



New & low GWP eco-friendly refrigerants used for predicting thermodynamic (energy-exergy) performances of cascade vapour compression refrigeration system using for replacing R134a, R245fa, and R32

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Abstract

The ozone depletion and global warming due to the use of various refrigerants is very serious for environmental degradation which affect living of human standard. Therefore, it is essential to search and use new and low GWP and zero ODP eco-friendly refrigerants. Thermodynamic first and second law performances (energy-exergy efficiencies) of cascade vapour compression refrigeration system using new HFO eco-friendly refrigerants for reducing global warming and ozone depletion performance parameters such as COP, exergetic efficiency and exergy destruction ratio and power required to run whole systems have been presented in this paper. The various combinations of using six different ecofriendly refrigerants used in high temperature cycle in the temperature range of from 50°C to 0°C for which other five ecofriendly low GWP refrigerants in the temperature range of from 0°C to -50°C have been compared. It is found that the first and second law performances of cascade vapour compression refrigeration system using R1234ze (Z) in higher temperature cycle and R1233zd (E) in low temperature cycle gives best thermodynamic performance as compared to R1234ze(E) and R1224ze(z) and R1243z in high temperature cycle. Moreover, lowest performances were found by using R1234yf in high or low temperature cycles as compared to other HFO refrigerants. The comparison was made between HFO-1234yf and HFC-134a in low temperature cycle up to temperature of -50°C and also found the first and second law efficiencies are 3.245% lower than using R-1234yf in low temperature cycle as compared to HFC-134a in low temperature cycle and R1234ze(Z) in high temperature cycle with 5.195% decrement in the exergy destruction ratio.

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Keywords: HFO refrigerants in HTC, Thermodynamic Analysis, Cascade vapour compression, Refrigeration Systems.

1. Introduction

Refrigeration plays a very significant role in industrial, domestic and commercial sectors for cooling, heating and food preserving applications. There are numerous applications of such systems and they are the major consumer of electricity around the world because energy utilization is directly proportional to the economic development of any nation. However, this area is in huge interest now a days because of increase in the cost of conventional fuels and environmental concerns globally. The scientists are searching for new/alternate renewable energy sources in order to reduce the costs. Due to the ever-increasing energy demand and degradation of environment due to global warming and depletion of ozone layer etc, there is urgent need of efficient energy utilization and waste heat recovery for useful

applications. A refrigerant is a substance or mixture, usually a fluid, used in a refrigeration cycle. In most cycles it undergoes phase transitions from a liquid to a gas and back again. Many working fluids have been used for such purposes. The researchers are paying attention on the alternate and environment friendly refrigerants, especially HFCs after the Kyoto and the Montreal protocols. However, it is essential to find alternate and environment friendly refrigerants such as HFOs and others in terms of Blends of HFCs with HFOs, for the energy efficiency of the equipment having HFC refrigerants. Although, natural and conventional refrigerants are also very important in the present age of competitive dealing community because the aim of the scientific group of people all over the world is to find out the new and renewable energy sources besides, efficient utilization of all conventional sources. The use of refrigerant was started in

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<https://doi.org/10.36037/IJREI.2020.4301>

early 1800 century with use of natural refrigerants, which were replaced by CFCs in 1928 with increase in thermal performance, which were banned under Montreal Protocol (1987) due to their high ozone layers depletion (ODP) properties and then they are substituted by hydrochloro carbon (HCFCs) and hydrocarbons in 1980s. Thereafter researchers noted that HCFCs are responsible for ozone depletion and bear high global warming potential. As per guidelines of Kyoto Protocol (1997), HCFCs have to be phased out by 2020-2030 and HFCs by 2025-2040.

1.1 Low GWP ecofriendly Refrigerants

In current operating low temperature applications, the working refrigerants of the hydrocarbons (HC) and hydrofluorocarbons (HFC) groups are dominating. More recently, new working refrigerants have been used by Mishra [10] which are in the hydro-fluoro-olefines (HFO) and hydro chloro-fluoro-olefines (HCFO) group. 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), with the 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 0.42% 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 refrigerants 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 HFO-1336mzz(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 7.5°C boiling point, critical temperature of 137.7°C and critical pressure of 3.15 MPa. Whereas R-1336mzz(Z) has slightly higher boiling point of 33.4°C, critical temperature of 171.3°C and lower critical pressure of 2.90 MPa. The compressor efficiency, superheat (ΔT_{sh}), sub cooling (ΔT_{sc}) and lift temperatures were fixed variables in 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 is 8.63% higher than R245fa.

