC}$	4.701	6.145	3.34	6.868	9.049
Eva_$_{LTC}$	18.96	18.72	19.12	19.50	18.99
Eva_$_{Total}$	23.67	24.86	22.46	26.36	28.04
Valve_$_{HTC}$	10.64	10.20	11.11	7.318	6.941
Valve_$_{LTC}$	8.674	8.562	8.747	8.921	8.685
Valve_$_{Total}$	19.32	18.77	19.86	16.24	15.63
% Total Exergy Destruction in HTC	32.81	32.5	31.04	29.67	31.53
% Total Exergy Destruction in LTC	42.29	41.75	42.65	43.5	42.35
EDR_Rational	0.7391	0.7424	0.7369	0.7317	0.7387
Exergetic_Efficiency	0.2609	0.2576	0.2631	0.2683	0.2613
EDR_System	2.833	2.882	2.80	2.727	2.827

5.2 *Effect of ecofriendly HFO refrigerants in LTC Circuit using R1234ze in HTC*

Table-4(a) shows the effect of ultra-low GWP ecofriendly HFO refrigerants on the thermal performances of cascade vapour compression refrigeration system using low GWP R1234ze (E) refrigerants in high temperature cycle and following refrigerants in low temperature cycle and it is found that highest overall system first law performance in terms of coefficient of performance (COP_Overall) is highest by using R1233zd (E) is nearly similar with R245fa. Although first and second law exergetic thermal performances are slightly higher and difference in performance around 0.22%. It is also found that first law efficiency in terms of coefficient of performance by using performance was found by using R-32a is lowest. The difference in second law exergetic performance between R1233zd(E) and HFO1336mzz(Z) refrigerants is nearly 2% and between R1233zd(E) & R1225ye(Z), the thermodynamic exergetic performance difference 0.44% below than half percent. Similarly power consumption to run whole system using R1225ye(Z) and R1233zd(E) R1233zd(E)is also nearly same and by using HFO1336mzz(Z) refrigerant is around 2.08% . The mass flow rate of HFO1336mzz (Z) refrigerant in high temperature cycle is different which significantly effecting the size of the system with same cooling capacity also lower than using R1233zd(E) and R1225ye(Z) . Similarly power required to run high temperature compressor is also lowest by using R1233zd (E) as comparison to HFO1336mzz (Z) and R1225ye (Z). Also, heat rejection from condensers is also lowest by using R1233zd (E) as compared to HFO-1336mzz (Z). The power required to run low temperature cycle compressor using R1233zd (E) is also lowest as compared to R1225ye(Z) and HFO-1336mzz(Z). Table-4(b) shows the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system using ultra low GWP R1234ze(E) refrigerants in high temperature and following refrigerants in low temperature cycle and following refrigerants in low temperature cycle and it is found that highest exergy destruction in lower temperature cycle (LTC) is around 25.3% than the exergy destruction in high temperature cycle .It was also found that exergy destruction in LTC cycle is highest as using R1233zd(E) in high temperature cycle and lowest in high temperature cycle as compared to other HFO refrigerants used in high temperature cycle. The total exergy destruction in compressors was found highest by using HFO-1336mzz (Z) and lowest by using R1233zd (E) and exergy destruction in high compressor using R1233zd (E) in high temperature cycle is slightly higher than exergy destruction in low temperature compressor. It is also found that the total exergy destruction in compressors using HFO-1336mzz (Z) and using R1225ye (Z) is nearly same. Similarly for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor and throttle valves for all HFO refrigerants used in high temperature cycle. For comparison, it was also found that the exergy destruction in evaporators are highest by using HFO1336mzz (Z) in high temperature cycle and using R-1233zd(E) is lowest. Similarly in the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred in the throttle valves. The exergy destruction using HFC-245fa in low temperature cycle is 9% lower than HFO1336mzz (Z) and 3.56% lower than using R1225ye (Z), but R245fa has high global warming potential as compared to HFO refrigerants which has ultra-low GWP. Therefore HFO refrigerants of ultra-low GWP can easily replace HFC-32, HFC-245fa, HFC-152a and HFC-134a in near future.

