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Thermodynamic analysis of two stages cascade refrigeration system using r-1234ze in high temperature circuit and r1234yf in low temperature circuit for replacing HFC (R-134a) refrigerant

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Abstract

This paper present the thermodynamic performance evaluation using Energy-Exergy method for cascade vapour-compression refrigeration system by using for HFO-1234yf (2, 3, 3, 3-Tetrafluoropropene) in the low temperature circuit and HFO-1234ze (trans-1, 3, 3, 3-tetrafluoroprop-1-ene) in the high temperature circuit. Both HFO refrigerants have ultra-low Global Warming Potential (GWP) with zero Ozone Depletion Potential (ODP) and comparison was made of the computed results using HFO refrigerants with HFC-134a refrigerant as possible alternative replacements in low temperature refrigeration circuit in the range evaporator temperature variation between -35oC of -50oC. A numerical computation has been carried out for calculating first law efficiency in terms of system coefficient of performance (SCOP), Second law efficiency in terms of exergetic efficiency, exergy destruction ratio based on exergy of fuel and also exergy destruction ratio based on exergy of product, first law efficiency for high temperature circuit and first law efficiency for low temperature circuit, power required to run whole system and power required for each compressors, mass flow rate in each evaporators with variation of high temperature condenser temperature ranging between 30oC to 55oC and cascade evaporator temperature ranging between -20oC to 20oC using HFO1234ze along with effect of temperature overlapping in terms of approach. It was observed that Cascade Refrigeration system gives comparable thermal performances which can replace HFC-134a in the low temperature applications and efficiency defects for HFO-1234yf, HFO-1234ze and HFC-134a. During the investigation, condenser temperature is kept at 313K and evaporator temperature is kept in the range from 223K to 273K .Results obtained indicate that HFO-1234yf and HFO-1234ze can be good replacement of R-134a. Among the system components, condenser shows highest efficiency defect value and low temperature evaporator shows the lowest.

Keywords: Thermodynamic Analysis, Two stage Vapour compression refrigeration system, Entropy Generation, Energy-Exergy Analysis.

1. Introduction

In recent years, the climate change and environmental damage caused by the greenhouse gases have attracted increased attention to the environmental protection. Heat pump water heater has been widely concerned with high efficiency and environmental protection. Currently the heat pump systems are widely using R22 as refrigerant, which is a HCFCs type refrigerant and the main chemical substance that damages the ozone layer and generates greenhouse effect. Montreal Protocol requires developed countries to completely phase out HCFCs in 2020, and developing countries to phase out HCFCs in 2030 [1]. R410A is a substitute of R22. While its ODP is zero, the GWP value is 1924.The F-gas regulations are ended by the European Union in 2014, stipulate that refrigerators and freezers for home use, and those for business use, which contain HFCs and whose GWP value are above 150, are banned from market since January 1st 2015 and January 1st 2022 respectively [2] Said M . et.al [3] assessed the theoretical performances of HCFC123, HFC134a, CFC11, and CFC12 as coolants and carried out energy-exergy analysis of vapour compression refrigeration systems using CFC and other ecofriendly refrigerants and found that for a specific amount of desired exergy, more compression work is required by using

