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Use of fourth generation ecofriendly refrigerants in two and three cascade refrigeration systems for reducing global warming and ozone depletion

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Abstract

The recent global agreement is signed in Kigali to limit the use of hydrofluorocarbons (HFCs) as refrigerants, starting by 2019, has promoted an active area of research toward the development of new eco-friendly refrigerants of low global warming potential (GWP). The fourth generation refrigerants namely Hydro-fluoro-olefins (HFOs) have been proposed as a low GWP alternatives to third generation HFC refrigerants in the cascade refrigeration systems. , To assess their performance to replace R12, R22 and R13 refrigerants in current use. In this paper, the HFO-based commercial refrigerants as fourth generation low GWP refrigerants, have been considered and their thermal performances in terms of first law efficiency (in terms of coefficient of performance (COP Overall), system exergy destruction ratio based on exergy of product, second law efficiency in terms of exergetic efficiency have been computed. It was observed that two stage cascade refrigeration system using R1234ze in high temperature circuit and R1234yf in the low temperature evaporator (up to -50^{0}C) cascade system, can replace R134a. The numerical computations have been carried out for three stage proposed system (system-1: using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and fifteen ecofriendly refrigerants in low temperature circuit). To validate the results obtained by developed model, proposed three stage cascade refrigeration system (system-1) and three stage conventional cascade refrigeration system (system-2) have been compared in terms of their thermal first and second law performances and power consumption by system and its compressors. The proposed three stage cascade refrigeration system (System-1) using HFO refrigerants up to -100^{0}C gives similar thermodynamic performances and 2% less power consumption than conventional three stage cascade refrigeration system (system-2). In case of three stage cascade refrigeration using HFO-1234ze in the high temperature circuit and HFO-1234yf in intermediate temperature circuit two stage refrigeration cascade system circuit andR245fa in low temperature circuit gives better thermal performances. The first and second law thermal performance parameters using HFO-245fa in low temperature circuit are around 0.75% higher than that of HFC-134a.

Keywords: Thermodynamic Analysis, HFO refrigerants, Fourth generation refrigerants, Cascade refrigeration system.

1. Introduction

The most commonly used refrigerants in recent past were R12 in high temperature circuit and R22in intermediate temperature circuit, along with R13 in the low temperature cascade refrigeration systems which because of their high ODP have been either phased out or under consideration for the same. After the revelation of the harmful effects of CFC and HCFC refrigerants on the ozone layer, search to find alternative working fluids gained more interest in the recent few years. The HFC134a was found to be a suitable candidate for replacing R13 and is being successfully used. HFC134a has very high GWP which is a matter of environmental concern [1]. Therefore the use of HFO refrigerants in the cascade refrigeration is proposed [1, 2, 3, 12]. HFO stands for hydro-fluoro-olefin (HFO-1234yf) is a low global warming potential (GWP) refrigerant for use in automotive air-conditioning systems. HFC-134a is a hydro-fluoro-carbon refrigerant, while (HFO-1234yf) is a hydro-fluoro-olefin refrigerant. Hydro-fluoro-olefin, or in short HFO, is a definition that is familiar to many of us. R1234yf, R1234ze are few examples of HFOs. They are used in a number of applications today, but have been barely studied just a decade ago. HFO-1234yf was developed to meet the European directive 2006/40/EC in 2011 requiring

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use of HFO refrigerant in AC system with a GWP below 150. HFO-1234yf, which has a 100-year GWP lower than 1. These refrigerants are used as a "near drop-in replacement" for R-134a, used in automobile AC systems, which has a 100-year GWP of 1430. HFO-1234yf has the lowest cost among the currently proposed alternatives (i.e.R134a). Thermophysical properties of Refrigerants are shown in table-1

Table 1: Thermo-physical properties of HFO Refrigerants.