1.3 R1243zf

The HFO (hydrofluoroolefin) 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 R410a and R32 alternatives which are presently used in refrigerators and room air conditioners. R1243zf is expected to be a good alternative with its flammability, which is A2 category for replacing R134a. Triple point data of a refrigerant, is very important for refrigerating industry defined the lowest temperature range at which any refrigerant may circulate in liquid state. The triple point of R1243zf is 122.8K and the normal boiling temperature and critical pressure are 247.73 K and 3630.6 kPa, respectively.

2. Thermodynamic (Energy-Exergy) Performances of vapour compression refrigeration system

A cascade refrigeration cycle is a multi-stage thermodynamic cycle. An example two-stage process is shown at right. The cascade cycle is often employed for devices such as ultra-low temperature freezers as shown in fig-1. Cascade refrigeration system is a low temperature refrigeration system and is used for very low temperature range about (-40C to -130C). At such low temperature simple Vapour Compression Refrigeration Cycle (VCRS) is not efficient due to very high compression ratio that further leads to high discharge problem and low volumetric efficiencies whereas, cascade refrigeration is much efficient for such conditions. Cascade refrigeration cycle is nothing but simply a combination of two VCRS cycles named as low and high temperature circuit that are combined together by a cascade condenser. This cascade condenser unit act as evaporator for low temperature circuit and condenser for high temperature circuit, the low temperature circuit uses low boiling refrigerants such as R23, R744 etc. and high temperature uses high boiling point refrigerants such as R717, R290, R404A, R1270, R507A etc. To condense refrigerants that are capable of achieving ultra-low temperatures that would not be able to condense at room

temperature. This is achieved by using a low temperature evaporator of one system as the condenser the other, condensing and sub cooling the liquid before entering the metering device. Normally in a cascade refrigeration system two types of compressors, are used and they run individually with different ecofriendly refrigerants, connected among them so that evaporator of first high temperature cycle used for cooling of second (low temperature) cycle condenser (i.e. the evaporator with the first unit cools the condenser of the second unit). In practice, an alternative approach using a common capacitor with a booster circuit to provide two separate temperature limits of the evaporator. The cascade refrigeration cycle is a combination of two vapour compression cycles which utilizes two different refrigerants. The primary refrigerant flows from low temperature circuit evaporator to low stage compressor and condensed in cascade condenser which also acts as evaporator for high temperature circuit. The heat rejected from condenser of low temperature circuit is extracted by evaporator of high temperature circuit containing secondary refrigerant then, this secondary refrigerant gets compressed in high stage compressor and finally condensed to outer atmosphere. The desired refrigerating effect is occurred from evaporator of low temperature circuit. The temperature difference in cascade condenser is an important design parameter that decides the COP of the entire refrigeration system.

The following advantages of cascade vapour compression systems are as follow.

- In the cascade vapour compression refrigeration system using different refrigerants, it is possible to select an ecofriendly refrigerant is best suited for different temperature range. Therefore, very high pressure can be avoided as in case of simple vapour compression refrigeration system.
- In the cascade vapour compression refrigeration system migration of lubricating oil from one compressor to the other compressor is prevented.
- The saving of energy is more because the system allows use of refrigerants that have suitable temperature limits characteristics for each of the higher-temperature side and the lower-temperature side.
- It allows especially for stable ultra-low-temperature operation around -160°C using four stages cascading repair and maintenance is also easy.
- The objective of present research work is the technology is development in the field of refrigeration and air conditioning, remarkable comfort for reducing global warming and ozone depletion by using newly low GWP and around zero ODP are achieved by using energy & exergy analysis.