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HCFC123 and HFC134a than for CFC11 and CFC12. Although these differences are not very significant at high evaporation temperatures and hence HCFC123 should not be excluded as alternative coolants. There is an optimum evaporation temperature for each condensation temperature which yields the highest exergetic efficiency. For a exergetic assessment of the coolants such as HCFC123, HFC134a, CFC11, and CFC12, it was found that the value of exergetic efficiency decreases with increasing the evaporator temperature. The highest exergetic efficiency occurs at the optimum evaporation temperature. The Exergetic efficiency was decreased by 9.24, 12.03, 5.66, 13.78, 20.92, 9.53, 11.34 and 13.04% by using refrigerants such as R-134a, R-143a, R-152a, R-404A, R-407C, R-410A, R-502 and R-507A, respectively. Probert and Nikoldas [4] used the exergy method to examine the behaviour of two stage compound compression cycle with flash inter cooling using R32. The condenser saturation temp was varied form 298K – 308K. The effect of temp changes in the condenser and evaporator on the plants irreversibility rate was determined. It is established that greater the temp difference b/w either (a) the condenser and environment (b) the evaporator and the cold room, the higher irreversibility rate. Any reduction in the irreversibility rate of the condenser gives approximately 2.40 times greater reduction in the irreversibility rate for the whole plant and any reduction in the evaporators' non-reversible rate gives a 2.87 times greater mean reduction in the non-reversible rate of whole plant. Because changes in the temperature in the condenser and the evaporator contribute so significantly to the plants overall irreversibility. They pointed out that there is considerable scope for the optimization of conditions imposed upon the condenser and evaporator. Getu and Bansal [5] had optimized the design and operating parameters of like condensing temperature, subcooling temperature, evaporating temperature, superheating temperature and temperature difference in cascade heat exchanger R744-R717 cascade refrigeration system. A regression analysis was also done to obtain optimum thermodynamic parameters of same system. Esbri, et al. [6] experimentally analyzed HFO-1234yf as a drop-in replacement for HFC-134a in a vapour compression system and fond that , the cooling capacity of HFO-1234yf is about 9% lower than that of HFC-134a and also the volumetric efficiency was about 5% less than that obtained with HFC-134a. Jung, et al. [7] evaluated the performance of HFO-1234yf and HFO-1234yf/HFC- 134a mixture in three compositions and drawn the results that COP, capacity and discharge temperature of HFO-1234yf and mixture of refrigerants are similar to those of HFC-134a, with decrement in flammability as the content of HFC-134a increased. Kerber. et al. [8] evaluated experimentally and compared the performance of HFC-134a to HFO-1234yf and HFO-1234ze, and concluded that HFO-1234yf had 2.7% higher energy consumption than HFC-134a, indicating that HFO-1234yf is a suitable drop-in replacement of HFC-134a in domestic refrigerators. While HFO-1234ze had 6% lower energy consumption than HFC-134a, hence to replace HFC-134a with HFO-1234ze lower capacity refrigerators were required, Minor et al. [9] performed optimization of beverage cooler using HFO1234yf and found that performance is comparable to HFC-134a.. Reaser et al. [10] investigated and compared the thermophysical properties of HFO-1234yf to those of HFC-134a and R410a to determine the drop-in replacement potential of HFO-1234yf and concluded that properties were similar to that of HFC-134a and not similar to that of R410a..Chopra Kapil,et.al [11], carried out thermodynamic analysis utilizing first and second law of eight ecofriendly R152a, R600, R600a, R410a, R290, R1234yf, R404a and R134a refrigerants in the two stage vapor compression refrigeration system based on energetic and exergetic performances. The thermal performance parameters, for example, generation of entropy, first law efficiency regarding COP, second-law effectiveness in terms of exergetic efficiency , entropy were explored at various ambient condition and found that both energy and exergy efficiencies of R134a is 8.97% and 5.38% lower than R152a and R600 respectively. To validate the proposed thermal model, numerical calculation was carried out by utilizing ecofriendly refrigerants and found that the irreversibility was negligible at higher evaporator temperatures while condenser temperature was in charge of most noteworthy irreversibility as far as thermal energy losses in the two stage vapour compression refrigeration system. Mishra R. S. [12] carried out first law and second law analysis, and comparison of eight ecological friendly refrigerants on multiple stage vapour compression refrigerator with flash intercooler and individual throttle valves (system-1) and multiple stage vapour compression refrigerator with flash intercooler and multiple throttle valves (system-2) and observed that irreversibility occurred in the system- 1 is higher than the system-2 for eight chosen ecofriendly refrigerants. The first law effectiveness (i.e. COP) and exergy efficiency of system-1is lower than the sytem-2. It was observed that exergetic performance of R600 and R717 is better in comparison of other chosen ecofriendly refrigerants for the two systems where as ecofriendly R125 refrigerant indicated lowest thermal performances in terms of first law efficiency (COP) and exergetic effectiveness (second law efficiency) and higher irreversibility as far as exergy destruction ratio (EDR) . As ecofriendly R717 refrigerant is harmful due to toxic in nature and confined to restricted applications and furthermore hydrocarbon R600 is somewhat lower performance than R717 and 2-3% higher performance than R134a refrigerant is additionally incombustible in nature can be utilized with taking of any security safeguards. Along these lines R134a may likewise be utilized for pragmatic applications. Additionally R134A is effectively accessible, The thermal performance of R1234yf (GWP four with zero ozone consumption potential) gives somewhat slightly lower thermal performance than R134a.. Mishra R.S. [13] carried out relative computation for performance assessment of sixteen ecofriendly refrigerants utilized as a part of the two stage vapor compression refrigeration system in light of energetic and exergetic performance for finding system and components irreversibility utilizing entropy generation principle. The numerical calculation was done for finding rational exergy destruction ratio(EDR_Rational) _ in light of system exergy contribution to terms of total work done by compressors ,exergy destruction ratio exergy destruction ratio (based on exergy of product and first law efficiency in terms of COP)and second law efficiency in terms of exergetic efficiency at different input variations and found that the flash chamber is responsible for highest exergy destruction for all refrigerants taken under consideration . It was observed that the R123 shows best first law efficiency and R125 shows lowest first law performance among selected sixteen ecofriendly refrigerants. It was found that the R123 demonstrates best first law effectiveness in terms of COP and R125 indicates most minimal first law efficiency among chose sixteen ecofriendly refrigerants. HFO-1234yf, which has a 100 year GWP of 4 as compared to that of CO_2 could be used as a "near drop-in replacement" for HFC134a. The first and second law efficiency of utilizing R1234ze (of GWP =6) is superior to R1234yf (of GWP=4) for higher temperature applications .The global warming potential of R134a is higher than R152a. Therefore R1234yf (GWP = 4) and R1234ze(GWP = 6) refrigerant can be utilized for medium and higher temperature applications, which can replace R134a around 2030 and R152a, R600a, , R290, R600 are combustible in nature can be utilized by utilizing security measures. In this manner R134a prescribed for all sort of applications before 2030 and R1234yf and R1234ze after 2030.

