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Performance evaluation of three stages cascaded vapour compression refrigeration systems using new low GWP ecofriendly refrigerants for ultra-low temperature applications

R. S. Mishra

Department of Mechanical Engineering, Delhi Technological University Delhi, India

Abstract

In today's world, more importance is given to use clean, green and efficient utilization of energy resources. Therefore the eco-friendly refrigerants are used for reducing global warming and ozone depletion. These systems are working on vapour compression refrigeration cycles. Furthermore, it is necessary to use eco-friendly cascade refrigeration technology. In order to appreciate the three and four cascade refrigeration cycles are used for ultra-low temperature applications.

In this paper, we proposed sixteen new multi cascaded vapour compression refrigeration systems consisting of vapour compression cycle in which cascaded evaporator of using HFO refrigerant is coupled with the cascaded condenser of medium temperature vapour compression refrigeration cycle with temperature overlapping (MTC approach of 10°C) using another HFO refrigerant. Similarly cascaded evaporator (of temperature up to -70°C) is again cascaded with the condenser of medium/intermediate temperature cycle with temperature overlapping (MTC approach of 10°C). The cascaded intermediate temperature evaporator of -70°C was again cascaded with ultra-low cascaded condenser using low GWP of HFO refrigerants with temperature overlapping (LTC approach of 10°C) in vapour compression cycle to produce cooling at evaporator temperature of -140°C and thermodynamic performances are compared with R134a which has high GWP. Numerical computations were carried out by using HFO refrigerants and found that three-stage cascade vapour compression refrigeration system using R1234ze(Z) in the high-temperature cycle between the temperature range of (55°C to 0°C) and R1233zd(E)in medium temperature cycle between the temperature range of (0°C to -70°C) and R1225ye(Z) in a low-temperature cycle between the temperature range of (-70°C to -140°C) is optimal system gives better thermodynamic performances.

1. Introduction

Refrigeration is accountable for 20% of global energy consumption. Furthermore, the refrigeration process is associated with a series of environmental problems such as the ozone layer depletion and the global warming phenomenon due to the destructive refrigerants. Therefore, there is a need for launching a cascade refrigeration system with high efficiency and environmentally-friendly refrigerants. There are many ultra-low temperature cascade refrigeration systems in use today with evaporator temperatures from -50°C to -80°C is used biomedical applications.

Single-stage vapour compression refrigeration system is not capable to achieve such low temperatures with the use of a reciprocating compressor, due to a very high-pressure ratio across the compressor. Higher pressure ratios and volumetric efficiency give you an idea about higher condenser temperatures and for this reason, the capacity of the reciprocating compressor drastically reduces. Though multistage or screw compressors can assist in excluding the use of single refrigerant at low temperature is limited by solidification temperature of the refrigerant, extremely low pressures in the evaporator, large suction volumes in the evaporator for a high boiling point refrigerant and high condenser pressure for a low boiling refrigerant. This necessitates integrating for other viable options to partially or fully overcome the above shortcomings. The characteristics of any refrigerant to exhibit the best performance, when operating in a certain range of temperature and pressure, provide cascade refrigeration systems with an edge over single-stage and multistage refrigeration systems for low-temperature applications. Cascade refrigeration

Corresponding author: R.S. Mishra
Email Address: hod.mechanical.rsm@dtu.ac.in

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systems employ a series of single-stage units which are thermally coupled with evaporator/condenser cascades.

For ultra-low temperature applications required refrigeration in the range of - 80°C to -150°C. Three stages cascade refrigeration cycles are commonly used in the liquefaction of natural gas, which consists basically of hydrocarbons of the paraffin series, of which methane has the lowest boiling point at atmospheric pressure.

According to the European Parliament Directive 517/2014 [1], the use of refrigerants with high global warming potential (GWP) has to be abridged. A general limit in the GWP can be selected at 150, especially for the domestic refrigeration systems and so the use of refrigerants with lower GWP has to be used in the new systems or to replace the present refrigerants.

Vapour compression refrigeration systems using R152a is found to be the most efficient refrigerant compared with other HFC and hydrocarbon refrigerants. Although R134a is a widely used refrigerant due to its commercial availability, similar properties to R152a, with ODP value, excellent thermal stability, nontoxic and non-flammability etc have high GWP value around 1430. The only issue is to reduce global warming by using low GWP refrigerants. The thermodynamic performance comparison with using R152a and R245fa and R32 with R134a not many differences and can replace R134a in the near future. Although the refrigerants R152a and R245fa are highly effective for the cooling vapour compression cycles. These refrigerants are non-toxic and have a higher GWP than HFC refrigerants. Therefore HFC refrigerants are a reliable choice for future cooling systems.