First law analysis (energy analysis) is restricted to calculate only coefficient of performance of system but exergy analysis is the one of the most useful analyses to evaluate the plant losses, the actual amount of energy flow through process exergetic efficiency and exergetic destruction Ratio. Exergy based

investigation of the VCRS and evaluated thermodynamic performance of hydrocarbons, mixture of hydrocarbons, & R134a carried out. Additionally, they found that higher exergy destruction occurred in compressor as rivaled with other VCRS' components and they emphasized on the possibilities of researches in the field of exergy analysis in various vapor compression refrigeration systems. Exergy losses, exergetic efficiency, and irreversibility of the system components as well as in the vapour compression system using R134a, R290 and R600a refrigerants [1]. Exergy parameters in the compressor, evaporator, condenser and expansion devices are computed and found that the exergy losses depend on evaporator temperatures, condensing temperature, type of refrigerants and ambient temperature and concluded that maximum exergy destruction occurred in the condenser and lowest in the Expansion devices. He also observed the exergy destruction using butane or isobutene are less than using R134a refrigerant in the VCRS. In the higher evaporating temperature exergy loss is decreased for all refrigerants because exergetic efficiency is also higher for butane as compared to isobutene and R-134a as refrigerants. Exergy loss in the compressor is higher than that in the other parts of the system i.e. around 70% of the total exergy loss occurs in the system. The experimental analysis of 2TR (ton of refrigeration) vapor compression refrigeration cycle for different percentage of refrigerant charge using exergy analysis [2]. An experimental setup has been developed and evaluated on different operating conditions using a test rig having R22 as working fluid. The coefficient of performance, exergy destruction, and exergetic efficiency for variable quantity of refrigerant has been calculated. The present investigation has been done by using 2TR window air conditioner. A 2TR window air conditioner equipped with different pressure, temperature, and flow measuring devices has been studied experimentally using energy and exergy analysis. The unit is charged with refrigerant R-22 in four steps, i.e., 25, 50, 75, and 100%, respectively, and the system performance is analyzed in each case. The reference temperature is measured to be 25°C . The results indicate that the losses in the compressor are more pronounced, while the losses in the condenser are less pronounced as compared to other components, i.e., evaporator and expansion device. The total exergy destruction is highest when the system is 100% charged, whereas it is found to be least when the system is 25% charged. Theoretical analysis of actual VCRS with liquid vapour heat exchanger & also carried out analysis on basis of energy, entropy, & exergy in specific temperature range of evaporator and condenser. Besides, they concluded that R502 fluid was best refrigerant as compared to R404A and R507A fluid. The main objective is to investigate the thermodynamic performances of a cascade vapour compression refrigeration systems (VCRS) based on energy-exergy principles. In this investigations, several new HFO refrigerants flowing in the high temperature circuit between temperature range from 50°C to 0°C have been compared in terms of first law efficiency known as coefficient of performance (COP) and second law efficiency commonly known as exergetic efficiency (Exergy Efficiency) and exergy destruction ratio ($\text{EDR}_{\text{System}}$) and other

ecofriendly new HFO refrigerants are also compared with HFC-134a, R245fa and R32 in low temperature circuit up to -50°C by doing exergy analysis [3-4]. The thermodynamic performances of vapour compression refrigeration system using multiple evaporators and compressors with individual or multiple expansion valves have been considered by using first law and second law analysis. Numerical models for parallel and series expansion valves in the VCR. Thermodynamic analysis in terms of energy and exergy analysis of multiple evaporators and compressors with individual expansion valves (system-1) and multiple evaporators and compressors with multiple expansion valves (system-2) have been carried out and following conclusions was drawn from present investigation. For same degree of subcooling, fixed evaporators and condenser temperatures system-2 is the best system with comparisons of system-1. R600, R600a and R152A show better performances than other refrigerants for both systems (system-1 & system-2) but due to inflammable property of R600 and R600a, R134a is preferred for both systems. First law efficiency and second law efficiency of system-2 is 3%- 6% higher than System-1 [5]. Thermodynamic analysis of an R744–R717 cascade refrigeration system and concluded that by increasing the condenser temperature which increases refrigerant mass flow rates and also the decreasing COP. Similarly by increasing evaporating temperature increased COP of the system and decreases mass flow ratios. By increasing temperature difference in cascade condenser reduced both COP and mass flow ratios and by increasing isentropic efficiency of compressors also increases COP linearly [6]. Experimental investigation on a domestic refrigerator and concluded that compressor's exergetic destruction was highest in contrast to other components [7]. The detailed energy and exergy analysis of multi-evaporators at different temperatures with single compressor and single expansion valve using liquid vapour heat exchanger vapour compression refrigeration systems have been done in terms of performance parameter for R507a, R125, R134a, R290, R600, R600a, R1234ze, R1234yf, R410a, R407c, R707, R404a and R152a refrigerants. The numerical computations have been carried out for both systems. It was observed that first law and second law efficiency improved by 20% using liquid vapour heat exchanger in the vapour compression refrigeration systems. The First law efficiency (COP) and Second law efficiency (Exergetic efficiency) of vapour compression refrigeration systems using R717 refrigerant is higher but is has toxic nature can be used by using safety measure for industrial applications. COP and exergetic efficiency for R152a and R600 are nearly matching the same values are better than that for R125 at 313K condenser temperature and showing higher value of COP and exergetic efficiency in comparison to R125. For practical applications R-134a is recommended because it is easily available in the market has second law efficiency slightly lesser than R-152a which was not applicable for commercial applications. The increase in dead state temperature has a positive effect on exergetic efficiency and EDR, i.e. EDR decreases and exergetic efficiency increases with increase in dead state temperature. [8-10]. The numerical