2. Thermal modelling of two stage cascade vapour compression refrigeration system

2.1 Energy Analysis of HTC Circuit

In each components of vapour compression refrigeration system energy changes :
Evaporators: it takes out the heat (Qe) from the cold room, which is given by

Q_evaporator = m_HTC (h_1-h_4) (1)

Where m_HTC can be computed ub using following energy balance equation

m_LTC. (h6-h7)= m_HTC (h_1-h_4) (2)

2.2 Compressor

The isentropic work input to HTC compressor (Wcs_HTC) is shown below

Wcs_HTC = m_HTC. (h_2-h_1) (3)

whereas actual HTC compressor work is termed as (Wc_HTC)

W_HTC_Compressor = W_cs_HTC/Ƞ_comp (4.a)

W_HTC_Compressor = m_HTC (h_2-h_1) (4.b)

2.3 Throttle valve

In throttle valve the enthalpy remains constant. We know that the first law is the measure of thermal performance of refrigeration cycle is COP and is termed as net refrigeration effect formed per unit of work required can be computed by using energy analysis of HTC vapour compression refrigeration cycle using R1234ze refrigerant .

COP_HTC = Q_HTC_ evaporator / Compressor (5)

2.4 Volumetric cooling capacity

The volumetric cooling capacity is the cooling capacity per unit vol. flow rate at the inlet to the compressor.
Volumetric cooling capacity = Q_ HTC_evaporator / (m_HTC x Vs_HTC) KJ/m^3 (6)

Where
m_HTC = mass flow of refrigeration (Kg/sec)
Vs_HTC= specific vol. at the inlet to compressor.

2.5 Pressure ratio

Compressor pressure ratio (Pr_HTC) is termed as

P_ratio_HTC = P_HTC_condenser/P_HTC_evaporator (7)
P_HTC _condenser = pressure of condenser at stage 2 (bar)
P_HTC _condenser = pressure of evaporator at stage 1 (bar)

2.6 Energy Analysis of LTC Circuit

In each components of LTC vapour compression refrigeration cycle using R1234yf, the energy changes in the various components are given below.

2.7 Evaporators

It takes out the heat (Q_LTC_evaporator) from the cold room, which is given by

Q_evaporator = m_LTC. (h_5-h_8) (8)

Compressor: the isentropic work input to LTC compressor (Wcs_LTC) is shown below

Wcs_LTC = m_LTC. (h_6-h_5) (9)

Where as actual compressor work is termed as (W_LTC_Compressor)

W_LTC_Compressor=W_cs_LTC/Ƞ_comp_LTC (10.a)
W_LTC_Compressor = m_LTC (h_2-h_1) (10.b)

2.8 Throttle valve-2

In the throttle valve the enthalpy remains constant because the first law, the measure of performance of refrigeration LTC cycle is COP_LTC and is termed as net LTC refrigeration effect formed per unit of LTC work required.

$COP_{\_LTC} = Q_{\_LTC\_\ evaporator} / W_{\_LTC\_Compressor}$ (11)

2.9 Volumetric cooling capacity

The volumetric cooling capacity is the cooling capacity per unit vol. flow rate at the inlet to the compressor.

Volumetric cooling capacity = $Q_{\_\ LTC\_evaporator} / (m_{\_LTC} \times V_{s\_LTC})$ KJ/m^3 (12)

Where

$m_{\_LTC}$ = mass flow of refrigeration (Kg/sec)

V_{s_LTC}= specific vol. at the inlet to compressor.

2.10 Pressure ratio

Compressor pressure ratio (Pr) is termed as

$P_{\_ratio\_LTC} = P_{\_LTC\ \ \_condenser} / P_{\_LTC\_evaporator}$ (13)

$P_{\_LTC\ \ \_condenser}$ = pressure of condenser at stage 3 (bar)

$P_{\_LTC\ \ \_condenser}$ = pressure of evaporator at stage 4 (bar)

$COP_{\_Overall} = (Q_{\_LTC\_evaporator} / W_{\_Total\ \_System})$ (14)

Where Total work done by system ($W_{\_Total\ \_System}$) is the sum of work done by high temperature compressor (kW) plus work done by low temperature compressor (kW)

$W_{\_Total\ \_System} = (W_{\_HTC\_Compressor} + W_{\_LTC\_Compressor})$ (15)

3. Exergy Analysis of HTC Circuit using R1234ze

3.1 Exergy Analysis of HTC Evaporator

Exergy entering in the HTC evaporator =

$m_{\_HTC}\ (h_4.T_{0s4}) + m_{\_HTC}\ (1- \{T_0/T_r\})$ (16)

Exergy leaving the evaporator = $m_{\_HTC}\ (h_1 - T_{\ 0S1})$ (17)

Exergy destruction ($Ed_{\_HTC\_Eva}$) in HTC cascade evaporator is given as :

$ED_{\_HTC\_evaporator} = [m_{\_HTC.}\ (h_4.T_{0S4}) + Q_{\_HTC\_\ evaporator}\ (1- \{T_0/T_r\}) - m_{\_HTC}\ (h_1- T_{\ 0S1})]$ (18)

Where,

$m_{\_HTC}$ = mass flow of refrigerant (kg/sec) flowing in the high temperature (HTC) circuit

$Q_{\_HTC\_Evaporator}$ = Refrigeration effect (kW)= 35 "kW"

h =enthalapy (kJ/Kg)

T = temp.