Properties	HFO-1234yf	HFO-1234ze	HFC-134a
Boiling Point, Tb	-29°C	-19°C	-26°C
Critical Point, Tc	94.7°C	109.4°C	101°C
Pvap, MPa at 25°C	0.682	0.500	0.665
Pvap, MPa at 80°C	2.519	2.007	2.635
Liquid Density, kg/m3 at 25°C	1092	1162	1207
Vapour Density, kg/m3 at 25°C	37.94	26.76	32.34

Although the initial cost of refrigeration and air conditioning system using R1234yf is much higher than that of R-134a and handled in repair shops in the same way as R-134a with different, specialized equipment to perform the service due to the mild flammability of HFO-1234yf and another issue affecting the compatibility between HFO-1234yf and R-134a-based systems due to choice of lubricating oil due to damage to plastic and aluminum, and issues with health, rashes, and sore throat, among other effects including mouth dryness.

2. Literature Review

HFO-1234yf would be adopted as a replacement of R-134a automotive air-conditioning refrigerant. Mishra [1] concluded that the first law efficiency in terms of coefficient of performance COP and second law efficiency in terms of exergetic efficiency of HFC-134a and HFO- 1234ze is almost same having a difference of 5.6%, which decreases with the increase in evaporator temperature, whereas it is 14.5-5% higher than HFO-1234yf. Hence HFO-1234yf can be a good drop-in' replacement of HFC-134a at higher value of evaporator temperature and HFO-1234ze can be a good replacement after certain modification [3]. From the irreversibility or exergy destruction viewpoint, worst component is condenser followed by compressor, throttle valve, evaporator and liquid vapour heat exchanger, the most efficient component. Total efficiency defect is more for HFO-1234yf followed by HFO-1234ze and HFC-134a, but the difference is small. Increase in ambient state temperature has an increasing (positive) effect on second law efficiency in terms of exergetic efficiency and exergy destruction ratio which was computed based on exergy of fuel or based on exergy of product (EDR). When exergy destruction ratio (EDR) reduced, then exergetic efficiency increases. Therefore HFO-1234yf gives lesser values of exergetic efficiency whereas HFO-1234ze gives approximately similar values.4. HFC-134a gives higher COP and exergetic efficiency than HFO-1234yf but lesser value than HFO- 1234ze. However reverse trend is seen when effectiveness of heat exchanger is increased from 0 to 1. Hence, it can be concluded that even though the values of performance parameters for HFO-1234yf are smaller than that of HFC-134a, but the difference is small, so it can a good alternative to HFC-134a because of its environmental friendly properties. HFO-1234ze can replace the conventional HFC-134a after having slight modification in the design as the performance parameters are almost similar.