investigation of VCRS by using R134a, R143a, R152a, R404A, R410A, R502, & R507A fluid and reported that temperature of evaporator and condenser have crucial effect on both COP & exergetic efficiency. In addition, they found that R134a fluid has better performance than R407C fluid [11]. The energy analysis of vapour compression refrigeration system using refrigerants R134a, R152a, R600a, R290, R1234yf and R1234ze(E) (HFOs) and found that these can be a good alternative to R134a without compromising the performance of refrigeration system [12]. The above investigators did not carried out detailed thermodynamic first and second law analysis using energy and exergy principles for predicting performances using latest and new ecofriendly of low GWP refrigerants of cascade refrigeration systems for replacing high GWP refrigerants in near future. In this paper, thermodynamic first law efficiency in terms of coefficient of performance (COP) and second law efficiency in terms of exergetic efficiency have been computed for low temperature applications used for bio medical applications and best solution for replacing High GWP refrigerants and important results have been presented in next section.

3. Results and Discussion

Following input data have been chosen for numerical computations in the– cascade vapour compression refrigeration system using new HFO eco-friendly refrigerant for reducing global warming and ozone depletion:

- Temperature of low temperature evaporator using eco-friendly refrigerants = -50°C ,
- Compressor efficiency of low temperature cycle compressor = 80%
- Temperature overlapping between low temperature condenser and intermediate temperature evaporator = 10°C
- Load on low temperature evaporator = 175 “kW”
- Compressor efficiency of high temperature cycle compressor = 80%
- Temperature of high temperature evaporator using ecofriendly refrigerants = 0°C ,
- Temperature of high temperature condenser using ecofriendly refrigerants = 50°

Table-1 shows the effect of various ecofriendly refrigerants in high temperature circuit between temperature range of 50°C to 0°C and R134a in the low temperature cycle at -50°C of evaporator with 10°C temperature overlapping (approach) and found that R1234ze(Z) gives best/highest thermodynamic performances with lowest exergy destruction ratio as compared to R1224yd(Z) and R1234ze(E) and R1243zf. However lowest performances was observed by using R1234yf in high temperature circuit and R134a in low temperature cycle. Table-2 show the effect of various ecofriendly refrigerants in high temperature circuit between temperature range of 50°C to 0°C and HFO-1234yf in the low temperature cycle at -50°C of evaporator with 10°C temperature overlapping (approach) and found that R1234ze(z) gives best/highest thermodynamic performances with lowest