S = entropy

0 = refrence state

3.2 Exergy Analysis of HTC Compressor

Exergy entering in HTC compressor =

$m_{\_HTC}\ (h_1 - T_{0s1}) + W_{\_HTC\_Compressor}$ (19)

Exergy leaving in HTC compressor = $m_{\_HTC}\ (h_2- T_{0s2})$

Destruction of exergy in compressor ($ED_{\_compressor}$)

$ED_{\_HTC\_compressor} = [m_{\_HTC}\ (h_1 - T_{\ 0s1}) + Wc_{\_HTC\_Compressor} - m_{\_HTC}\ (h_2 - T_{0s2})]$ (20)

Where

$W_{_HTC}$_compressor.= High temperature compressor work

3.3 Exergy Analysis of HTC Condenser

Exergy entering the HTC condenser = $m_{\_HTC}\ (h_2 - T_eS_2)$ (21)

Exergy leaving the HTC condenser = $m_{\_HTC}\ (h_3 - T_{\ e}S_3)$ (22)

Exergy destruction in HTC condenser ($ED_{\_HTC\_\ cond}$.) can be expressed as

$ED_{\_\ HTC\_condenser} = m_{\_HTC}(h_2 - T_0S_2) - m_{\_HTC}(h_3-T_0S_3)$ (23)

3.4 Exergy Analysis of Throttle valve

As enthalpy across the throttle valve remains const. therefore destruction of exergy across the throttle valve (EDt) is given as : $ED_{\_HTC\_Throttling\_Valve} = m_{\_HTC}\ (s_4 - s_3)$ (24)

3.5 Total energy destruction in high temperature circuit using HFO-1234ze eco-friendly refrigerant

The total energy destruction in the HTC circuit using HFO-1234ze refrigerant is the summation of exergy destruction in the various components of the two stage vapour compression cascade refrigeration system in the HTC circuit and is given below as

$ED\_Total_{\_HTC} = ED_{\_HTC\_Throttling\_Valve\_} + ED_{\_HTC\_condenser}. + ED_{\_HTC\_compressor} + ED_{\_HTC\_evaporator}$ (25)

4. Exergy Analysis of LTC Circuit using R1234yf refrigerant

4.1 Exergy Analysis of LTC Evaporator

Exergy entering in the LTC evaporator = $m_{\_LTC}\ (h_8.T_0\ S_{\ 8}) + m_{\_LTC}\ (1- \{T_0/T_r\})$ (26)

Exergy leaving the LTC evaporator = $m_{\_LTC}\ (h_5 - T_{\ 0}S_5)$ (27)

Exergy destruction ($Ed_{\_LTC\_Eva}$) in LTC cascade evaporator is given as:

$ED_{\_LTC\_evaporator} = [m_{\_LTC.}\ (h_8.T_0S_8) + Q_{\_LTC\_\ evaporator}\ (1- \{T_0/T_r\}) - m_{\_LTC}\ (h_5- T_{\ 0}S_5)]$ (28)

Here,

$m_{\_LTC}$ = mass flow of refrigerant (kg/sec) flowing in the LTC circuit

$Q_{\_LTC\_Evaporator}$ = Refrigeration Effect. (KW)= 35 "kW" (29)

h = enthalapy (kJ/Kg)

T = temp.
S = entropy
0 = refrence state

4.2 Exergy Analysis of LTC Compressor

Exergy entering in LTC compressor = [$m_{\_LTC}$ ($h_5 - T_0 S_5$) + $W_{\_LTC\_Compressor}$] (30)
Exergy leaving in LTC compressor = $m_{\_LTC}$ (h_6- $T_0 S_6$) (31)
Destruction of exergy in LTC compressor ($ED_{\_compressor}$)
$ED_{\_LTC\_compressor} = m_{\_LTC} (h_5 - T_0 S_5) + Wc_{\_LTC\_Compressor} - m_{\_LTC} (h_6 - T_0 S_6)$ (32)

Where
$W_{_LTC}$_compressor.= low temperature compressor work

4.3 Exergy Analysis of LTC cascade Condenser

Exergy entering the LTC condenser = $m_{\_LTC}$ ($h_6 - T_e S_6$) (33)
Exergy leaving the LTC condenser = $m_{\_LTC}$ ($h_7 - T_e S_7$) (34)
Exergy destruction in LTC condenser ($ED_{\_LTC\_ cond}$.)
$ED_{\_LTC\_condenser} = [m_{\_LTC} (h_6 - T_0 S_6) - m_{\_LTC} (h_7 - T_0 S_7)]$ (35)

4.4 Exergy Analysis of Throttle valve in LTC

As enthalpy across the throttle valve remains const. therefore destruction of exergy across the throttle valve (EDt) is given as

$ED_{\_LTC\_Throttling\_Valve} = m_{\_LTC} (s_8 - s_7)$ (36)

4.5 Total energy destruction in low temperature circuit(LTC) using HFO-1234yf eco-friendly refrigerant

The total energy destruction in the LTC is the summation of exergy destruction in the various componenets of the cascade system in the LTC circuit and is given below as
$ED\_Total_{\_LTC} = ED_{\_LTC\_Throttling\_Valve\_} + ED_{\_LTC\_condenser}.+ ED_{\_LTC\_compressor} + ED_{\_LTC\_evaporator}$ (37)

4.6 Exergetic efficiency of the cascade system

The exergetic efficiency is the ratio of exergy of product to the exergy of fuel. The exergetic efficiency of the cascade system (ηex) is the ratio of exergy equivalent of refrigerating effect to the exergy of fuel in terms of total work of compressors. Where exergy of fuel in terms of total compressor work.

