International Journal of Research in Engineering and Innovation Vol-3, Issue-3 (2019), 187-194

International Journal of Research in Engineering and Innovation (IJREI)

journal home page: http://www.ijrei.com

ISSN (Online): 2456-6934

Exergy destruction computation in three stages cascade vapour compression refrigeration systems for low temperature applications

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Abstract

Cascade refrigeration systems work with two or more cycles in serial and can obtain internal temperatures below -80°C, necessary to several activities in medicine and scientific research. The main objective of this paper is to present a thermodynamic analysis of three stages vapour compression cascade refrigeration system with the use of HFO refrigerants in the high temperature cycle and HFO and HFC refrigerants in intermediate (medium temperature cycle and HFC refrigerants & hydrocarbon fluids in the low temperature cycle. The energy and exergy analysis for three stages cascade vapour compression refrigeration systems were carried out for two different conditions (i) temperature 103ºC and (ii) 95ºC and thermodynamic model based on the law of conservation of mass, on the first and second laws of Thermodynamics was developed. The numerical computed results of developed model were compared to validate results obtained from developed models using R12 in the high temperature circuit and R22 in intermediate (medium)at -60ºC temperature circuit and R13 in the low temperature circuit at -90ºCand found that our model validates results with the variation in overall first law efficiency of cascade system (1.67 % (higher) $COP\_{Overall}$) , total electrical power required to run whole system (i.e. running three compressors) in terms of 1.667% (lower) exergy of fuel, 10.96% (higher) circuit high temperature cycle first law efficiency (COP_{HTC}) , 1.27% (lower) intermediate circuit (Medium) temperature cycle first law efficiency (COP_{ITC}) and 0.615% (higher) Low temperature circuit first law efficiency (COP_{LTC}) .The Detailed comparison of two different conditions have been predicted for twenty four cascade three stages vapour compression refrigeration systems using various ecofriendly refrigerants for low temperature applications and important conclusions were drawn.

Keywords: Ecofriendly refrigerants, Exergy Destruction Computations, Cascade Vapour Compression Refrigeration Systems

1. Introduction

Biomedical preservation requires storing biological specimens like stem cells, sperm, blood and organs, at a storage temperature of around -90ºC. For long-term storage of biological materials, temperatures below -100ºC are generally considered to safeguard against the effects of devitrification and Crystallization. The use of a single-cycle vapour compression refrigeration system can only achieve effective cooling of about -40ºC, and the efficiency begins to deteriorate under -35ºC due to the vast difference between the evaporating and condensing temperatures.

2. Cascade refrigeration system

Cascade refrigeration systems contained minimum two or more refrigeration cycles that work individualistically. The three refrigeration cycles are connected by a cascade heat exchanger where heat is released in the condenser low-temperature circuit and it is absorbed from the evaporator high-temperature circuit). Therefore, the desired refrigeration effect occurs in the evaporator low-temperature, and rejection of heat from the cycle as a whole takes place in the high temperature condenser. In these three cascade refrigeration systems in which the same refrigerant passes through the stages of high and low temperature, extreme values of pressure and specific volume can cause problems. In fact, when the evaporation temperature is too low, the specific volume of refrigerant vapor in the compressor suction is high, which implies a high volumetric capacity compressor. The important aspect of the three cascade system is that the refrigerant in three stages can be selected so as to present reasonable pressures in the evaporator and the condenser in three temperature intervals. In a three stages cascade vapour compression system, a

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refrigerant to be selected for each of the cycle has a relationship between the saturation pressure and temperature that permits refrigeration at a relatively low temperature without excessively low pressure in the evaporator. The refrigerant cycle B and C must have characteristics of saturation that allows condensation to the desired temperature in the absence of excessively high pressures in the condenser. The two stage cascade refrigeration systems consist of at least two refrigeration systems that work independently. The two refrigeration systems are connected by a cascade heat exchanger where heat is released in the condenser low temperature circuit (LTC) using HFO-1234yf up to -53^{o}C and is absorbed from the evaporator high-temperature circuit (HTC) using HFO-1234ze up to -30^{o}C. While by using two stage cascade refrigeration one can reach minimum temperature of -70^{o}C to -80^{o}C using hydrocarbons and HFC refrigerants. Bhattacharyya et al. [3] studied a carbon dioxide–propane (R744–R290) optimum cascade evaporating system to define an evaporating temperature of R744 for application in heating circuits.