2. Use of HFO refrigerants for replacing HFC refrigerants

In recent years, the fourth generation Hydro-fluoro-olefins (HFOs)-R1234yf and R1234ze are being considered as an alternative to R134a. A number of studies have been carried out using HFO 1234yf. The European Union (EU) regulation is phasing out the current generation HFCs like R134a due to its high GWP and environmental consequences. The European Union (EU) regulation is phasing out the current generation HFCs like R134a due to its high GWP and environmental consequences. A number of studies have been carried out using R1234yf and R1234ze(E) [2, 3] and 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 the lowest thermodynamic performances.

Mishra [2] analyzed the hydro-fluoro-olefines (HFO) and hydro chloro-fluoro-olefines (HCFO) used in vapour compression refrigeration systems. The HFO R1234yf and R1234ze (E), as well as the HCFO R1233zd(E) and R1224yd(Z), are especially promising low-GWP alternatives to the HFC R134a and R245fa.For instance, the German Environment Agency intends to prohibit the application of R1233zd(E), due to its ODP of 0.00024. However, R1233zd(E) has several favorable aspects, such as a very low GWP and no flammability and toxicity (safety classification of A1). This proves, that the very small ODP by R1233zd(E) and R1224yd lead to no significant increase of the external costs. Thus, a general prohibition of potentially promising refrigerants with a very small ODP appears not be justifiable based on the presented results. The electrical powers are lower by using HCFO-1233zd-E as compared to R134a As a conclusion, it can be stated, that both novel fluids R1233zd(E) and R1224yd(Z) are suitable for the drop-in replacement of R245fa in refrigeration systems. However, the results show, that the compatibility of R1233zd(E) and R1224yd(Z) is compared to replace R245fa and R134a , it is found that when R1233zd(E)is used, for finding the system performances, the highest power output is still obtained with the high-GWP fluid R245fa and R134a which is 7% to 9% The exergy of fuel with R245fa is 0.40% higher compared to R1233zd(E) and 8% higher compared to R1224yd(Z). In terms of thermal efficiency of the ORC system, R1233zd(E) leads to approximately 2% higher values compared to R245fa. In contrast to that, the thermal efficiency of R245fa and R1224yd(Z) is equal over a wide range of operation conditions. 1.2 HFO-1336mzz(E) and R1336mzz(Z) R1336mzz(Z) (also referred to as HFO1336mzz(Z)) provides approximate thermodynamic property data for cis-1,1,1,4,4,4-Hexafluoro-2-butene, MW 164.056 gm/mole, CAS# 692-49-9). The fundamentals of choosing a good working refrigerant are based on system optimization to maximize the thermodynamic performance characteristics in terms of first and second law efficiencies, these novel HFOs are being developed, like HFO1336mzz(E) and R1336mzz(Z), to meet the more stringent regulations of low GWP and no ODP and they demonstrate the known characteristics of a good working fluids stability, compatibility, favorable toxicity and performance even at high temperatures. The HFO-1336mzz(E) has a 7.5ºC boiling point, the critical temperature of 137.6ºC and critical pressure of 3.15 MPa. Whereas R-1336mzz(Z) has a slightly higher boiling point of 33.4oC, critical temperature of 171.3ºC and lower critical pressure of 2.90 MPa. The compressor efficiency, superheat, sub cooling and lift temperatures were fixed variables is this calculation, the condensing temperatures were adjusted so higher temperature effects could be evaluated for each working fluid. HFO1336mzz isomers (E and Z) and had the excellent first law efficiency (COPs) amongst than the HFC Refrigerants (such as R134a, R410a, R404a, R407c, R507a, R125a) but lower than R245fa due to and power required to run compressors are 8.63% higher than R245fa. Mishra et al. [2] performed exergy analysis on a vapour compression refrigeration systems using liquid vapour heat exchanger and several HFO refrigerants (i.e. R1234yf, R1234ze(Z) R1234ze(E), R1243zf, R1224yd(z), R1225ye(z) and HFO-1336mzz(Z)) for replacing R134a refrigerants. The HFO refrigerants were good alternatives to R134a regarding their environment-friendly properties. The ecofriendly refrigerants such as R134a, R1234yf, and R1234ze(E) are pure substances. The HFO (hydro-fluoro-olefin) are going to be our future refrigerants with low ozone depletion potential (ODP) and low global warming potential (GWP). The basic properties of new future HFO refrigerants expected as R134a and R32 alternatives which are presently used in refrigerators. R1243zf is probably to be a good alternative with its flammability, which is A2 category for replacing R134a [3]. Attila Gencer [4] were theoretically evaluated the thermodynamic behaviour in terms of energy parameters (i.e., cooling capacity and COP) for three different vapour compression refrigeration systems (i.e. Basic cycle, basic cycle with liquid-to-suction heat exchanger and two-stage cascade cycle) and compared exergetic efficiency using low GWP alternative refrigerants (i.e. R1234yf, R1234ze(E), R513A, R445A and R450A) for replacing R134a. The comparison of the energy parameters for two different evaporation temperatures (-30°C and 0°C) and two condensing temperatures (40°C and 55°C) was carried out and numerical results show that R450A which almost has the same COP values as R134a comes into prominence with 58% lower GWP value compared to R134a. They suggested that R445A gives highest exergetic efficiency with liquid shell heat exchanger and also concluded that the studied refrigeration cycles, a system for providing a better effect in terms of COP for the considered refrigerants and temperature cases as well as assumed system parameters. It is found that system with liquid shell heat exchanger gives better effect in terms of COP for the considered refrigerants and temperature cases as well as assumed system parameters.