3. Energy Exergy Analysis of Vapour Compression Refrigeration Systems

The second law analysis (i.e. exergy Computation) is widely accepted as a useful tool for obtaining overall performances of any system for finding various exergy losses occurred in its components Exergy analysis also helps in taking account the important engineering decisions regarding design parameters of a system by finding maximum exergy destruction using entropy generation principle Many researchers have carried out exergy studies of different thermal energy conversion systems describing various approach for exergy analysis and its usefulness for improving existing designs by reducing exergy destruction in a more simple and effective manner [2-3] Padilla et al. [4] carried out the exergy performance of vapour compression refrigeration system (VCRS) by using zeotropic mixture (R413A) for direct replacement of R12 and found that the overall energy and exergy performances of this system working with R413A is far better than R12. Arora and Kaushik [5] presented a detailed exergy analysis of an actual vapour compression refrigeration (VCR) cycle and developed computational model for computing coefficient of performance (COP), exergy destruction, exergetic efficiency and efficiency defects for R502, R404A and R507A and found that the R507A is a better substitute to R502 than R404A. The efficiency defect in condenser is highest, and lowest in liquid vapour heat exchanger for R502, R404A and R507A refrigerants in the range of −50°C to 0°C evaporator temperature and in the range and 40°C to 55°C condenser temperature respectively. Anand S and Tyagi S. K. [6] presented a detailed experimental analysis of 2 ton of refrigeration capacity vapor compression refrigeration cycle using R22 as working fluid for different percentage of refrigerant charge using exergy analysis and evaluated thermal performances. Yumrutas et al [7] investigated of the effects of the evaporating and condensing temperatures on the pressure losses, exergy losses, second law of efficiency, and the COP of a vapour compression cycle. Dincer [8] asserts that conventional energy analysis, based on the first law of thermodynamics, evaluates energy mainly on its quantity but analysis that are based on second law considers not only the quality of energy, but also quantity of energy. Kumar et al. [9] also computed the exergetic analysis of a VCR system using R11 and R12 as refrigerants. Nikolaidis and Probert [10] used exergy method for calculating ting thermodynamic performances of R22 in a two-stage compound compression cycle, with flash intercooling. Bejan [11] developed, thermodynamic model by using heat transfer irreversibility and showed that the exergetic efficiency decreases as evaporator temperature decreases. From the irreversibility or exergy destruction viewpoint, worst component is condenser followed by compressor, throttle valve, evaporator and liquid vapour heat exchanger, the most efficient component. Total efficiency defect is more for HFO-1234yf followed by HFO-1234ze and HFC-134a, but the difference is small. Increase in ambient state temperature has an increasing (positive) effect on second law efficiency in terms of exergetic efficiency and exergy destruction ratio which was computed based on exergy of fuel or based on exergy of product (EDR). When exergy destruction ratio (EDR) reduced, then the exergetic efficiency increases. Therefore HFO-1234yf gives lesser values of exergetic efficiency whereas HFO-1234ze gives approximately 4% less values. HFC-134a gives higher COP and exergetic efficiency than HFO-1234yf but lesser value than HFO- 1234ze [12].

4. Result and Discussion

The developed thermal model has been tested using three stage cascade refrigeration system-2 [13]. It was observed that developed models verified the results [13] shown in Table-2(a) to Table2(c) respectively

Table-2(a): Validation of First law Thermal performances in terms of coefficient of performance (COP) of three stage cascade vapour compression refrigeration system from developed Model [10]

Parameters	Ref [13]	Developed Model (proposed)
System First law Efficiency (COP_Over_All)	0.858	0.8723
High temperature Circuit First law Efficiency (COP_HTC)	2.88	3.018
Intermediate temperature Circuit First law Efficiency (COP_MTC)	3.7	3.653
Low temperature Circuit First law Efficiency (COP_LTC)	3.74	3.763

For a given data T9=173K, T5=223K, T3=313K, Ambient= 298K, QEva3=175kW, ETA_Comp1=0.8, ETA_Comp2=0.8, ETA_Comp3=0.8, Temp_Over_Lapping_MTC=10, Temp_Over_Lapping_LTC=10

Table-2(b): Validation of Thermal performances in terms of power required of three stage cascade vapour compression refrigeration system from developed Model [10]

Parameter	Ref [13]	Developed Model
Power required to run Total System (Exergy of fuel) kW	204	200.6
Power required to run first Compressor (W_Comp_1) kW	97.4	93.49
Power required to run second Compressor (W_Comp_2) kW	59.8	60.04
Power required to run third Compressor (W_Comp_3) kW	46.8	46.5

For a given data T9=173K, T5=223K, T3=313K, T_Ambient= 298K QEva3=175kW, ETA_Comp1=0.8 ETA_Comp2=0.8, ETA_Comp3=0.8, Temp_Over_Lapping_MTC=10 Temp_ Over _ Lapping LTC=10

Table-2(c): Validation of Thermal performances of three stage cascade vapour compression refrigeration system from developed Model [10]

Parameter	Ref [13]	Developed Model
High temperature Circuit Mass flow rate _HTC(Kg/sec)	2.72	2.732
Intermediate temperature Circuit Mass flow rate _MTC (Kg/sec)	1.15	1.16
Low temperature Circuit Mass flow rate _LTC (Kg.sec)	1.5	1.501

For a given data T9=173K, T5=223K, T3=313K, T_Ambient= 298K, QEva3=175kW, ETA_Comp1=0.8 ETA_Comp2=0.8, ETA_Comp3=0.8Temp_Over_Lapping_MTC=10, Temp_Over_Lapping_LTC=10

Similarly for reducing of global warming and ozone depletion the comparisons were made between two refrigeration systems of three stage cascade vapour compression types. Two systems (of three stage cascade vapour compression refrigeration Systems) have been considered in the present investigations. The system_1 consists of: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and ecofriendly R134a Refrigerant in low temperature circuit. The Properties of refrigerants used in the low temperature circuit in the three stage cascade refrigeration is given in Table-3.