Table-4(a) Thermal Performances of cascade vapour compression refrigeration systems using low GWP R1234ze(E) refrigerant in high temperature and following refrigerants in high temperature cycle (T$_{\_Cond\_HTC}$ =50ºC, T$_{\_EVA\_HTC}$=-20ºC, T$_{\_EVA\_LTC}$=-90ºC, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

Performance Parameters	HFO1336mzz(Z)	R1225ye(Z)	R1233zd(E)	R245fa	R-32
Overall cascaded First law efficiency (COP)	0.5704	0.5796	0.5823	0.5836	0.5536
Cascaded Exergy Destruction Ratio (EDR)	1.790	1.745	1.733	1.727	1.875
Cascaded Exergetic Efficiency	0.3584	0.3643	0.3659	0.3668	0.3479
Power required to run system & Exergy of Fuel"kW"	61.66	60.67	60.40	60.26	63.53
Cascaded Exergy of Product "kW"	22.1	22.1	22.1	22.1	22.1
High temperature cycle first law Efficiency (COP$_{\_HTC}$)	84.7	82.5	82.93	83.03	78.36
Low temperature cycle first law Efficiency COP$_{\_LTC}$)	1.86	1.860	1.860	1.86	1.86
Mass flow rate in high temperature cycle (DOTM$_{\_HTC}$) Kg/s	1.265	1.295	1.303	1.308	1.212
Mass flow rate in low temperature cycle (DOTM$_{\_LTC}$) Kg/s	0.6319	0.6255	0.6237	0.4912	0.6441
Power required to run high temperature cycle compressor (W$_{\_Comp\_HTC}$)	0.2711	0.2996	0.2275	0.2711	0.1205
Power required to run low temperature cycle compressor (W$_{\_Comp\_LTC}$)	33.85	33.51	33.42	33.36	34.51
Heat rejected by high temperature condenser (Q$_{\_Cond\_HTC}$) "kW"	27.8	27.16	26.98	26.98	29.02
Heat rejected by low temperature condenser (Q$_{\_Cond\_LTC}$) "kW"	96.82	95.84	95.56	95.42	98.69
Cooling load on low temperature evaporator (Q$_{\_Eva\_LTC}$) "kW"	62.97	62.33	62.15	62.06	64.19
Overall cascaded First law efficiency (COP)	35.167	35.167	35.167	35.167	35.167

Table-4(b) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP ecofriendly R1234ze(E) refrigerants in high temperature and following refrigerants in low temperature cycle (T$_{\_Cond\_HTC}$ =50ºC, T$_{\_EVA\_HTC}$=-20ºC, T$_{\_EVA\_LTC}$=-90ºC, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

% Exergy Destruction in Components	HFO1336 mzz(Z)	R1225ye(Z)	R1233zd(E)	R-245fa	R-32
High temperature Compresor$_{\_HTC}$	7.32	7.425	7.379	7.358	8.065
Low temperature Compresor Comp$_{\_LTC}$	6.386	6.312	5.933	5.995	5.014
Total Exergy destruction in Compressors$_{\_Total}$	13.71	13.74	13.31	13.35	13.08
High temperature Condenser$_{\_HTC}$	8.591	9.079	9.023	8.998	9.862
Low temperature Condenser Cond$_{\_LTC}$	8.269	8.128	7.447	7.572	1.753
Total Exergy destruction in Condenser$_{\_Total}$	17.22	17.21	16.47	16.57	11.62
High temperature Evaporator$_{\_HTC}$	4.701	4.855	4.849	4.848	5.0
Low temperature Evaporator$_{\_LTC}$	18.96	18.67	20.54	20.50	24.74
Total Exergy destruction in Eva$_{\_Total}$	23.67	23.62	26.39	25.35	29.77
High temperature Valve$_{\_HTC}$	10.64	10.79	10.73	10.7	11.72
Low temperature Valve$_{\_LTC}$	8.674	7.999	7.455	7..419	5.631
Total Exergy destruction in Valves$_{\_Total}$	19.32	18.79	18.18	18.12	17.35
% Total Exergy Destruction in HTC	31.61	32.16	31.98	31.90	34.65
% Total Exergy Destruction in LTC	42.29	41.11	41.37	41.48	37.14
EDR_Rational and Total Exergy Destruction	0.7391	0.7326	0.7335	0.7339	0.7180
EDR_system	2.833	2.740	2.7523	2.758	2.547
Rational Exergetic_Efficiency	0.2609	0.2674	0.2665	0.2661	0.2820

5.3 *Effect of ecofriendly HFO refrigerants in HTC Circuit using HFO-1336mzz(Z) in LTC*

Table-5(a) &Table-5(b) shows the effect of high temperature ecofriendly HFO refrigerants on the thermal performances of cascade vapour compression refrigeration system using ultra low GWP ecofriendly HFO-1336mzz (Z) refrigerant in low temperature and following refrigerants in high temperature cycle and it is found that highest overall system first law performance in terms of coefficient of performance (COP$_{\_Overall}$) is highest by using R1234ze (Z). It is also found that cascaded overall first law efficiency in terms of coefficient of performance by using R1234yf was found to be lowest The cascaded overall first law performance (COP) of cascade system using R1234ze(Z) is higher as compared to using R134a in high temperature cycle. The overall COP of cascade vapour compression refrigeration system using R1225ye (Z) in high temperature cycle is 2.299% higher, 3.0% using R1224yd (Z) and 4.067% higher than using R134a. Similarly The cascaded overall second law exergetic performance of cascade system using R1234ze (Z) is 6.13% ,2.997% using R1224 yd(Z), 2.34% using R1225ye(Z)in high temperature cycle as compared to R134a used in high temperature cycle. The second law exergetic performance using R1224yd(Z) and R152a is nearly same. Similarly by using R1225ye(Z) refrigerant in high temperature cycle has second law exergetic performance slightly higher than using R134a.