Sanchez et al. [5] compared five low GWP refrigerants R152a, R1234yf, R1234ze, R290 and R600a for the replacement of R134a using hermetic the compressor in the experimental test rig and found that the R1234yf can be considered a suitable drop-in alternative to R134a by considering the energy consumption and the cooling refrigerating capacity of the facility.

Mota-Babiloni, A [6]. Evaluated energy performances of two low-GWP refrigerants such as R1234yf and R1234ze(E), as drop-in replacements for R134a, and conducted various tests in the vapour compression system by combining different values of evaporation and condensation temperature, and without/with the adoption of an internal heat exchanger. Thermodynamic parameters such as volumetric efficiency, cooling capacity and COP are analyzed by taking R134a as a baseline and found without internal heat exchanger the average volumetric efficiency for R1234yf and R1234ze is 4% and 5% lower as compared with R134a. Also found that the cooling capacity with R1234yf and R1234ze is reduced, with an average difference of 9% and 30% without an internal heat exchanger, respectively. Similarly, first law efficiency (COP) values are about 7% lower for R1234ye and 6% are lower for R1234ze than using R134a. Although, the use of an internal heat exchanger reduces the COP differences for both replacements and energy performance evaluation of two low-GWP refrigerants, R1234yf and R1234ze(E), as drop-in replacements for R134a.

Mota-Babiloni, A., Novarro-Esbri J., Barragan-Cervera, A., Moles, F., Peris, B. [7] performed an experimental investigation on the direct use of R1234yf in a system operating with R134a and found that the reduction in the cooling capacity of 6% to 13% approximately using R1234yf instead of R134a. Mota-Babiloni et al. [8] experimentally studied R513A as a substitute for R134a. They found that both cooling capacity and COP values of R513A were better than that of R134a at different evaporation and condenser temperatures.

Yang et al. [9] found that the use of R152a in a cascade system with CO_2 is more efficient than the use of R134a/CO_2 and R124/CO2 cascade systems. Bolaji [10] studied a simple refrigeration system with R152a, R134a and R32. It is found that the use of R152a leads to 8.5% higher coefficient of performance (COP) than R134a, while R32 is the less efficient refrigerant. Cabello et al. [11] carried out an experimental comparison of a cascade refrigeration system working with the refrigerant pairs R134a/R744 and R152a/R744and found that the replacement of R134a with R152a is technically and energetically feasible.

Above investigators have not carried out the performance evaluation for low-temperature applications in cryogenics and the effect of performance parameters using HFO-refrigerants in intermediate temperature circuit and other HFO-refrigerants such as HFO-1336mzz(z) and R1225ye(in low-temperature circuit. Therefore, this paper mainly deals with performance evaluations at -140°C used for cryogenics applications and comparison at -70°C evaporator the temperature in the low-temperature circuit using HFO refrigerants in the intermediate/medium temperature circuit.

3. Results and Discussion

The following sixteen cascade vapour compression system for low temperature applications have been considered for numerical computations

System-1: Three stage cascade vapour compression system for low temperature applications using R-1234ze(Z) in high temperature cycle (HTC), R1233zd(E) in medium temperature cycle (MTC) and HFO-1336mzz(Z)in in low temperature cycle (LTC).

System-2: Three stage cascade vapour compression system for low temperature applications using R-1234ze(Z) in HTC, R1233zd(E) in MTC and R1225ye(Z) in LTC.

System-3: Three stage cascade vapour compression system for low temperature applications using R-1234ze(Z) in HTC, HFO-1336mzz(Z) in MTC and R1225ye(Z)in LTC.

System-4: Three stage cascade vapour compression system for low temperature applications using R-1234ze(Z) in HTC, R1225ye(Z) in MTC and HFO-1336mzz(Z) in LTC.