3. Concept of Exergy

Exergy is the maximum theoretical work that can be obtained from a global system, as it comes into equilibrium with the environment (reaches the dead state). Thus, if the pressure and temperature are equal to room temperature, this is the dead state, with no longer able to generate work. Therefore, exergy is a property that measures the availability of a system, which is generally largely destroyed because of the irreversible nature of thermodynamic processes. However, the exergy not only can be destroyed by irreversibilities, but can also be transferred to others systems. The exergy transferred from one system to its surroundings and which is not used usually represents a loss for better utilization of energy resources by reducing the exergy destruction within a system and / or reducing exergy losses in terms of exergy destruction ratio based on exergy of fuel/input known as rational exergy destruction ratio or reducing exergy losses in terms of exergy destruction ratio based on exergy of product known as exergy destruction ratio of the system [1] H.M. Getu and P.K. Bansal [2] carried out Thermodynamic analysis of an R744–R717 cascade Refrigeration system, and found that an increase in condensing temperature resulted in a decrease in first law efficiency (COP) and an increase in refrigerant mass flow ratios. Similarly the increase in evaporating temperature increased COP of the system and decreased mass flow ratios. An increase in temperature difference in cascade condenser reduced both COP and mass flow ratios. Kilicarslan [4] experimentally inspected the effects of the refrigeration load and water mass flow rate on the performance of cascade and single stage refrigeration systems both using R134a and compared the COP, work of compression, discharge pressure and refrigerant mass flow rate of the cascade system with those of the single stage refrigeration system.

4. Refrigerant fluids used in the cascade refrigeration systems

Since the establishment of the Montreal Protocol, the refrigeration engineering has required substitutes for CFCs and HCFCs refrigerants. The use of hydrocarbons (HCs) as refrigerants in some applications of refrigeration and air conditioning has been an effective alternative. Compared with CFCs, hydro-choro-fluocarbons (HCFCs) and hydrofluorocarbons (HFCs), hydrocarbons refrigerants offer zero Ozone Depletion Potential (ODP) and extremely low Global Warming Potential (GWP). In regard the performances, they offer in general use for high efficiency, reduces charge sizes, good miscibility with mineral oils, lower compressor discharge temperatures, and slightly better heat transfer within heat exchangers.

5. Use of hydrocarbons in cascade refrigeration systems

Several Hydrocarbons are used in the vapour compression refrigeration system which includes (i) isobutene (R600a) is the maximum commonly used refrigerant. Even in the Europe, the R600a (isobutene) is used in household refrigerators, with a market share of more than 95% in the many European countries. Propane (R290) and propylene (R1270) are also used in the heat pump systems, and have also been used in air conditioners in commercial refrigeration systems (Palm, 2008). Ethylene (R-1150) is one of the greatest important raw materials in the petrochemical industry which is also used in the synthesis of a series of products such as: ethylene oxide, ethylene glycol, ethyl alcohol, and polyethylene, polystyrene. These fluids are HFCs, are not inflammable and have low toxicity were used in the cascade refrigeration systems. The cascade systems still uses refrigerant fluids with high GWP, such as R-508B and R-404a which has low thermodynamic performances.

6. Applicability of several refrigerants in cascade refrigeration systems

In vapour compression cascade refrigeration systems, several refrigerants (such as R-717, R152a, R134a, R-12, R22, R410a, R407c, R-404A, HFO-1234yf, R1234ze etc) are used from high temperature cycle and R134a, R410a, R407c, HFO-1234yf, R123, R125,R143a, R141b, R227ea, R236fa, R245fa R507a,and hydrocarbons (R-290, R600 and R600a) etc are used in the medium temperature cycle (i.e. intermediate temperature cycle) and R13, R404a, R134a, R-508B, R290, R600a, R 600,etc R-508B refrigerant fluids are used temperature below -90^{o}C from low temperature cycle. The global warming potential (GWP) of hydrocarbons is 3, while for R-508B it is 10350 very high, and for R-404A it is 3260 (Hansen and Haukas, 2000). Thus, R404a, R134a, and R125, R407c up to -95^{o}C and hydrocarbons can be substitutes also relevant for these systems, being technically feasible and can operate over a wide range of evaporation temperature up the lower limit of -170 °C

7. Results and Discussions

For validation data from developed model for R12 in high temperature circuit and R22 in intermediate circuit and R13 in low temperature circuit, the following input data have been taken from ref [5]