exergy destruction ratio as compared to R1224yd(Z) and R1234ze(E) and R1243zf. However lowest performances was observed by using R134a in high temperature circuit and R1234yf in low temperature cycle. The thermodynamic performances of cascade vapour compression refrigeration systems was compared between HFC-134a and HFO-1234yf and it is found that HFC-134a gives better cycle thermodynamic performances 4.845 % higher than R1234yf and overall cascade system thermodynamic first law performances 6.708% The second law performance (exergetic efficiency) using R134a in low temperature cycle is 6.665% higher than using R1234yf in low temperature cycle. Table-3 shows the effect of various ecofriendly refrigerants in the low temperature circuit between temperature range of -50°C to 0° C and R1234ze(Z) in the high temperature cycle at 50°C of evaporator with 10 °C temperature overlapping (approach) and found that R1233zd(E) gives best/highest thermodynamic performances with lowest exergy destruction ratio as compared to R1224yd(Z) and HFO1336mzz(Z). However lowest performances was observed by using R1234yf in high temperature circuit and R134a in low temperature cycle. The power required to run both compressors in whole cascade system is lowest by using R1233zd(E) in lower temperature while highest by using R1234yf in low temperature cycle. The second law performance using R1233zd(E) is higher than using HFO-1336mzz(Z) or R1225ye(Z) in lower temperature circuit. It was also observed that the thermodynamic performances using HFO-1336mzz(Z) and R1225ye(Z) are nearly same nearly 0.5% differences. The lowest thermodynamic first and second law performances was found by using R1234yf in the low temperature circuit.

Table-4 shows the effect of various ecofriendly refrigerants in the low temperature circuit between temperature range of -50°C to 0° C and R1234ze(E) in the high temperature cycle at 50°C of evaporator with 10 °C temperature overlapping (approach) and found that R1233zd(E) gives best/highest (more than 2.183% thermodynamic performances with lowest exergy destruction ratio as compared to R1225ye(Z) and HFO1336mzz(Z)). However lowest performances was observed by using R1234yf in high temperature circuit and R134a in low temperature cycle. The power required to run both compressors in whole cascade system is lowest by using R1233zd(E) in lower temperature while highest by using R1234yf in low temperature cycle. The second law performance using R1233zd(E) is higher than using HFO-

1336mzz(Z) or R1225ye(Z) in lower temperature circuit. It was also observed that the thermodynamic performances using HFO-1336mzz(Z) and R1225ye(Z) are nearly same nearly 0.5% differences. The lowest thermodynamic first and second law performances was found by using R1234yf in the low temperature circuit. Table-5 shows the effect of various ecofriendly refrigerants in the low temperature circuit between temperature range of -50°C to 0° C and R1224zd(Z) in the high temperature cycle at 50°C of evaporator with 10 °C temperature overlapping (approach) and found that R1233zd(E) gives best/highest (more than 2.183% thermodynamic performances with lowest exergy destruction ratio as compared to R1225ye(Z) and HFO1336mzz(Z)). However lowest performances was observed by using R1234yf in high temperature circuit and R134a in low temperature cycle. The power required to run both compressors in whole cascade system is lowest by using R1233zd(E) in lower temperature while highest by using R1234yf in low temperature cycle. The second law performance using R1233zd(E) is higher than using HFO-1336mzz(Z) or R1225ye(Z) in lower temperature circuit. It was also observed that the thermodynamic performances using HFO-1336mzz(Z) and R1225ye(Z) are nearly same nearly 0.5% differences. The lowest thermodynamic first and second law performances was found by using R1234yf in the low temperature circuit. Table-6 shows the effect of various ecofriendly refrigerants in the low temperature circuit between temperature range of -50°C to 0° C and R1243zf in the high temperature cycle at 50°C of evaporator with 10 °C temperature overlapping (approach) and found that R1233zd(E) gives best/highest (more than 2.183% thermodynamic performances with lowest exergy destruction ratio as compared to R1225ye(Z) and HFO1336mzz(Z)). However lowest performances was observed by using R1234yf in high temperature circuit and R134a in low temperature cycle. The power required to run both compressors in whole cascade system is lowest by using R1233zd(E) in lower temperature while highest by using R1234yf in low temperature cycle. The second law performance using R1233zd(E) is higher than using HFO-1336mzz(Z) or R1225ye(Z) in lower temperature circuit. It was also observed that the thermodynamic performances using HFO-1336mzz(Z) and R1225ye(Z) are nearly same nearly 0.5% differences. The lowest thermodynamic first and second law performances was found by using R1234yf in the low temperature circuit.