Table-3: Input Data for three stage cascade vapour compression refrigeration systems (Proposed System)

Refrigerant in circuit	GWP	ODP
HFO1234ze in high temperature circuit	6	0
HFO1234yf in medium temperature circuit	4	0
R134a in low temperature circuit	1430	0
Hepta Fluoropropane (R227ea)	3500	0
Hexa fluoro propane R236ea	1200	0
Pentra fluoro propane R245fa	950	0

The sytem-2 Consists of Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit is used and comparisons between proposed system (system-1) and conventional cascade system (system-2) in terms of thermal performances were made.it is clear that system -2 produces global warming and ozone depletion was replaced by system-1 due to similar thermal performances in terms of first law efficiency (system COP) and second law efficiency and System Exergy Destruction Ratio (Based on Exergy product) as shown in tables-4. Respectively. Table-4 shows the exergy of fuel in terms of total power required to run all three compressors in the three stage vapour compression refrigeration systems, it was observed that proposed system (system-1) required less power consumptions than conventional cascade refrigeration system (system-2). The By using R134a, the minimum exergy input in terms of exergy of fuel (kW) needed as compared to R1234yf and R1234ze in the proposed system (system-1) as compared to conventional cascade refrigeration system (system-2).

Table-4(a): comparison of thermal performances of two systems System-1: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and system-2: Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	First Law Efficiency (COP_Overall)	System Exergy Destruction Ratio (Based on Exergy product)	Second Law Efficiency (Exergetic Efficiency)
Proposed(System-1)	0.5074	1.728	0.3666
System-2	0.5075	1.727	0.3667

Table-4(b) comparison of thermal performances of two systems (System-1: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and system-2: Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	High Temperature Circuit First Law Efficiency (COP_HTC)	Medium (Intermediate) Temperature Circuit First Law Efficiency (COP_MTC)	Low Temperature Circuit First Law Efficiency (COP_LTC)
System-1	3.215	2.204	1.790
System-2	3.362	2.305	1.676

Table-4(c): comparison of thermal performances of two systems (System-1: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and system-2 : Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	Mass Flow Rate in High temperature Cascade Evaporator (kg/sec)	Mass Flow Rate in Intermediate Temperature cascade Evaporator (kg/sec)	Mass Flow Rate in Low Temperature Evaporator (kg/sec)
System-1	3.488	2.321	0.9285
System-2	352.0	225.6	126.4

Table-4(d) comparison of thermal performances of two systems (System-1: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and system-2: Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	Exergy of Fuel (kW)	Exergy of product (kW)	System Exergy losses
Proposed System-1	344.9	126.44	218.5
System-2	344.8	126.44	218.4

Table-4(e): comparison of thermal performances of two systems (System-1: Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and system-2: Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	Power required to run the whole system (Exergy of Fuel) (kW))	Total Exergy Losses in the system (kW))	Exergy Product of the system (kW))
Proposed System-1	344.9	218.5	126.4
System-2	352.0	225.6	126.4

Table-4(f) comparison of thermal performances of two systems (Proposed system(System-1): Cascade Refrigeration system using R1234ze in high temperature circuit and R1234yf in intermediate temperature circuit and eco Friendly R134a Refrigerant in low temperature circuit and Conventional cascade refrigeration system (system-2) : Cascade Refrigeration system using R12 in high temperature circuit and R22 in intermediate temperature circuit and R13 Refrigerant in low temperature circuit) for low temperature applications.