Exergy of Fuel=($W_{\_HTC\_Compressor}$ +$W_{\_LTC\_Compressor}$) (38)

4.7 Exergy destruction ratio ($EDR_{\_System}$)

$EDR_{\_System}$ is defined as the ratio of total exergy destruction in the system to exergy in the product.

EDR_System = [ED_ total_System / (EP)] (39)

Where exergy of product (EP) can be expressed by following equation

EP=$Q_{_LTC}$_Evaporator*((1-(T_ambient/T_Ref.) (40)

T_Ref= $T_{_LTC}$_Eva + Super Heating temperature and ED_ total_System=(ED_Total$_{_HTC}$ + ED_Total$_{_LTC}$)

Super Heating temperature is ranging from (0, 5 & 10)^{o}C
And Condenser Subcooled temperature is ranging from (0, 5 & 10w ^{o}C

Therefore ηex=[1/(1+EDR_System)] (41)

Defect in efficiency

The efficiency defect is the ratio between the exergy flow destroyed in each components and the exergy flow required to sustain the process, that is the electrical power supplied to the compressor

δ = EDi / Exergy of fuel (42)

i= used for particular component.
The defects in efficiency in the components are linked to the exergetic efficiency of the whole cascade system by means of following relation:

$\eta ex = (1 - \Sigma \delta i)$ (43)

Where **δi** is the exergy destruction ratio of each component.

5. Result and Discussion

Numerical computations have been carried out for two stage cascade refrigeration system using HFO-1234ze in high temperature circuit has condenser temperature of 50^{o}C and evaporator temperature of zero degree centigrade along with HFO-1234yf in low temperature cascade circuit has condenser temperature of 50^{o}C and evaporator temperature of -50^{o}C and cooling load capacity of 35 "kW' has two compressors have compressor efficiency of 0.80% respectively. Following input data have been used for predicting thermodynamic performances of two stages cascade refrigeration systems using ecofriendly refrigerants.

Condenser temperature=50^{o}C, Cascade evaporator temperature =0^{o}C, Low temperature evaporator= -50^{o}C.Efficiency of HTC Compressor =0.80. Efficiency of HTC Compressor =0.80, Load on Evaporator=70 kW, approach (Temperature overlapping)=10

Table-1(a)-(1(d) show the performance variation with different refrigerants of two systems and it was found that system-1 consists of Variation of refrigerants in high temperature circuit and R134a in the low temperature circuit and system-2 consists of Variation of refrigerants in high temperature circuit and R1234yf in the low temperature circuit and it was found that using R717 in the high temperature circuit, the first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency is higher and exergy destruction ratio of cascade system and exergy of fuel and mass flow rate (kg/sec) in the high temperature circuit is lower. It was also observed that the thermal performances (i.e. first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency) of system-1(consists of HFO-1234ze in high temperature circuit and R134a in the low temperature circuit) is higher than the system-2 (consists of HFO-1234ze refrigerants in high temperature circuit and R1234yf in the low temperature circuit). Table-2(a)-2(d) show the performance variation of two stage cascade refrigeration system with variation of temperature overlapping in terms of approach (i.e. temperature of low temperature condenser - temperature the hot fluid evaporator circuit) and it was observed that as increasing temperature overlapping in terms of approach, the first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency and first law efficiency of low temperature is decreases and exergy destruction ratio of cascade system and exergy of fuel and mass flow rate (kg/sec) in the high temperature circuit and mass flow rate (kg/sec) in the low temperature circuit is increases. Table-3(a)-3(b) show the performance variation of two stage cascade refrigeration system with variation of condenser temperature in the hot fluid circuit and it was observed that as increasing condenser temperature, the first law efficiency in terms of COP and second law efficiency in terms of exergetic efficiency is decreases and exergy destruction ratio of cascade system and exergy of fuel and mass flow rate (kg/sec) in the high temperature circuit is increases. From fig-4(a)-4(b) as decreasing low temperature evaporator temperature, decreases first law low temperature efficiency in terms of $COP_{overall,}$ exergy destruction ratio, and first law low temperature efficiency in terms of $COP_{\_LTC}$ while by decreasing low temperature evaporator temperature also increases both mass flow rates (Kg/sec) in low and high temperature circuits . similarly decreasing low temperature evaporator temperature, also increases the work done by both compressors, and also increases exergy of fuel (w) and exergy of product (W), From fig-5(a)-5(b) as increasing cascade evaporator temperature increases exergy destruction ratio, first law high temperature efficiency in terms of COP_HTC, exergy of fuel (W) work done by low temperature circuit compressor and also mass flow rates in low and high temperature circuits while by increasing cascade evaporator temperature decreases overall system first law efficiency in terms of system overall coefficient of performance, second law efficiency. in terms of exergetic efficiency, first law efficiency of low temperature circuit in terms of $COP_{\_LTC}$ and work done by high temperature circuit compressor.