Table-1: Thermodynamic (Energy-Exergy) performance Parameters of- cascade vapour compression refrigeration system using new HFC (R134a) refrigerant in low temperature circuit and following ecofriendly refrigerant in high temperature circuit for reducing global warming and ozone depletion

First & second Law performances	R1234ze(Z)	R1234ze(E)	R1224yd(Z)	R1243zf	R1234yf
High temperature First Law Efficiency (COP _{HTC})	3.669	3.215	3.448	3.169	2.986
Low temperature First Law Efficiency (COP _{LTC})	2.294	2.294	2.294	2.294	2.294
Overall Cascade First Law Efficiency (COP _{Overall Cascade})	1.209	1.133	1.173	1.125	1.091
Overall Cascade Second law efficiency	0.4065	0.3811	0.3945	0.3783	0.3668
System Exergy Destruction Ratio (EDR _{Overall Cascade})	1.46	1.621	1.535	1.644	1.726
Total power required to run whole system (kW)	144.8	154.5	149.2	155.6	160.4

Table- 2: Thermodynamic (Energy-Exergy) performance Parameters of cascade) vapour compression refrigeration system using new HFO (R1234yf) refrigerant in low temperature circuit and following ecofriendly refrigerant in high temperature circuit

First & second Law performances	R1234ze(Z)	R1234ze(E)	R1224yd(Z)	R1243zf	R1234yf
High temperature First Law Efficiency (COP _{HTC})	3.669	3.215	3.448	3.169	2.986
Low temperature First Law Efficiency (COP _{LTC})	2.188	2.188	2.188	2.188	2.188
Overall Cascade First Law Efficiency (COP _{Overall Cascade})	1.171	1.099	1.137	1.091	1.104
Overall Cascade Second law efficiency	0.3938	0.3695	0.3824	0.3669	0.3713
System Exergy Destruction Ratio (EDR _{Overall Cascade})	1.54	1.706	1.615	1.726	1.693
Total power required to run whole system (kW)	149.5	159.3	153.9	160.4	158.5

Table- 3: First law performance Parameters of– cascade) vapour compression refrigeration system using new HFO (R1234ze(Z) in high temperature circuit and following ecofriendly refrigerant in low temperature circuit

First & second Law performances	HFO-1336mzz(Z)	R1234yf	R1225ye(Z)	R1233zd(E)	R124	R245fa	R32
High temperature First Law Efficiency (COP _{HTC})	3.669	3.669	3.669	3.669	3.669	3.669	3.669
Low temperature First Law Efficiency (COP _{LTC})	2.286	2.188	2.289	2.363	2.312	2.349	2.249
Overall Cascade 1 st Law Effi (COP _{Overall Cascade})	1.206	1.171	1.20	1.233	1.218	1.228	1.193
Overall Cascade Second law efficiency	0.4058	0.3998	0.4036	0.4147	0.4087	0.4130	0.401
System Exergy Destruction Ratio (EDR _{Overall Cascade})	1.466	1.540	1.478	1.412	1.447	1.421	1.493
Total power required to run whole system (kW)	145.1	149.5	145.8	141.9	144.0	142.5	146.7
High temperature First Law Efficiency (COP _{HTC})	58.86	58.86	58.86	58.86	58.86	58.86	58.86

Table- 4: Thermodynamic (Energy-Exergy) performance Parameters of– cascade) vapour compression refrigeration system using new HFO refrigerant (R1234ze(E) in high temperature circuit and following ecofriendly refrigerant in low temperature circuit

First & second Law performances	HFO1336 mzz(Z)	R1234yf	R1225ye(Z)	R1233zd(E)	R32	R245fa	R124
High temperature First Law Efficiency (COP _{HTC})	3.215	3.215	3.215	3.215	3.215	3.215	3.215
Low temperature First Law Efficiency (COP _{LTC})	2.286	2.188	2.289	2.363	2.249	2.349	2.312
Overall Cascade First Law Efficiency (COP _{Overall Cascade})	1.139	1.109	1.125	1.155	1.119	1.151	1.139
Overall Cascade Second law efficiency	0.3802	0.3695	0.3784	0.3885	0.3762	0.3870	0.383
System Exergy Destruction Ratio (EDR _{Overall Cascade})	1.63	1.540	1.642	1.574	1.493	1.421	1.611
Total power required to run whole system (kW)	154.8	159.3	155.5	151.5	156.7	154.1	153.7