System-5: Three stage cascade vapour compression system for low temperature applications using R-1234ze(E) in HTC, R1233zd(E) MTC and HFO-1336mzz(Z)in in low LTC.

System-6: Three stage cascade vapour compression system for low temperature applications using R-1234ze(E) in HTC, R1233zd(E) in MTC and R1225ye(Z) in LTC.

System-7: Three stage cascade vapour compression system for low temperature applications using R-1234ze(E) in HTC, HFO-1336mzz(Z) in MTC and R1225ye(Z) in LTC.

System-8: Three stage cascade vapour compression system for low temperature applications using R-1234ze(E) in HTC, R1225ye(Z) in MTC and HFO-1336mzz(Z) in LTC.

System-9: Three stage cascade vapour compression system for low temperature applications using R-1243zf in HTC, HFO-1336mzz(Z) in MTC and R1225ye(Z)in LTC.

System-10: Three stage cascade vapour compression system for low temperature applications using R-1243zf in HTC, R1225ye(Z) in MTC and HFO-1336mzz(Z) in LTC.

System-11: Three stage cascade vapour compression system for low temperature applications using R-1243zf in HTC, R1233zd(E) in MTC and R1225ye(Z) in LTC.

System-12: Three stage cascade vapour compression system for low temperature applications using R-1243zf in HTC, R1233zd(E) in MTC and HFO-1336mzz(Z) in LTC.

System-13: Three stage cascade vapour compression system for low temperature applications using R-1224 yd(Z) in HTC, HFO-1336mzz(Z) in MTC and R1225ye(Z)in LTC.

System-14: Three stage cascade vapour compression system for low temperature applications using R-1224 yd(Z) in HTC, R1225ye(Z) in MTC and HFO-1336mzz(Z) in LTC.

System-15: Three stage cascade vapour compression system for low temperature applications using R1233zd(E) in HTC, HFO-1336mzz(Z)) in MTC and R1225ye(Z) in LTC.

System-16: Three stage cascade vapour compression system for low temperature applications using R1233zd(E) in HTC, R1225ye(Z) in MTC and HFO-1336mzz(Z) in LTC.

The input data for each three stages vapour compression refrigeration cascaded systems are given below:
Three stages cascade vapour compression refrigeration systems using ecofriendly refrigerants has been considered with following input conditions.

- Temperature of High temperature condenser = 55^{o}C
- Refrigerant used High temperature cycle =HFO refrigerant
- Temperature of High temperature evaporator = 0^{o}C
- Isentropic efficiency of high temperature compressor = 80%
- Refrigerant used low temperature cycle = HFO refrigerant
- Temperature of low temperature evaporator = - 70^{o}C
- Isentropic efficiency of medium temperature compressor = 80%
- Refrigerant used low temperature cycle = HFO refrigerant
- Temperature of low temperature evaporator = - 140^{o}C
- Isentropic efficiency of low temperature compressor = 80%
- Cooling Load on low temperature evaporator = 10x3.51 kW.
- Temperature overlapping between low temperature cascade condenser and High temperature evaporator = 10 ^{o}C
- Temperature overlapping between low temperature cascade condenser and medium temperature evaporator = 10 ^{o}C

Table-1 shows the thermodynamic performances of four systems in which ecofriendly refrigerant using R-1234ze(E) in the high temperature cycle at 55^{o}C of condenser temperature systems (system-1 to system-4) with 10 ^{o}C temperature overlapping (approach) and found that System-2:containing R-1234ze(Z) in high temperature cycle (HTC) of condenser temperature of 55^{o}C and 0^{o}C of evaporator temperature and R1233zd(E) in medium temperature cycle (MTC) at evaporator temperature of -70^{o}C and R1225ye(Z)in ultralow evaporator temperature in low temperature cycle (LTC) gives best first and second law performances as compared to system-3 using R-1234ze(E) in high temperature cycle HTC, and HFO1336mzz(Z) in medium temperature cycle (MTC) and R1225ye(Z)in low temperature cycle(LTC). However lowest performances was observed in system-4 using R-1234ze(E) in high temperature cycle HTC and R1225ye(Z) in medium temperature cycle MTC and HFO-1336mzz(Z) in ultra-low temperature cycle (LTC). The power required to run both compressors in whole cascade system is lowest in system-15. The second law performance is also high in system-2.