Table-1(a): Effect of following ecofriendly refrigerants in HTC Circuit and R134a in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Refrigerant	$COP_{\_Over\_All}$	$EDR_{\_System}$	Exergetic Efficiency	$COP_{\_HTCl}$	$COP_{\_LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
R717	1.189	1.502	0.3997	3.546	2.294	0.04946	0.2282
R-1234yf	1.099	1.708	0.3692	3.027	2.294	0.5341	0.2282
R1234ze	1.133	1.628	0.3808	3.215	2.294	0.4441	0.2282

Table-1(b) Effect of following ecofriendly refrigerants in HTC Circuit and R134a in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Refrigerant	$Exergy_{\_fuel}$ (W)	Exergy_Product (W)	Exergetic Efficiency	$W_{\_Comp\_HTCl}$	$W_{\_Comp\ LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
R717	29.57	11.82	0.3997	14.24	15.33	0.04946	0.2282
R-1234yf	32.02	11.82	0.3692	16.68	15.33	0.5341	0.2282
R1234ze	31.03	11.82	0.3808	15.71	15.33	0.4441	0.2282

Table-1(c): Effect of following ecofriendly refrigerants in HTC Circuit and R134a in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Refrigerant	$COP_{\_Over\_All}$	$EDR_{\_System}$	Exergetic Efficiency	$COP_{\_HTCl}$	$COP_{\_LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
R-717	1.158	1.570	0.3891	3.546	2.204	0.050	0.2992
R134a	1.109	1.683	0.3728	3.246	2.204	0.4026	0.2992
R1234ze	1.104	1.696	0.3710	3.215	2.204	0.4497	0.2992

Table-1(d) Table-1(c): Effect of following ecofriendly refrigerants in HTC Circuit and R134a in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Refrigerant	$Exergy_{\_fuel}$ (W)	$Exergy_{\_Product}$ (W)	Exergetic Efficiency	$W_{\_Comp\_HTCl}$	$W_{\_Comp\ LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
R134a	30.38	11.82	0.3891	14.42	15.96	0.050	0.2992
R-1234yf	31.71	11.82	0.3728	15.75	15.96	0.4026	0.2992
R1234ze	31.86	11.82	0.3710	15.90	15.96	0.4497	0.2992

Table-2 (a) Effect of Approach (i.e. temperature over lapping) usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Approach (°C)	$COP_{\_Over\_All}$	$EDR_{\_System}$	Exergetic Efficiency	$COP_{\_HTCl}$	$COP_{\_LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
0	1.295	1.292	0.4353	3.215	2.844	0.4148	0.2695
5	1.196	1.487	0.4020	3.215	2.497	0.4332	0.2834
10	1.104	1.696	0.3710	3.215	2.204	0.4497	0.2992
15	1.017	1.925	0.3419	3.215	1.951	0.4679	0'3171

Table-2(b) Effect of Approach (i.e. temperature over lapping) usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Approach (°C)	$Exergy_{\_Fuel}$ (W)	$Exergy_{\_Product}$ (W)	Exergetic Efficiency	$W_{\_Comp\_HTCl}$	$W_{\_Comp\ LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
0	27.15	11.82	0.4353	14.78	12.37	0.4148	0.2695
5	29.4	11.82	0.4020	15.32	14.08	0.4332	0.2834
10	31.86	11.82	0.3710	15.9	15.96	0.4497	0.2992
15	34.57	11.82	0.3419	16.55	18.03	0.4679	0.3171

Table-2(c) Effect of Approach (i.e. temperature over lapping) usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Approach (°C)	$COP_{\_Over\_All}$	$EDR_{\_System}$	Exergetic Efficiency	$COP_{\_HTCl}$	$COP_{\_LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
0	1.295	1.292	0.4353	3.215	2.844	0.4148	0.2695
2	1.255	1.371	0.4217	3.215	2.698	0.4240	0.2749
4	1.215	1.448	0.4020	3.215	2.562	0.430	0.2805
6	1.177	1.528	0.3956	3.215	2.497	0.4363	0.2864
8	1.140	1.610	0.3831	3.215	2.435	0.4429	0.2927
10	1.104	1.696	0.3710	3.215	2.204	0.4497	0.2992
12	1.069	1.785	0.3591	3.215	2.098	0.4567	0.3061
14	1.034	1.877	0.3475	3.215	1.998	0.4641	0.3133

Table-2(d) Effect of Approach (i.e. temperature over lapping) usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Approach (°C)	$Exergy_{\_Fuel}$ (W)	$Exergy_{\_Product}$ (W)	Exergetic Efficiency	$W_{\_Comp\_HTCl}$	$W_{\_Comp\ LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
0	27.15	11.82	0.4353	14.78	12.37	0.4148	0.2695
2	28.03	11.82	0.4217	14.99	13.04	0.4240	0.2749
4	28.93	11.82	0.4020	15.21	13.73	0.430	0.2805
6	29.87	11.82	0.3956	15.43	14.49	0.4363	0.2864
8	30.85	11.82	0.3831	15.66	15.19	0.4429	0.2927
10	31.86	11.82	0.3710	15.9	15.96	0.4497	0.2992
12	32.91	11.82	0.3591	16.15	16.76	0.4567	0.3061
14	34.01	11.82	0.3475	16.41	17.60	0.4641	0.3133