Cascade Refrigeration system	Power required to Run High Temperature Compressor (kW)	Power required to Run Intermediate Temperature Compressor (kW)	Power required to Run Low Temperature Compressor (kW)
Proposed System-1	123.3	123.8	97.79
Conventional Cascade three stage system (System-2)	119.2	121.2	104.4

Table-5(a) presents the variation of first law efficiency in terms of c0efficient of performance and second law efficiency in terms of energetic efficiency with ecofriendly refrigerants (for condenser temperature=50^{0}C, temperature overlapping in both cascade is 10^{0}C, Temperature of high temperature cascade evaporator is 0oC and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that first law efficiency in terms of system coefficient of performance of the system is maximum using R600a refrigerant and minimum using R407c in the low temperature circuit. Similarly System Exergy Destruction Ratio (Based on Exergy product) of the whole system is is minimum using R600 in the low temperature circuit and higher using R32 refrigerant in low temperature circuit. Table—5(b) presents the variation of High Temperature Circuit First Law Efficiency (COP_HTC), Medium (Intermediate) Temperature Circuit First Law Efficiency (COP_MTC) Low Temperature Circuit First Law Efficiency (COP_LTC) with ecofriendly refrigerants (for condenser temperature=50^{0}C, temperature overlapping in both cascade is 10oC, Temperature of high temperature cascade evaporator is 0^{0}C and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that High Temperature Circuit First Law Efficiency (COP_HTC), Medium (Intermediate) Temperature Circuit First Law Efficiency (COP_MTC) is remains constant due to no change of refrigerants in the high temperature circuit and low temperature circuit while Low Temperature Circuit First Law Efficiency (COP_LTC) of the low temperature circuit. is maximum using R600a in the low temperature circuit and lower using R32 refrigerant in low temperature circuit. Table-5(c) presents the variation of exergy of fuel and second law efficiency in terms of exergetic efficiency with ecofriendly refrigerants (for condenser temperature=50oC, temperature overlapping in both cascade is 10^{0}C, Temperature of high temperature cascade evaporator is 0^{0}C and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that second law efficiency in terms of exergetic efficiency of the system is maximum using R600a refrigerant and minimum using R407c in the low temperature circuit. Similarly exergy of fuel required to run the whole system is in the whole system is minimum using R600 in the low temperature circuit and higher using R123 refrigerant in low temperature circuit. Table-5(d) presents the variation of Mass Flow Rate in High Temperature Cascade Evaporator with ecofriendly refrigerants (for condenser temperature=50^{0}C, temperature overlapping in both cascade is 10^{0}C, Temperature of high temperature cascade evaporator is 0^{0}C and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that Mass Flow Rate in High Temperature Cascade Evaporator in high temperature compressor is minimum using R600a refrigerant and R407c is maximum. Similarly Mass Flow Rate in intermediate Temperature Cascade Evaporator is minimum using R134a refrigerant and is maximum by using R142b in the low temperature circuit. The Mass Flow Rate in low Temperature Evaporator is minimum using R600a refrigerant and is maximum by using R410a in the low temperature circuit.Table-5(e) presents the variation of power required to run various compressors with ecofriendly refrigerants (for condenser temperature=50^{0}C, temperature overlapping in both cascade is 10^{0}C, Temperature of high temperature cascade evaporator is 0^{0}C and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that power required to run high temperature compressor is minimum using R600a refrigerant and R407c is maximum. Similarly power required to run intermediate temperature compressor and low temperature compressor is minimum using R600a refrigerant and is maximum by using R407c in the low temperature circuit. Table-5(f) presents the variation of exergy of fuel with ecofriendly refrigerants (for condenser temperature=50^{0}C, temperature overlapping in both cascade is 10^{0}C, Temperature of high temperature cascade evaporator is 0oC and intermediate cascade evaporator temperature is -50^{0}C, for compressor efficiency of each compressor is 80 %) and it was observed that exergy of fuel in terms of total power required to run the whole system is maximum using R123 refrigerant and R600 is minimum. Similarly exergy losses in the whole system is minimum using R600 in the low temperature circuit.