Table-2 shows the thermodynamic performances of four systems in which ecofriendly refrigerant using R-1234ze(E) in the high temperature cycle at 55^{o}C of condenser temperature systems (system-5 to system-8) with 10 ^{o}C temperature overlapping (approach) and found that System-6:containing R-1234ze(E) in high temperature cycle (HTC) of condenser temperature of 55^{o}C and 0^{o}C of evaporator temperature and R1233zd(E) in medium temperature cycle (MTC) at evaporator temperature of -70^{o}C and R1225ye(Z)in ultralow evaporator temperature in low temperature cycle (LTC) gives best first and second law performances as compared to system-7 using R-1234ze(E) in high temperature cycle HTC, and HFO1336mzz(Z) in medium temperature cycle (MTC) and R1225ye(Z)in low temperature cycle(LTC). However lowest performances was observed in system-8 using R-1234ze(E) in high temperature cycle HTC and R1225ye(Z) in medium temperature cycle MTC and HFO-1336mzz(Z) in ultra-low temperature cycle (LTC). The power required to run both compressors in whole cascade system is lowest in system-15. The second law performance is also high in system-6.

Table-3 shows the thermodynamic performances of four systems in which ecofriendly refrigerant using R1243zf in the high temperature cycle at 55^{o}C of condenser temperature in four systems (system-9 and system-12) with 10 ^{o}C temperature overlapping (approach) and found that System-11:containing R-

1243zf in high temperature cycle (HTC) of condenser temperature of 55°C and 0°C of evaporator temperature and R1233zd(E) in medium temperature cycle (MTC) at evaporator temperature of -70°C and R1225ye(Z)in ultralow evaporator temperature in low temperature cycle (LTC) gives best first and second law performances as compared to system-9 using R-1243zf in high temperature cycle HTC, and HFO1336mzz(Z) in medium temperature cycle (MTC) and R1225ye(Z)in low temperature cycle(LTC). However lowest performances was observed in system-10 using R-1243zf in high temperature cycle HTC and R1225ye(Z) in medium temperature cycle MTC and HFO-1336mzz(Z) in ultra-low temperature cycle (LTC). The power required to run both compressors in whole cascade system is lowest in system-15. The second law performance is also high in system-11. Table-4 shows the thermodynamic performances of four systems in which ecofriendly refrigerant R-1224 yd(Z in the high temperature cycle at 55°C of evaporator in two systems (system-13 and system-14) and R1233zd(E) in the high temperature cycle at 55°C of evaporator in two systems (system-15 and system-16) with 10 °C temperature overlapping (approach) and found that System-15:containing R1233zd(E) in high temperature cycle (HTC) of condenser temperature of 55°C and 0°C of evaporator temperature and HFO-1336mzz(Z) in MTC at evaporator temperature of -70°C and R1225ye(Z)in ultralow evaporator temperature in low temperature cycle (LTC) gives best first and second law performances.to system-13 using R-1224 yd(Z) in high temperature cycle HTC, and HFO1336mzz(Z) in medium temperature cycle (MTC) and R1225ye(Z)in low temperature cycle(LTC). However lowest performances was observed in system-14 using System-14: R-1224 yd(Z) in high temperature cycle HTC and R1225ye(Z) in medium temperature cycle MTC and HFO-1336mzz(Z) in ultra-low temperature cycle (LTC). The power required to run both compressors in whole cascade system is lowest in system-15. The second law performance is also high in system-15,

Table-5 shows the best system to be considered based on maximum first law efficiency (i.e. System COP_$_{Cascade}$), maximum second law efficiency (i.e. System Exergetic Efficiency $_{Cascade}$),minimum system exergy destruction ratio (System EDR_$_{Cascade}$), power required to run whole system (all three compressors) in terms of exergy of fluid (kW) and also minimum power required to run compressors , it is found that system-2 of three stage cascade vapour compression refrigeration system using R1234ze(Z) in high temperature cycle between temperature range of (55°C to 0°C) and R1233zd(E)in medium temperature cycle between temperature range of (0°C to -70°C) and R1225ye(Z) in low temperature cycle is best. However the above sixteen system can replace HFC and HCFC refrigerants in near future .The best systems chosen, based on the utility of HFO refrigerants in high temperature cycle Best systems are system-2: R-1234ze(Z) in HTC, R1233zd(E)in MTC and R1225ye(Z) in LTC out of four systems containing R1234ze(Z) in high temperature cycle while System-6: R-1234ze(E) in HTC, R1233zd(E)in MTC and R1225ye(Z) in LTC out of four systems containing R1234ze(E) in high temperature cycle while System-11: R1243zf in HTC, R1233zd(E) in MTC and R1225ye(Z)in LTC out of four systems containing R1243zf in high temperature cycle while System-15: R1233zd(E) in HTC, HFO-1336mzz(Z) in MTC and R1225ye(Z)in LTC out of two systems containing R1233zd(E) in high temperature cycle in HTC and R-1224 yd(Z) in high temperature cycle in remaining two systems

Table-1: Three stage cascade vapour compression refrigeration system using ecofriendly R1234ze(Z) refrigerant in high temperature cycle and other ecofriendly refrigerants in medium and low temperature cycles ($Q_{\_Eva\_LTC}$=35.167'kW', $T_{\_Cond\_HTC}$=55°C, $T_{\_Eva\_HTC}$=0°C,$T_{\_Eva\_MTC}$=0°C, $T_{\_aevs\_LTC}$=-140°C,Temperature overlapping between medium temperature condenser and high temperature evaporator=10, temperature overlapping between low temperature condenser and medium temperature evaporator=10.