However thermodynamic performances as using R1234ze(E) refrigerant is 0.5% lower than using R134a Similarly power consumption to run whole system is also nearly using R1234ze(Z) is lowest while by using R1234yf is highest. The power required to run both compressors is nearly same by using R1243zf or R1234ze(E) refrigerant in high temperature cycle . But mass flow rate of refrigerant in high temperature cycle is different which significantly effecting the size of the system with same cooling capacity and highest by using R1234yf and lowest by using R1234ze(Z) . Similarly power required to run high temperature compressor is also lowest by using R1234ze(Z) a and highest by using R1234yf. For comparison to R1234ze(E) and R-1225ye(Z), the power required to run whole cascade system is slightly lower by using HFO-1225ye(Z) . Also, heat rejection from condensers is also lowest by using R1233zd (Z) and also highest by using R1234yf in high temperature cycle. The power required to run high temperature cycle compressor using R1234ze(Z) is lowest and using HFO-1234yf is highest. The thermodynamic performances using R152a is best as compared to HFO refrigerants but HFO refrigerants has ultra low GWP as compared to R152a up to high temperature evaporator temperature of -20^{o}C . For high temperature application of evaporator temperature above 0^{o}C, the HFO refrigerant R1234ze(Z) has best thermodynamic performance as compared to R152a and R245fa. Similarly the thermodynamic performances using R-1224yd(Z) is similar than using R152a in high temperature cycle for HTC evaporator temperature of 0^{o}C.

Table-5(a) Thermal Performances of cascade vapour compression refrigeration systems using low GWP HFO1336mzz(Z) refrigerant in low temperature and following refrigerants in high temperature cycle (T_{Cond_HTC} =50^{o}C, T_{EVA_HTC}=0^{o}C, T_{EVA_LTC}=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

Performance Parameters	R1234ze(Z)	R1234ze(E)	R1243zf	R1224yd(Z)	R1233zd(E)
Overall cascaded First law efficiency (COP)	1.206	1.131	1.122	1.170	1.183
Cascaded Exergy Destruction Ratio (EDR)	1.466	1.630	1.649	1.54	1.514
Cascaded Exergetic Efficiency	0.4055	0.3802	0.3774	0.3936	0.3978
Power required to run system & Exergy of Fuel"kW"	29.16	31.11	31.34	30.05	29.73
Cascaded Exergy of Product "kW"	11.83	11.83	11.83	11.83	11.83
High temperature cycle first law Efficiency (COP_$_{HTC}$)	41.5	42.84	43.28	41.86	41.88
Low temperature cycle first law Efficiency COP_$_{LTC}$)	3.669	3.215	3.169	3.448	3.523
Mass flow rate in high temperature cycle (DOTM_$_{HTC}$) Kg/s	2.286	2.286	2.286	2.286	2.286
Mass flow rate in low temperature cycle (DOTM_$_{LTC}$) Kg/s	0.3144	0.4446	0.3987	0.4267	0.3547
Power required to run high temperature cycle compressor "kW"	0.2665	0.2665	0.2665	0.2665	0.2665
Power required to run low temperature cycle compressor "kW"	13.78	15.72	15.95	14.66	14.36
Heat rejected by high temperature condenser ($Q_{\_Cond\_HTC}$) "kW"	15.38	15.38	15.38	15.38	15.38
Heat rejected by low temperature condenser ($Q_{\_Cond\_LTC}$) "kW"	64.33	66.27	66.50	65.21	64.9
Cooling load on low temperature evaporator ($Q_{\_Eva\_LTC}$) "kW"	50.55	50.55	50.55	50.55	50.55
Overall cascaded First law efficiency (COP)	35.167	35.167	35.167	35.167	35.167

Table-5(b) Thermal Performances of cascade vapour compression refrigeration systems using low GWP HFO1336mzz(Z) refrigerant in low temperature and following refrigerants in high temperature cycle (T_{Cond_HTC} =50^{o}C, T_{EVA_HTC}=0^{o}C, T_{EVA_LTC}=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