Table 5: Thermodynamic (Energy-Exergy) performance Parameters of– cascade) vapour compression refrigeration system using new HFO refrigerant (R1224zd(Z) in high temperature circuit and following ecofriendly refrigerant in low temperature circuit

First & second Law performances	HFO1336 mzz(Z)	R1234yf	R1225ye(Z)	R1233zd(E)	R32	R245fa	R124
High temperature First Law Efficiency (COP _{HTC})	3.448	3.448	3.448	3.448	3.448	3.448	3.448
Low temperature First Law Efficiency (COP _{LTC})	2.286	2.188	2.269	2.363	2.249	2.349	2.312
Overall Cascade First Law Efficiency (COP _{Overall Cascade})	1.142	1.131	1.192	1.196	1.158	1.192	1.179
Overall Cascade Second law efficiency	0.4007	0.3824	0.4007	0.4023	0.3894	0.4007	0.3966
System Exergy Destruction Ratio (EDR _{Overall Cascade})	1.495	1.615	1.445	1.486	1.568	1.445	1.521
Total power required to run whole system (kW)	146.9	153.9	146.9	146.3	151.1	146.9	148.4

Table- 6 : Thermodynamic (Energy-Exergy) performance Parameters of– cascade) vapour compression refrigeration system using new HFO (R1243zf) refrigerant in high temperature circuit and following ecofriendly refrigerant in low temperature circuit

First & second Law performances	HFO1336 mzz(Z)	R1234yf	R1225ye(Z)	R1233zd(E)	R32	R245fa	R124
High temperature 1 st law Efficiency (COP _{HTC})	3.169	3.169	3.169	3.169	3.169	3.169	3.169
Low temperature 1 st law Efficiency (COP _{LTC})	2.286	2.188	2.269	2.363	2.249	2.349	2.312
Overall Cascade 1 st law Eff (COP _{Overall Cascade})	1.122	1.091	1.117	1.141	1.111	1.142	1.131
Overall Cascade Second law efficiency	0.3774	0.3669	0.3750	0.3856	0.3735	0.3841	0.3802
EDR _{Overall Cascade}	1.649	1.726	1.662	1.594	1.677	1.604	1.630
Total power required to run whole system (kW)	155.9	160.4	156.7	152.6	157.6	153.2	154.8

4. Conclusions

The following conclusions were drawn from present investigation.

- The first and second law performances of cascade vapour compression refrigeration system using R1234ze(Z) in higher temperature cycle is highest.
- The first and second law performances of cascade vapour compression refrigeration system using R1234ze(Z) in higher temperature cycle and HFO and HFC refrigerants in lower temperature is higher than R1234ze(E) R1224zd(Z) and (R1243zf) in high temperature cycle.
- The power required to run both compressors in whole cascade system is lowest by using R1233zd(E) in lower temperature while highest by using R1234yf in low temperature cycle while using R1234ze(z), R1234ze(E), R1224ze(Z) and (R1243zf) in high temperature cycle
- The thermodynamic performances using HFO-1336mzz(Z) and R1225ye(Z) in low temperature cycle are nearly same nearly 0.5% differences using R1234ze(z) or R-1234ze(E) in high temperature cycle. The lowest thermodynamic first and second law performances was found by using R1234yf in the low temperature circuit.
- R1243zf gives lower thermodynamic performance as compared to using R1234ze(Z) and R1234ze(E) in high temperature cycle.
- The thermodynamic performances using R1234yf in higher temperature cycle and even in low temperature cycle gives lower performances as compared to other HFO refrigerants.

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Cite this article as: R.S. Mishra, New & low GWP eco-friendly refrigerants used for predicting thermodynamic (energy-exergy) performances of cascade vapour compression refrigeration system using for replacing R134a, R245fa and R32, International Journal of Research in Engineering and Innovation Vol-4, Issue-3 (2020), 124-130. <https://doi.org/10.36037/IJREI.2020.4301>.