Performance Parameters	System-1 R-1234ze(Z)	System-2 R-1234ze(Z)	System-3 R-1234ze(Z)	System-4 R-1234ze(Z)
System Cascaded COP_$_{Cascade}$	0.3695	0.3815	0.3752	0.3646
System Cascaded EDR_$_{Cascade}$	4.763	4.635	4.730	4.84
System Cascade Exergetic Efficiency_$_{Cascade}$	0.1735	0.1775	0.1745	0.1712
System Exergy of Fuel "kW"	95.18	92.18	93.73	96.44
System Exergy of Product "kW"	16.51	16.31	16.36	16..51
High Temperature Cycle Compressor Work_$_{HTC}$"kW"	30.71	30.01	30.37	31.01
Medium Temperature Cycle Compressor Work_$_{MTC}$"kW"	36.14	35.31	36.49	37.11
Low Temperature Cycle Compressor Work_$_{LTC}$"kW"	26.33	26.33	26.86	28.33
High Temperature Cycle (Q_Cond_$_{HTC}$) "kW"	130.3	127.3	128.9	131.6
Medium Temperature Cycle (Q_Cond_$_{ITC}$) "kW"	99.63	97.37	98.52	100.6
Low Temperature Cycle(Q_Cond_$_{LTC}$) "kW"	63.49	62.03	62.03	63.49
Low Temperature Cycle (Q_Eva_$_{LTC}$) "kW"	35.167	35.167	35.167	35.167
High Temperature Cycle COP_$_{HTC}$	3.244	3.244	3.244	3.244
Medium Temperature Cycle COP_$_{MTC}$	1.757	1.757	1.70	1.711
LowTemperature Cycle COP_$_{LTC}$	1.242	1.309	1.309	1.242
High Temperature Cycle Mass flow Rate "Kg/sec"	0.6450	0.6301	0.6376	0.6512
Medium Temperature Cycle Mass flow Rate "Kg/sec"	0.4079	0.3985	0.4753	0.5432
Low Temperature Cycle Mass flow Rate "Kg/sec"	0.2024	0.2287	0.2287	0.2024

Cascade COP_$_{MTC}$	0.9498	0.9498	0.9277	0.9321
Cascade EDR_$_{MTC}$	1.002	1.002	1.128	1.168
Cascade Exergetic Efficiency_$_{MTC}$	0.4995	0.4995	0.4696	0.4612

Table-2: Three stage cascade vapour compression refrigeration system using ecofriendly R1234ze(E) refrigerant in high temperature cycle and other ecofriendly refrigerants in medium and low temperature cycles (Q_$_{Eva\_LTC}$=35.167'kW', T_$_{Cond\_HTC}$=55°C, T_$_{Eva\_HTC}$=0°C,T_$_{Eva\_MTC}$=0°C, T_$_{aevs\_LTC}$=-140°C,Temperature overlapping between medium temperature condenser and high temperature evaporator=10, Temperature overlapping between low temperature condenser and medium temperature evaporator=10.