Performance Parameters	R1225ye(Z)	R1234yf	R152a	R245fa	R32	R134a
Overall cascaded First law efficiency (COP)	1.121	1.088	1.171	1.172	1.117	1.136
Cascaded Exergy Destruction Ratio (EDR)	1.653	1.732	1.536	1.536	1.661	1.617
Cascaded Exergetic Efficiency	0.3769	0.3661	0.3938	0.3943	0.3758	0.3821
Power required to run system & Exergy of Fuel"kW"	31.38	32.31	30.03	30.0	31.47	30.95
Cascaded Exergy of Product "kW"	11.83	11.83	11.83	11.83	11.83	11.83
High temperature cycle first law Efficiency (COP_$_{HTC}$)	42.73	43.6	42.74	42.09	42.19	42.9
Low temperature cycle first law Efficiency COP_$_{LTC}$)	3.16	2.986	3.451	3.459	3.142	3.246
Mass flow rate in high temperature cycle (DOTM_$_{HTC}$) Kg/s	2.286	2.286	2.286	2.286	2.286	2.286
Mass flow rate in low temperature cycle (DOTM_$_{LTC}$) Kg/s	0.5269	0.2345	0.3556	0.3656	0.2311	0.3981
Power required to run high temperature cycle compressor "kW"	0.2665	0.2665	0.2665	0.2665	0.2665	0.2665
Power required to run low temperature cycle compressor "kW"	16.0	15.72	14.65	14.61	16.09	15.57
Heat rejected by high temperature condenser ($Q_{\_Cond\_HTC}$) "kW"	15.38	16.93	15.38	15.38	15.38	15.38
Heat rejected by low temperature condenser ($Q_{\_Cond\_LTC}$) "kW"	66.55	67.48	65.2	65.16	66.64	66.12
Cooling load on low temperature evaporator ($Q_{\_Eva\_LTC}$) "kW"	50.55	50.55	50.55	50.55	50.55	50.55
Overall cascaded First law efficiency (COP)	35.167	35.167	35.167	35.167	35.167	35.167

Table-5(c)& Table-5(d) show the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system using ultra low GWP ecofriendly HFO-1336mzz(Z) refrigerant in low temperature and following refrigerants in high temperature cycle and it is found that highest exergy destruction in lower temperature cycle (LTC is more than the exergy destruction in high temperature cycle .It was also found that exergy destruction in LTC cycle is lowest as using R1234ze(Z) in high temperature cycle and highest by using R1234yf in high temperature cycle as compared to other HFO refrigerants used in high temperature cycle. The total exergy destruction in compressors was found highest by using R32 and lowest by usingR-245fa. The percentage change percentage change total exergy destruction in cascade system using HFO-1225ye (Z) is 0.152% lower than using R134a in high temperature cycle. Similarly the percentage change percentage change total exergy destruction in cascade system using HFO-1243zf is 1.15% higher than using R1234ze (Z) in high temperature cycle. The total exergy destruction in compressors using R1234yf is highest than using R32 and lowest.It was also found that the exergy destruction in compressors using various HFO refrigerants are less than 1.3% .Similarly for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor and throttle valves for all HFO refrigerants used in high temperature cycle. To comparison, it was also found that the exergy destruction in evaporators are highest by using R1234ze (Z) in high temperature cycle and using R-1234ze(E) is lowest. Similarly in the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred in the throttle valves. Therefore HFO refrigerants of ultra-low GWP can easily replace R152a, R245fa, R32 and R134a which has high GWP in near future.

Table-5(c) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP HFO1336mzz(Z) refrigerants in low temperature and following refrigerants in high temperature cycle ($T_{\_Cond\_HTC}$ =50°C, $T_{\_EVA\_HTC}$=0°C, $T_{\_EVA\_LTC}$=-90°C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

% Exergy Destruction in Components	R1234ze(Z)	R1234ze(E)	R1243zf	R1225ye(Z)	R1224yd(Z)	R1233zd(E)
High temperature Compressor_$_{HTC}$	5.899	6.756	6.692	6.881	6.454	6.281
Low temperature Compressor Comp_$_{LTC}$	7.581	7.344	7.269	7.362	7.515	7.511
Total Exergy destruction in Compressors_$_{Total}$	13.48	14.10	13.96	14.24	13.97	13.79
High temperature Condenser_$_{HTC}$	12.34	12.06	12.05	12.14	12.13	12.1
Low temperature Condenser Cond_$_{LTC}$	6.164	5.971	5.91	5.986	6.11	6.107
Total Exergy destruction in Condenser_$_{Total}$	18.51	18.03	17.96	18.13	18.24	18.2
High temperature Evaporator_$_{HTC}$	7.248	5.825	6.664	5.054	6.267	7.065
Low temperature Evaporator_$_{LTC}$	20.83	20.18	19.97	20.23	20.65	20.64
Total Exergy destruction in Eva_$_{Total}$	28.08	26.0	26.64	26.28	26.92	27.70
High temperature Valve_$_{HTC}$	4.207	7.26	7.189	7.649	5.454	4.902
Low temperature Valve_$_{LTC}$	7.228	7.0	6.93	7.019	7.165	7.162
Total Exergy destruction in Valves_$_{Total}$	11.44	14.26	14.12	14.67	12.62	12.06
% Total Exergy Destruction in HTC	29.7	31.9	32.59	31.73	30.31	30.34
% Total Exergy Destruction in LTC	41.8	40.49	40.08	40.59	41.44	41.42
EDR_Rational and Total Exergy Destruction	0.7150	0.7239	0.7267	0.7232	0.7175	0.7176
Rational Exergetic_Efficiency	0.2850	0.2639	0.2732	0.2752	0.2825	0.2824
EDR_system	2.5088	2.7431	2.6598	2.628	2.54	2.541