Table-5(a): Variation of system performance parameters in terms of first law efficiency (system coefficient of performance), second law efficiency (exergetic efficiency) and system exergy destruction ratio (based on exergy product) with ecofriendly refrigerants

Eco Friendly Refrigerant	First Law Efficiency (COP_Overall)	System Exergy Destruction Ratio (Based on Exergy product)	Second Law Efficiency (Exergetic Efficiency)
R134a	0.5074	1.728	0.3666
R404a	0.4971	1.784	0.3592
R236fa	0.5084	1.722	0.3673
R245fa	0.5112	1.707	0.3694
R32	0.4829	1.866	0.3489
R227ea	0.4991	1.773	0.3606
R410a	0.5038	1.747	0.3640
R142b	0.5084	1.722	0.3673
R407c	0.4367	1.728	0.3155
R123	0.5099	1.728	0.3685
R125	0.5020	1.728	0.3627
R507a	0.5045	1.728	0.3645
R290	0.510	1.714	0.3685
R600a	0.5148	1.688	0.3720
R600	0.5123	1.701	0.3702

Table-5(b) Variation of High Temperature Circuit First Law Efficiency (COP_HTC), Medium (Intermediate) Temperature Circuit First Law Efficiency (COP_MTC)and Low Temperature Circuit First Law Efficiency (COP_LTC with ecofriendly refrigerants

Eco Friendly Refrigerant	High Temperature Circuit First Law Efficiency (COP_HTC)	Medium (Inter-mediate) Temperature Circuit First Law Efficiency (COP_MTC)	Low Temperature Circuit First Law Efficiency (COP_LTC)
R134a	3.215	2.204	1.790
R404a	3.215	2.204	1.724
R236fa	3.215	2.204	1.796
R245fa	3.215	2.204	1.825
R32	3.215	2.204	1.636
R227ea	3.215	2.204	1.736
R410a	3.215	2.204	1.769
R142b	3.215	2.204	1.796
R407c	3.215	2.204	1.377
R123	3.215	2.204	1.806
R125	3.215	2.204	1.755
R507a	3.215	2.204	1.771
R290	3.215	2.204	1.837
R600a	3.215	2.204	1.939
R600	3.215	2.204	1.822

Table-5(c) Variation of Exergy of Fuel (kW)second law efficiency (exergetic efficiency) and Exergy of product (kW)) with ecofriendly refrigerants

Eco Friendly Refrigerant	Exergy of Fuel (kW)	Exergy of product (kW)	Second Law Efficiency (Exergetic Efficiency)
R134a	344.9	126.44	0.3666
R404a	352.0	126.44	0.3592
R236fa	344.0	126.44	0.3673
R245fa	362.9	126.44	0.3694
R32	362.4	126.44	0.3489
R227ea	343.3	126.44	0.3606
R410a	350.0	126.44	0.3640
R142b	347.3	126.44	0.3673
R407c	344.2	126.44	0.3155
R123	400.7	126.44	0.3685

R125	343.2	126.44	0.3627
R507a	348.6	126.44	0.3645
R290	346.9	126.44	0.3685
R600a	343.2	126.44	0.3720
R600	339.9	126.44	0.3702

Table-5(d) : Variation of Mass Flow Rate in High Temperature Cascade Evaporator (kg/sec), Mass Flow Rate in Intermediate Temperature cascade Evaporator (kg/sec)and Mass Flow Rate in Low Temperature Evaporator (kg/sec)with ecofriendly refrigerants

Eco Friendly Refrigerant	Mass Flow Rate in High Temperature Cascade Evaporator (kg/sec)	Mass Flow Rate in Intermediate Temperature cascade Evaporator (kg/sec)	Mass Flow Rate in Low Temperature Evaporator (kg/sec)
R134a	3.488	2.321	0.9285
R404a	3.538	2.353	1.102
R236fa	3.483	2.318	1.255
R245fa	3.605	2.399	0.5221
R32	3.471	2.309	0.5221
R227ea	3.526	2.346	0.9444
R410a	3.504	2.322	1.655
R142b	3.483	2.388	0.7495
R407c	3.863	2.57	0.8651
R123	3.476	2.213	0.8543
R125	3.513	2.337	1.063
R507a	3.501	2.33	1.398
R290	3.476	2.313	1.126
R600a	3.454	2.298	0.5164
R600	3.466	2.306	0.5476