Performance Parameters	System-5	System-6	System-7	System-8
System Cascaded COP_$_{Cascade}$	0.3506	0.3618	0.3559	0.3460
System Cascaded EDR_$_{Cascade}$	5.074	4.942	5.04	5.154
System Cascade Exergetic Eff._$_{Cascade}$	0.1646	0.1683	0.1656	0.1625
System Exergy of Fuel “kW”	100.3	97.19	98.8	101.6
System Exergy of Product “kW”	16.51	16.36	16.51	16.51
High Temperature Cycle Compressor Work_$_{HTC}$“kW”	35.86	35.02	35.45	36.2
Medium Temperature Cycle Compressor Work_$_{MTC}$“kW”	36.14	35.31	36.49	37.11
Low Temperature Cycle Compressor Work_$_{LTC}$“kW”	28.33	26.86	26.86	28.31
High Temperature Cycle (Q_Cond_$_{HTC}$) “kW”	135.5	132.4	134.0	136.8
Medium Temperature Cycle (Q_Cond_$_{ITC}$) “kW”	99.63	97.34	98.52	100.6
Low Temperature Cycle(Q_Cond_$_{LTC}$) “kW”	63.49	62.03	62.03	63.49
Low Temperature Cycle (Q_Eva_$_{LTC}$) “kW”	35.167	35.167	35.167	35.167
High Temperature Cycle COP_$_{HTC}$	2.779	2.779	2.779	2.779
Medium Temperature Cycle COP_$_{MTC}$	1.757	1.757	1.70	1.711
LowTemperature Cycle COP_$_{LTC}$	1.242	1.309	1.309	1.242
High Temperature Cycle Mass flow Rate “Kg/sec”	0.9387	0.9171	0.9282	0.9476
Medium Temperature Cycle Mass flow Rate “Kg/sec”	0.4079	0.3985	0.4753	0.5432
Low Temperature Cycle Mass flow Rate “Kg/sec”	0.2024	0.2287	0.2287	0.2024
Cascade COP_$_{MTC}$	0.8820	0.8820	0.8623	0.8662
Cascade EDR_$_{MTC}$	1.156	1.156	1.291	1.333
Cascade Exergetic Efficiency_$_{MTC}$	0.4639	0.4639	0.4365	0.4286

Table-3: Three stage cascade vapour compression refrigeration system using ecofriendly R1243zf refrigerant in high temperature cycle and other ecofriendly refrigerants in medium and low temperature cycles (Q_$_{Eva\_LTC}$=35.167'kW', T_$_{Cond\_HTC}$=55°C, T_$_{Eva\_HTC}$=0°C,T_$_{Eva\_MTC}$=0°C, T_$_{aevs\_LTC}$=-140°C,Temperature overlapping between medium temperature condenser and high temperature evaporator=10, Temperature overlapping between low temperature condenser and medium temperature evaporator=10.

Performance Parameters	System-9	System-10	System-11	System-12
System Cascaded COP_$_{Cascade}$	0.3544	0.3445	0.3602	0.3490
System Cascaded EDR_$_{Cascade}$	5.067	5.181	4.968	5.101
System Cascade Exergetic Eff._$_{Cascade}$	0.1648	0.1618	0.1676	0.1639
System Exergy of Fuel “kW”	99.24	102.1	97.62	100.8
System Exergy of Product “kW”	16.36	16.51	16.36	16.51
High Temperature Cycle Compressor Work_$_{HTC}$“kW”	35.88	36.64	35.45	36.29
Medium Temperature Cycle Compressor Work_$_{MTC}$“kW”	36.49	37.11	35.31	36.14
Low Temperature Cycle Compressor Work_$_{LTC}$“kW”	26.86	28.33	26.86	28.33
High Temperature Cycle (Q_Cond_$_{HTC}$) “kW”	134.4	137.2	132.8	135.9
Medium Temperature Cycle (Q_Cond_$_{ITC}$) “kW”	98.52	100.6	97.34	99.63
Low Temperature Cycle(Q_Cond_$_{LTC}$) “kW”	62.03	63.49	62.03	63.49
Low Temperature Cycle (Q_Eva_$_{LTC}$) “kW”	35.167	35.167	35.167	35.167
High Temperature Cycle COP_$_{HTC}$	2.746	2.746	2.746	2.746
Medium Temperature Cycle COP_$_{MTC}$	1.70	1.711	1.757	1.757
LowTemperature Cycle COP_$_{LTC}$	1.309	1.242	1.309	1.242
High Temperature Cycle Mass flow Rate “Kg/sec”	0.8301	0.8476	0.8203	0.8395
Medium Temperature Cycle Mass flow Rate “Kg/sec”	0.4753	0.5431	0.3985	0.4079
Low Temperature Cycle Mass flow Rate “Kg/sec”	0.2287	0.2024	0.2287	0.2024
Cascade COP_$_{MTC}$	0.8571	0.861	0.8767	0.8767
Cascade EDR_$_{MTC}$	1.305	1.347	1.169	1.169
Cascade Exergetic Efficiency_$_{MTC}$	0.4339	0.4260	0.4611	0.4611

Table-4: Cascade vapour compression refrigeration system using ecofriendly (R-1224yd(Z) and R1233zd(E) refrigerants in high temperature cycle (Q_EVA_$_{LTC}$=35.167'kW', T_$_{Cond\_HTC}$=55°C, T_$_{Eva\_HTC}$=0°C, T_$_{Eva\_MTC}$=0°C, T_$_{aevs\_LTC}$=-140°C,Temperature overlapping between medium temperature condenser and high temperature evaporator=10, Temperature overlapping between low temperature condenser and medium temperature evaporator=10