Table-5(d) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP HFO1336mzz(Z) refrigerants in low temperature and following refrigerants in high temperature cycle ($T_{\_Cond\_HTC}$ =50°C, $T_{\_EVA\_HTC}$=0°C, $T_{\_EVA\_LTC}$=-90°C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

% Exergy Destruction in Components	R1225ye(Z)	R1234yf	R152a	R245fa	R32	R134a
High temperature Compresor_$_{HTC}$	6.881	7.153	5.986	6.39	5.932	6.519
Low temperature Compresor Comp_$_{LTC}$	7.362	7.216	7.361	7.474	7.119	7.333
Total Exergy destruction in Compressors_$_{Total}$	14.24	14.37	13.35	13.86	13.05	13.85
High temperature Condenser_$_{HTC}$	12.14	12.06	12.43	12.02	14.03	12.22
Low temperature Condenser Cond_$_{LTC}$	5.986	5.867	5.985	6.077	5.788	5.962
Total Exergy destruction in Condenser_$_{Total}$	18.13	17.92	18.41	18.10	19.82	18.18
High temperature Evaporator_$_{HTC}$	5.054	4.797	8.218	6.893	7.975	6.414
Low temperature Evaporator_$_{LTC}$	20.23	19.83	20.23	20.54	19.56	20.15
Total Exergy destruction in Eva_$_{Total}$	26.28	24.63	28.44	27.43	27.54	26.56
High temperature Valve_$_{HTC}$	7.649	9.072	5.102	5.385	6.037	6.842
Low temperature Valve_$_{LTC}$	7.019	6.88	7.019	7.126	6.788	6.991
Total Exergy destruction in Valves_$_{Total}$	14.67	15.95	12.12	12.51	12.82	13.83
% Total Exergy Destruction in HTC	31.73	33.08	31.73	30.69	33.98	32.0
% Total Exergy Destruction in LTC	40.59	39.79	40.59	41.21	39.26	40.43
EDR_Rational and Total Exergy Destruction	72.32	72.87	72.33	71.9	73.24	72.43
Rational Exergetic_Efficiency	0.2763	0.2713	0.2767	0.2810	0.2676	0.2757
EDR_system	2.6174	2.686	2.6140	2.5587	2.737	2.627

Table-6(a) &Table-6(b) shows the effect of high temperature ecofriendly HFO refrigerants on the thermal performances of cascade vapour compression refrigeration system using ultra low GWP ecofriendly R1225ye(Z) refrigerant in low temperature and following refrigerants in high temperature cycle and it is found that highest overall system first law performance in terms of coefficient of performance (COP$_{\_Overall}$) is highest by using R1234ze(Z). It is also found that cascaded overall first law efficiency in terms of coefficient of performance by using R1234yf was found to be lowest The cascaded overall first law performance (COP) of cascade system using R1234ze(Z) is 6.1% higher as compared to using R134a in high temperature cycle. The overall COP of cascade vapour compression refrigeration system using HFO-1336mzz(Z) in high temperature cycle is 2.299% higher, 3.0% using R1224yd(Z) and 4.067% higher than using R134a. Similarly The cascaded overall second law exergetic performance of cascade system using R1234ze(Z) is 6.13%, 2.997% using R1224 yd(Z), 2.34% using HFO-1336mzz(Z) in high temperature cycle as compared to R134a used in high temperature cycle. The second law exergetic performance using R1224yd (Z) and R152a is nearly same. Similarly by using HFO1336mzz (Z) refrigerant in high temperature cycle has second law exergetic performance slightly higher than using R134a. However thermodynamic performances as using R1234ze(E) refrigerant is 0.5% lower than using R134a Similarly power consumption to run whole system is also nearly using R1234ze(Z) is lowest while by using R1234yf is highest. The power required to run both compressors is nearly same by using R1243zf or R1234ze(E) refrigerant in high temperature cycle . But mass flow rate of refrigerant in high temperature cycle is different which significantly effecting the size of the system with same cooling capacity and highest by using R1234yf and lowest by using R1234ze (Z). Similarly power required to run high temperature compressor is also lowest by using R1234ze (Z) and highest by using R1234yf. For comparison to R1234ze(E) and HFO-1336mzz(Z), the power required to run whole cascade system is slightly lower by using HFO-1336mzz(Z) . Also, heat rejection from condensers is also lowest by using R1233zd(Z) and also highest by using R1234yf in high temperature cycle. The power required to run high temperature cycle compressor using R1234ze (Z) is lowest and using HFO-1234yf is highest. The thermodynamic performances using R152a is best as compared to HFO refrigerants but HFO refrigerants has ultra-low GWP as compared to R152a up to high temperature evaporator temperature of -20^{o}C . For high temperature application of evaporator temperature above 0^{o}C, the HFO refrigerant R1234ze (z) has best thermodynamic performance as compared to R152a and R245fa. Similarly the thermodynamic performances using R-1224yd (Z) is similar than using R152a in high temperature cycle for HTC evaporator temperature of 0^{o}C.