Table3(a) Effect of Condenser Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Condenser Temperature (°C)	COP_Over_All	EDR_System	Exergetic Efficiency	COP_HTCl	COP_LTC	m_C_HTC (Kg/sec)	m_C_HTC (Kg/sec)
30	1.458	1.041	0.490	6.264	2.204	0.4148	0.2695
35	1.364	1.183	0.4580	5.192	2.204	0.4240	0.2749
40	1.273	1.338	0.4277	4.379	2.204	0.430	0.2805
45	1.187	1.508	0.3988	3.737	2.204	0.4363	0.2864
50	1.104	1.696	0.3710	3.215	2.204	0.4429	0.2927
55	1.024	1.907	0.3441	2.779	2.204	0.4497	0.2992
60	0.9455	2.145	0.3178	2.407	2.204	0.4567	0.3061

Table-3(b) Effect of Condenser Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Condenser Temperature (°C)	Exergy_Fuel (W)	Exergy_Product (W)	Exergetic Efficiency	W_Comp_HTCl	W_Comp LTC	m_C_HTC (Kg/sec)	m_C_HTC (Kg/sec)
30	24.12	11.82	0.490	8.162	15.96	0.3580	0.2992
35	25.81	11.82	0.4580	9.847	15.96	0.3768	0.2992
40	27.63	11.82	0.4277	11.68	15.96	0.3980	0.2992
45	29.64	11.82	0.3988	13.61	15.96	0.4221	0.2992
50	31.86	11.82	0.3710	15.9	15.96	0.4497	0.2992
55	34.35	11.82	0.3441	18.40	15.96	0.4817	0.2992
60	37.20	11.82	0.3178	21.24	15.96	0.5193	0.2992

Table4(a) Effect of LTC Evaporator Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Cascade Evaporator (°C)	COP_Over_All	EDR_System	Exergetic Efficiency	COP_HTCl	COP_LTC	m_C_HTC (Kg/sec)	m_C_HTC (Kg/sec)
-30	1.568	1.820	0.3546	3.215	4.011	0.3864	0.2682
-35	1.436	1.763	0.3619	3.215	3.404	0.4002	0.2763
-40	1.316	1.726	0.3669	3.215	2.921	0.4152	0.2828
-45	1.206	1.704	0.3699	3.215	2.529	0.4316	0.2907
-50	1.104	1.696	0.3710.	3.215	2.204	0.4497	0.2992

Table-4(b) Effect of LTC Evaporator Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Cascade Evaporator (°C)	Exergy_Fuel (W)	Exergy_Product (W)	Exergetic Efficiency	W_Comp_HTCl	W_Comp LTC	m_C_HTC (Kg/sec)	m_C_HTC (Kg/sec)
-30	22.43	7.955	0.3546	13.67	8.768	0.3864	0.2682
-35	24.48	8.860	0.3619	14.15	10.33	0.4002	0.2763
-40	26.72	9.804	0.3669	14.68	12.04	0.4152	0.2828
-45	29.17	10.79	0.3699	15.26	13.91	0.4316	0.2907
-50	31.86	11.82	0.3710.	15.90	15.96	0.4497	0.2992

Table-5(a) Effect of cascade evaporator Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Cascade Evaporator (°C)	COP_Over_All	EDR_System	Exergetic Efficiency	COP_HTCl	COP_LTC	m_C_HTC (Kg/sec)	m_C_HTC (Kg/sec)
-20	1.059	1.811	0.3558	1.860	3.777	0.4463	0.2458
-15	1.083	1.748	0.3639	2.117	3.261	0.4453	0.2570
-10	1.099	1.708	0.3693	2.42	2.844	0.4455	0.2695
-5	1.106	1.69	0.3717	2.78	2.497	0.4469	0.2834
0	1.104	1.696	0.3710	3.215	2.204	0.4497	0.2992
5	1.092	1.726	0.3669	3.75	1.951	0.4541	0.3171
10	1.069	1.783	0.3593	4.421	1.721	0.4605	0.3376
15	1.036	1.871	0.3483	5.287	1.533	0.4691	0.3614
20	0.9931	1.996	0.3338	6.446	1.356	0.4805	0.3892

Table-5(b) Effect of Cascade Evaporator /Cascade condenser Temperature usingHFO-1234ze ecofriendly refrigerants in HTC Circuit and R1234yf in LTC Circuit on the thermal performances of two stage cascade refrigeration systems

Cascade Evaporator (ºC)	$Exergy_{\_Fuel}$ (W)	$Exergy_{\_Product}$ (W)	Exergetic Efficiency	$W_{\_Comp\_HTCl}$	$W_{\_Comp\ LTC}$	$m_{\_C\_HTC}$ (Kg/sec)	$m_{\_C\_HTC}$ (Kg/sec)
-20	33.22	11.82	0.3558	23.91	9.311	0.4463	0.2458
-15	32.48	11.82	0.3639	21.70	10.76	0.4453	0.2570
-10	32.01	11.82	0.3693	19.64	12.37	0.4455	0.2695
-5	31.80	11.82	0.3717	17.71	14.08	0.4469	0.2834
0	31.86	11.82	0.3710	15.90	15.95	0.4497	0.2992
5	32.22	11.82	0.3669	14.19	18.03	0.4541	0.3171
10	32.89	11.82	0.3593	12.56	20.34	0.4605	0.3376
15	33.94	11.82	0.3483	10.99	22.95	0.4691	0.3614
20	35.41	11.82	0.3338	9.479	25.93	0.4805	0.3892

6. Conclusion

During this extensive energy and exergy analysis of two stage cascade refrigeration system of three types,(i) System-1 consists of HFO-1234ze in High temperature circuit and R134a in the low temperature circuit , System-2 consists of HFO-1234ze in High temperature circuit and R1234yf in the low temperature and System-3 consists of HFO-1234yf in High temperature circuit and R134a in the low temperature circuit , it was found that R134yf and R1234ze are good replacement of R134a. Numerical computations was carried out on above three system at T_Eva_LTC= --50ºC and Condenser temperature =50ºC and 0oC of Evaporator temperature of High temperature , by considering the effect of temperature overlapping, the following conclusions are given below.