Table-5(e): Variation of Power required to Run High Temperature Compressor (kW) Power required to Run Intermediate Temperature Compressor (kW)and Power required to Run Low Temperature Compressor (kW)with ecofriendly refrigerants

Eco Friendly Refrigerant	Power required to Run High Temperature Compressor (kW)	Power required to Run Intermediate Temperature Compressor (kW)	Power required to Run Low Temperature Compressor (kW)
R134a	123.3	123.8	97.79
R404a	125.0	125.5	101.5
R236fa	123.2	123.6	97.41
R245fa	127.5	127.9	106.9
R32	127.5	123.2	96.42
R227ea	127.7	125.1	100.8
R410a	124.7	124.4	99.06
R142b	123.2	123.6	97.42
R407c	136.6	137.1	127.1
R123	122.9	123.4	96.87
R125	124.2	124.7	99.72
R507a	123.8	124.3	98.81
R290	122.9	123.4	96.87
R600a	122.2	122.6	95.16
R600	122.6	123.0	96.84

Table-5(f):: Variation of Power required to run the whole system (Exergy of Fuel) (kW)) Total Exergy Losses in the system (kW))and Exergy Product of the system (kW)) with ecofriendly refrigerants

Eco Friendly Refrigerant	Power required to run the whole system (Exergy of Fuel) (kW))	Total Exergy Losses in the system (kW))	Exergy Product of the system (kW))
R134a	344.9	218.5	126.4
R404a	352	225.6	126.4
R236fa	344	217.8	126.4
R245fa	362.9	235.9	126.4
R32	362.4	235.9	126.4
R227ea	343.3	215.9	126.4
R410a	350	224.2	126.4
R142b	347.3	220.9	126.4

R407c	344.2	217.8	126.4
R123	400.7	274.3	126.4
R125	343.2	216.7	126.4
R507a	348.6	222.2	126.4
R290	346.9	220.4	126.4
R600a	343.2	216.7	126.4
R600	339.9	213.5	126.4

Similarly, By using R227ea and R236fa eco-friendly refrigerants, the power consumption is higher in the three stage systems by running all compressors as compared to R-134a while R245fa gives lower power consumption as compared to R227ea and R236fa.The power required to run various compressors in the three stage vapour compression refrigeration system using eco-friendly refrigerants are shown in Table-3 to Table-5 respectively. It was observed that R227ea gives maximum power consumptions in all compressors while less power consumptions required to run first compressor using R -134a. It was shown that first compressor used in system-3 gives lowest power consumption as compared to system-1 and system-2. By using new refrigerants, the power consumption is first compressor is more. Similarly, maximum power consumption using R227ea was observed as compared to R-236fa and R245fa. The lowest power consumption was observed using R134a in system -3 as compared to system-1 and system-2. Similarly, R1234yf and R1234ze gives slightly higher power consumption as compared to R1234yf and R1234ze. The power required to run compressor -3 in three stage vapour compression refrigeration system, the same trend was observed because system -3 is always gives better thermodynamic performance and lower power consumption.

5. Conclusion

Following conclusions were drawn from present investigations.

(i) The proposed three stage cascade refrigeration system (System-1) using HFO refrigerants gives similar thermodynamic performances and 2% less power consumption than conventional three stage cascade refrigeration system (system-2).

(ii) By using R245fa in low temperature circuit the percentage second law improvement in system-1 is varying from 1.5% to 2% while power consumption is around 2% % higher as compared to by usingR134a in the low temperature circuit.

(iii) Cascade refrigeration system using R1234ze in high temperature circuit and R1234yf in low temperature circuit can replace cascade refrigeration system using R134a in low temperature circuit up to a range of -50^{0}C.

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