Table-6(a) Thermal Performances of cascade vapour compression refrigeration systems using low GWP ecofriendly non toxic R1225ye(Z) refrigerant in low temperature and following refrigerants in high temperature cycle ($T_{\_Cond\_HTC}$ =50^{o}C, $T_{\_EVA\_HTC}$=0^{o}C, $T_{\_EVA\_LTC}$=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

Performance Parameters	R1234ze(Z)	R1234ze(E)	R1243zf	R1224yd(Z)	R1233zd(E)
COP	1.20	1.125	1.117	1.165	1.177
_EDR	1.478	1.642	1.662	1.553	1.526
Exergetic Efficiency	0.4036	0.3784	0.3757	0.3917	0.3959
Exergy of Fuel“kW”	29.31	31.25	31.48	30.15	29.88
Exergy of Product “kW”	11.83	11.83	11.83	11.83	11.83
Exergy-Input	41.05	42.39	42.83	41.41	41.43
COP$_{\_HTC}$	3.669	3.215	3.169	3.16	3.448
COP$_{\_LTC}$	2.269	2.269	2.269	2.269	2.269
DOTM$_{\_HTC}$	0.3151	0.4456	0.3996	0.4277	0.3555
DOTM$_{\_LTC}$	0.3015	0.3015	0.3015	0.3015	0.3015
W$_{\_Comp\_HTC}$“kW”	13.81	15.76	15.99	14.7	14.38
W$_{\_Comp\_LTC}$“kW”	15.50	15.50	15.50	15.50	15.50
Q$_{\_Cond\_HTC}$“kW”	64.47	66.42	66.65	65.36	65.05
Q$_{\_Cond\_LTC}$“kW”	50.55	50.55	50.55	50.55	50.55
Q$_{\_Eva\_LTC}$“kW”	35.167	35.167	35.167	35.167	35.167

Table-6(b) Thermal Performances of cascade vapour compression refrigeration systems using low GWP ecofriendly non toxic R1225ye(Z)refrigerant in low temperature and following refrigerants in high temperature cycle ($T_{\_Cond\_HTC}$ =50^{o}C, $T_{\_EVA\_HTC}$=0^{o}C, $T_{\_EVA\_LTC}$=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency$_{\_LTC}$=0.80

Performance Parameters	HFO1336 mzz(Z)	R1234yf	R152a	R245fa	R32	R134a
COP	1.157	1.083	1.165	1.167	1.112	1.131
_EDR	1.569	1.745	1.551	1.548	1.674	1.63
Exergetic Efficiency	0.3892	0.3644	0.3919	0.3924	0.374	0.3803
Exergy of Fuel “kW”	30.39	32.46	30.08	30.04	31.62	31.1
Exergy of Product “kW”	11.83	11.83	11.83	11.83	11.83	11.83
Exergy-Input	41.61	43.14	42.29	41.64	43.74	42.45
COP$_{\_HTC}$	3.402	2.986	3.451	3.459	3.142	3.246
COP$_{\_LTC}$	2.269	2.269	2.269	2.269	2.269	2.269
DOTM$_{\_HTC}$	0.4257	0.5428	0.2350	0.3667	0.2326	0.399
DOTM$_{\_LTC}$	0.3015	0.3015	0.3015	0.3015	0.3015	0.3015
W$_{\_Comp\_HTC}$“kW”	14.89	16.97	14.68	14.65	16.13	15.61