1. COP and exergetic efficiency of system-1 consist of HFO-1234ze and R134a in LTC gives best thermal performances in terms of first law efficiency (COP_Overall) and exergetic efficiency) than system-3 using HFO-1234yf in HTC and R134a in LTC
2. HFC-134a and HFO1234ze is nearly same thermodynamic performances in terms of over all system COP and exergetic efficiency having a difference of around 5% , in case of single stage vapour compression refrigeration syste while by using HFO-1234yf as compared to R134a , its thermal performances reduced around 10% to 15% respectively.
3. The exergetic efficiency of system-1, decreases with the increase in evaporator temperature, whereas it is 10% to 15% higher than HFO-1234yf. Hence HFO-1234yf can be a good 'drop-in' replacement of HFC-134a at higher value of evaporator temperature
4. HFO-1234ze can be a good replacement of R134a for higher temperature application using liquid vapour heat exchanger. after certain modification.
5. System-2, using HFO-1234ze in high temperature circuit and R1234yf in low temperature circuit gives better thermodynamic performances than system-3 consists of HFO-1234yf in high temperature circuit and R134a in the low temperature circuit.
6. In case of single stages cascade refrigeration system using energy -exergy analysis, irreversibility of each components have been computed and it was found that the worst component is condenser followed by compressor, throttle valve, evaporator and liquid vapour heat exchanger, the most efficient component. Total exergy destruction is more for HFO-1234yf followed by HFO-1234ze and HFC-134a,
7. Increase in ambient state temperature from 25ºC to 40ºC , has a increasing effect on second law efficiency in terms of exergetic efficiency.
8. The variation of increasing evaporator and condenser temperatures , the exergetic efficiency has significantly decreasing trend and EDR, i.e. EDR increasing effect in case of single stage vapour compression refrigeration system.

References

[1] Directive 2006/40/EC(2006) of the European Parliament and of the Council of 17 May 2006 Relating to Emissions from Air Conditioning Systems in Motor Vehicles and Amending Council Directive 70/156/EC, 2006.

[2] Regulation 517/2014/EU(2014) of the European Parliament and the Council of 16 April 2014 on Fluorinated Greenhouse Gases and Repealing Regulation (EC) No 842/2006. Official Journal of the European Union, 2014.

[3] Syed Mohammad Said (1994) Exergetic assessment of the coolants HCFC123, HFC134a, CFC11, and CFC12, Energy, Vol- 19, No-11, page-1181–1186

[4] C. Nikolaidis, D. Probert [1998] Exergy method analysis of a two-stage vapour-compression refrigeration-plants performance. Int J Applied Thermal Engineering.1998; 60:241-256.

[5] H.M Getu, P.K Bansal. Thermodynamic analysis of an R744-R717 cascade refrigeration system. Int J Refrigeration.2008; 31:45-54.

[6] J. N. Esbri, J.M.M. Miranda, A.M. Babiloni, A.B. Cervera and J.M.B. Flores, "Experimental analysis of R1234yf as a drop-in replacement for R134a in a vapor compression system," International Journal of Refrigeration 36, 870-880, 2012.

[7] D. Jung, Y. Lee and D. Kang, "Performance of virtually nonflammable azeotropic HFO1234yf/HFC134a mixture for HFC134a applications," International Journal of Refrigeration 36, 1203-1207, 2013.

[8] Karber K et.al..[(2012)]; "Experimental Performance of R-1234yf as a Drop-in Replacement for R-134a in Domestic Refrigerators" International Refrigeration and Air Conditioning Conference. Paper 1228. Page-1-10.

[9] Minor B. and M. Spatz,[2008] "HFO-1234yf low GWP refrigerant update," In: International Refrigeration and Air Conditioning Conference at Purdue, West Lafayette, IN, USA, Paper No. 2349.

[10] Reaser P.,et.al [2010]V. Aute and R. Radermacher, "Refrigerant R1234yf Performance Comparison Investigation," International Refrigeration and Air Conditioning Conference 1085, 20.

[11] R.S. Mishra [2014] Performance optimization of four stage cascade refrigeration systems using energy-exergy analysis in the R1234ze & R1234yf in high temperature circuit and ecofriendly refrigerants in intermediate circuits and ethane in the low temperature circuit for food, pharmaceutical, chemical industries" International Journal of Advance Research and Innovation, ISSN 2347 - 3258 , Volume 2, Issue 4 , page-701-709.

[12] R.S. Mishra [2014] Use of hydrocarbons in low temperature circuit in terms of first law and second law Efficiency of four stage cascade refrigeration of semen preservation" International Journal of Advance Research and Innovation, ISSN 2347 - 3258 , Volume 2, Issue 4, page-725-731.