Performance Parameters	System-13 R-1224 yd(Z)	System-14 R-1224 yd(Z)	System-15 R1233zd(E)	System-16 R1233zd(E)
System Cascaded COP_$_{Cascade}$	0.3666	0.3563	0.3699	0.3596
System Cascaded EDR_$_{Cascade}$	4.864	4.976	4.813	4.924
System Cascade Exergetic Efficiency_$_{Cascade}$	0.1705	0.1673	0.1720	0.1688
System Exergy of Fuel "kW"	95.93	98.69	95.08	97.82
System Exergy of Product "kW"	16.36	16..51	16.36	16..51
High Temperature Cycle Compressor Work_$_{HTC}$"kW"	32.57	33.26	31.72	32.39
Medium Temperature Cycle Compressor Work_$_{MTC}$"kW"	36.49	37.11	36.49	37.11
Low Temperature Cycle Compressor Work_$_{LTC}$"kW"	26.86	28.33	26.86	28.33
High Temperature Cycle (Q_Cond_$_{HTC}$) "kW"	131.1	133.9	130.9	133.0
Medium Temperature Cycle (Q_Cond_$_{ITC}$) "kW"	98.52	100.6	98.52	100.6
Low Temperature Cycle(Q_Cond_$_{LTC}$) "kW"	62.03	63.49	62.03	63.49
Low Temperature Cycle (Q_Eva_$_{LTC}$) "kW"	35.167	35.167	35.167	35.167
High Temperature Cycle COP_$_{HTC}$	3.025	3.025	3.106	3.106
Medium Temperature Cycle COP_$_{MTC}$	1.70	1.711	1.70	1.711
LowTemperature Cycle COP_$_{LTC}$	1.309	1.242	1.309	1.242
High Temperature Cycle Mass flow Rate "Kg/sec"	0.8761	0.8945	0.7238	0.7391
Medium Temperature Cycle Mass flow Rate "Kg/sec"	0.4753	0.5432	0.4753	0.5432
Low Temperature Cycle Mass flow Rate "Kg/sec"	0.2287	0.2024	0.2287	0.2024
Cascade COP_$_{MTC}$	0.8982	0.9024	0.9093	0.9136
Cascade EDR_$_{MTC}$	1.199	1.24	1.172	1.112
Cascade Exergetic Efficiency_$_{MTC}$	0.4547	0.4465	0.4603	0.4521

Table-5: Optimum three stage cascade vapour compression system for low temperature applications

First and second law performance parameters of three stages vapour compression cascaded refrigeration systems using HFO refrigerants for replacing HFC-134a	System-2 R1234ze(Z) in HTC, R1233zd(E)in MTC and R1225ye(Z) in LTC	System-6 R1234ze(E) in HTC, R1233zd(E)in MTC and R1225ye(Z) in LTC	System-11 R1243zf in HTC, R1233zd(E) in MTC and R1225ye(Z)in LTC	System-15 R1233zd(E) in HTC, HFO-1336mzz(Z) in MTC & R1225ye(Z) in LTC
System COP_$_{Cascade}$	0.3815	0.3618	0.3602	0.3699
System EDR_$_{Cascade}$	4.635	4.942	4.968	4.813
System Exergetic Efficiency_$_{Cascade}$	0.1775	0.1683	0.1676	0.1720
Exergy of Fuel "kW"	92.18	97.19	97.62	95.08
Exergy of Product "kW"	16.31	16.36	16.36	16.36
Compressor Work_$_{HTC}$"kW"	30.01	35.02	35.45	31.72
Compressor Work_$_{MTC}$"kW"	35.31	35.31	35.31	36.49
Compressor Work_$_{LTC}$"kW"	26.33	26.86	26.86	26.86

4. Conclusions

Following conclusions were drawn from present investigations.
The following conclusion were drawn:

- Three stage cascade vapour compression refrigeration system using R1234ze(Z) in high temperature cycle between temperature range of (55°C to 0°C) and R1233zd(E)in medium temperature cycle between temperature range of (0°C to -70°C) and R1225ye(Z) in low temperature cycle at evaporator temperature of -140°C is best
- HFO refrigerants have excellent potential for replacing R134a in near future. The performance using R1234yf is slightly less than R134a . The other HFO refrigerants gives better thermodynamic performances.
- The variation in the first law performance between best four systems range is 5.91% and 5.907% in terms of in second law performance along with 6.62% of exergy destruction range.
- Therefore all sixteen three stage cascade vapour compression refrigeration systems can replace highly GWP refrigerants (i.e.R134a, R410a, R404a, R407c, R-236fa, R227ea) in near future
- Although R245fa and R32 and hydrocarbons can also be used but hydrocarbons have flammable nature, therefore safety precautions to be taken before using.

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