$W_{\_Comp\_LTC}$“kW”	15.50	15.50	15.50	15.50	15.50	15.50
$Q_{\_Cond\_HTC}$“kW”	65.53	67.63	65.34	65.3	66.79	66.27
$Q_{\_Cond\_LTC}$“kW”	50.55	50.55	50.55	50.55	50.55	50.55
$Q_{\_Eva\_LTC}$“kW”	35.167	35.167	35.167	35.167	35.167	35.167

Table-6(c)& Table-6(d) show the effect of various HFO refrigerants on the percentage exergy destruction in various components and rational thermal performances of vapour compression refrigeration system using ultra low GWP ecofriendly R1225ye(Z) refrigerant in low temperature and following refrigerants in high temperature cycle and it is found that highest exergy destruction in lower temperature cycle (LTC) is around 26.8% more than the exergy destruction in high temperature cycle .It was also found that exergy destruction in LTC cycle is lowest as using R1234ze(Z) in high temperature cycle and highest by using R1234yf in high temperature cycle as compared to other HFO refrigerants used in high temperature cycle. The total exergy destruction in compressors was found highest by using R32 and lowest by usingR-245fa. The percentage change percentage change total exergy destruction in cascade system using HFO-1336mzz (Z) is 0.55% lower than using R1234ze(Z) in high temperature cycle. Similarly the percentage change percentage change total exergy destruction in cascade system using HFO-1243zf is 1.67% higher than using R1234ze (Z) in high temperature cycle. The total exergy destruction in compressors using R1234yf is highest than using R32 and lowest.It was also found that the exergy destruction in compressors using various HFO refrigerants are less than 1.2% .Similarly for low temperature applications, the percentage of exergy destruction in evaporator is highest as compared to condenser and compressor and throttle valves for all HFO refrigerants used in high temperature cycle. To comparison, it was also found that the exergy destruction in evaporators are highest by using R1234ze (Z) in high temperature cycle and using R-1234ze(E) is lowest. Similarly in the throttle valve, the exergy destruction is lower than evaporator but higher than condenser due to internal irreversibilities occurred in the throttle valves. Therefore HFO refrigerants of ultra-low GWP can easily replace R152a, R245fa, R32 and R134a which has high GWP in near future

Table-6(c) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP ecofriendly R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{EVA\_HTC}$=0^{o}C, T_$_{EVA\_LTC}$=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

% Exergy Destruction in Components	R1234ze(Z)	R1234ze(E)	R1243zf	R1224yd(Z)	R1233zd(E)
Comp_$_{HTC}$	5.977	6..843	6.777	6.54	6.364
Comp_$_{LTC}$	7.565	7.326	7.25	7.499	7.496
Comp_$_{Total}$	13.54	14.17	14.03	14.04	13.86
Cond_$_{HTC}$	12.51	12.21	12.20	12.29	12.25
Cond_$_{LTC}$	6.017	5.827	5.766	5.965	5.961
Cond_$_{Total}$	18.52	18.04	17.97	18.25	18.22
Eva_$_{HTC}$	7.336	5.889	6.739	6.339	7.149
Eva_$_{LTC}$	20.05	19.42	19.21	19.87	19.86
Eva_$_{Total}$	27.39	25.31	25.95	26.21	27.01
Valve_$_{HTC}$	4.263	7.354	7.281	5.530	4.966
Valve_$_{LTC}$	7.468	7.231	7.156	7.402	7.398
Valve_$_{Total}$	11.73	14.58	14.44	12.93	12.36
% Total Exergy Destruction in HTC	30.08	32.3	33.0	30.7	30.73
% Total Exergy Destruction in LTC	41.1	39.8	39.39	40.74	40.72
EDR_Rational and Total Exergy Destruction(%)	71.18	72.10	72.39	71.44	71.45
Rational Exergetic_Efficiency	0.2882	0.2790	0.2761	0.2856	0.2855
EDR_system	2.4698	2.5842	2.622	2.5014	2.5026

Table-6(d) Percentage exergy Destruction in various compression of cascade vapour compression refrigeration systems using low GWP ecofriendly R1225ye(Z) refrigerants in low temperature and following refrigerants in high temperature cycle (T_$_{Cond\_HTC}$ =50^{o}C, T_$_{EVA\_HTC}$=0^{o}C, T_$_{EVA\_LTC}$=-50^{o}C, Compressor Efficiency $_{HTC}$=0.80, Compressor Efficiency_$_{LTC}$=0.80

% Exergy Destruction in Components	HFO1336 mzz(Z)	R1234yf	R152a	R245fa	R32	R134a
Comp_$_{HTC}$	6.60	7.243	6.063	6.473	6.006	6.603
Comp_$_{LTC}$	7.462	7.197	7.343	7.457	7.098	7.315
Comp_$_{Total}$	14.06	14.44	13.41	13.93	13.1	13.92
Cond_$_{HTC}$	12.26	12.21	12.59	12.18	14.21	12.38
Cond_$_{LTC}$	5.935	5.725	5.481	5.931	5.646	5.818
Cond_$_{Total}$	18.2	17.93	18.43	18.11	19.86	18.2
Eva_$_{HTC}$	6.329	4.845	8.318	6.975	8.069	6.487
Eva_$_{LTC}$	19.78	19.06	19.46	19.76	18.81	19.39
Eva_$_{Total}$	26.11	23.92	27.78	26.74	26.88	25.87
Valve_$_{HTC}$	5.489	9.187	5.167	5.456	6.112	6.93
Valve_$_{LTC}$	7.366	7.104	7.248	7.361	7.007	7.22

Valve_$_{Total}$	13.21	16.29	12.42	12.82	13.12	14.15
% Total Exergy Destruction in HTC	31.04	33.48	32.14	31.08	34.4	32.40
% Total Exergy Destruction in LTC	40.54	39.10	39.89	40.51	38.57	39.74
EDR_Rational , Total Exergy Destruction (%)	71.58	72.59	72.03	71.06	72.92	72.14
Rational Exergetic_Efficiency	28.42	27.41	27.97	28.40	27.04	27.86
EDR_system	2.5079	2.6483	2.575	2.502	2.6967	2.5893

6. Conclusions

Following conclusions were drawn from present investigations

- Limited HFO refrigerants (i.e.R-1234ze(Z), R1224yd(Z) and R1243zf) can be used for evaporator temperature up to 0°C for replacing R134a
- Few HFO refrigerants (i.e.R-1234ze(E) and R1243zf) can be used for evaporator temperature up to -30°C for replacing R134a
- Few HFO refrigerants (i.e.R-1234yf and R1233zd(E) can be used for evaporator temperature up to -50°C for replacing R134a
- Limited HFO refrigerants (i.e.R-1225ye(Z), HFO-1336mzz(Z)) can be used for evaporator temperature up to -95°Cfor replacing R134a,R125, R410a, R407c, R507a , R227ea and R123
- Few HFO refrigerants (i.e.R-1225ye(Z), HFO-1336mzz(Z)) can be used for evaporator temperature up to -140°C for replacing R404a and R236fa
- For high temperature applications , up to evaporator temperature of 273.15K, the thermal performances using R-1234ze(Z) gives best results in simple vapour compression refrigeration systems and cascaded vapour compression refrigeration systems as comparing to all other HFO and HFC refrigerants
- The thermodynamic performances using R1224yd(Z), and R1233zd(E) are slightly lower than R1234ze(Z) and higher than other ecofriendly HFO refrigerants such as HFO-1236mzz(Z) up to temperature of 272K
- Thermodynamic performances using R1233zd(E) and R1225ye(Z) are greater than using HFO-1336mzz(Z) and R1243zf R1234yf in the VCRS with liquid vapour heat exchanger and also in cascaded VCRS, up to low temperature evaporator of -30°C,
- Thermodynamic performances of cascaded vapour compression refrigeration systems using HFO-1234ze(Z) , R1224yd(Z) in high temperature cycle up to evaporator temperature of 273K and using R1234yf in low temperature cycle up to evaporator is lower than R1225ye(Z)and HFO-1336mzz(Z) used in low temperature cycle (LTC) up to -50°C
- Thermodynamic performances of cascaded vapour compression refrigeration systems using HFO-1234ze(E) , R1233zd(E) and R1243zf in high temperature cycle up to evaporator temperature of 243K and using HFO-1336mzz(Z) in low temperature cycle is lower than R1225ye(Z)and used in low temperature cycle (LTC) up to -90°C
- Thermodynamic performances of three cascaded vapour compression refrigeration systems using HFO-1234ze(Z) HFO-1234ze(E) , R1224yd(Z) , R1233zd(E) and R1243zf in high temperature cycle up to evaporator temperature of 273K and using R1234yf in medium/intermediate temperature cycle up to evaporator temperature of -50°C and HFO-1336mzz(Z) in ultra-low temperature cycle up to evaporator temperature of -130°C is lower than R1225ye(Z) used in ultra-low temperature cycle (LTC)
- For cascaded vapour compression refrigeration systems , the exergy destruction in high temperature cycle is more than 70% lower than the exergy destruction in low temperature cycle
- In cascaded systems for 80% of compressors efficiency, the exergy destruction in low temperature evaporator is higher
- Total exergy destruction in evaporators is higher than total exergy destruction in throttling valves
- Total exergy destruction in condensers is higher than total exergy destruction in compressors working on 80% of efficiency
- Total exergy destruction in compressors is lowest working on 80% of isentropic efficiency.

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