(i) Condenser temperature of High Temperature circuit 40^0C.
(ii) Evaporator temperature of High Temperature circuit -22^0C.
(iii) Condenser temperature of High Temperature circuit -12^0C.
(iv) Evaporator temperature of Intermediate Temperature circuit -60^0C.
(v) Condenser temperature of High Temperature circuit -22^0C.
(vi) Evaporator temperature of Intermediate Temperature circuit -90^0C.
(vii) Compressor efficiency of HTC circuit=100%.
(viii) Compressor efficiency of ITC circuit=100%.
(ix) Compressor efficiency of LTC circuit=100%.
(x) Temperature overlapping of Condenser Temperature $_{ITC}$- Evaporator Temperature $_{HTC}$) and = 10.
(xi) Temperature overlapping of Condenser Temperature $_{LTC}$- Evaporator Temperature_$_{ITC}$) = 10.
(xii) Load on LTC evaporator=(50*3.5) kW

Table 1: Validation of data for three stages cascade vapour compression refrigeration system

Parameters	Ref [5]	Model	% variation
COP_$_{CASCADE}$	0.858	0.8723	1.667% (higher)
EXERGY_$_{FUEL}$ (kW)	204.0	200.6	1.667% (lower)
COP_$_{HTC}$ (i.e.COP_R12)	2.72	3.018	10.956%(higher)
COP_$_{ITC}$ (i.e.COP_R22)	3.7	3.653	1.2703% (lower)
COP_$_{LTC}$ (i.e.COP_R13)	3.74	3.763	0.615% (higher)

Case-1: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and Following refrigerants in low temperature circuit below -100ºC.

System-1: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and HFC-134a refrigerant in low temperature circuit.

System-2: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and HFC-404a refrigerant in low temperature circuit.

System-3: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-236fa refrigerant in low temperature circuit.

System-4: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-141b refrigerant in low temperature circuit.

System-5: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-32 refrigerant in low temperature circuit.

System-6: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-32 refrigerant in low temperature circuit.

System-7: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and HFC-404a refrigerant in low temperature circuit.

System-8: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-236fa refrigerant in low temperature circuit.

System-9: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-141b refrigerant in low temperature circuit.

System-10: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-143a refrigerant in low temperature circuit.

System-11: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-290 refrigerant in low temperature circuit.

System-12: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R134a in Intermediate (Medium) temperature circuit and R-600a refrigerant in low temperature circuit.

The following input data have been taken for computation of thermal performances of following cascade systems.

(i) Condenser temperature of High Temperature circuit (ºC)= 50.
(ii) Evaporator temperature of High Temperature circuit (ºC)= 0
(iii) Evaporator temperature of Intermediate Temperature

circuit (°C)= -50.
(iv) Evaporator temperature of Intermediate Temperature Circuit(°C)= -103
(v) Compressor efficiency of HTC circuit=0.8.
(vi) Compressor efficiency of ITC circuit=0.8.
(vii) Compressor efficiency of LTC circuit=0.8.
(viii) Temperature overlapping=zero, 5, 10, 15.
(ix) Load on LTC evaporator=35 kW

Table-2(a) and Table-2(b) shows the comparison of various thermodynamic performance parameters for twelve cascade systems. It is found that first law efficiency of system-1 to system-5 containing HFO-1234ze in high temperature circuit is higher than system-6 to system-12 containing HFO-1234yf in HTC circuit.

Table 2(a): Variation of First law efficiencies of various cascade vapour compression refrigeration systems using HFO-1234ze in HTC and HFO-1234yf in ITC and other ecofriendly refrigerants in the low temperature circuit.

Various systems	$COP_{\_Overall}$	$COP_{\_HTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$
System-1	0.6106	3.215	2.844	2.047
System-2	0.6001	3.215	2.844	1.981
System-3	0.6142	3.215	2.844	2.07
System-4	0.6198	3.215	2.844	2.105
System-5	0.6081	3.215	2.844	2.105

Table 2(b): Variation of First law efficiencies of various cascade vapour compression refrigeration systems using HFO-1234yf in HTC and HFC-134a in ITC and other ecofriendly refrigerants in the low temperature circuit.

Various systems	$COP_{\_Overall}$	$COP_{\_HTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$
System-6	0.6026	3.215	2.844	2.068
System-7	0.6062	3.215	2.844	2.092
System-8	0.5983	3.215	2.844	2.04
System-9	0.5973	3.215	2.844	2.033
System-10	0.5844	3.215	2.844	1.952
System-11	0.5701	3.215	2.844	1865
System-12	0.5805	3.215	2.844	1.864

It is also found that cyclic first law efficiency of low temperature circuit changes due to different ecofriendly refrigerants flowing in the low temperature circuit. It does not affect high temperature and intermediate temperature circuit first law efficiency as shown in Table-2(a) and Table-2(b) respectively. From table 2(a) and table-2(b), the first law efficiency of system-4 (cascade vapour compression refrigeration system using R1234ze in High temperature circuit (HTC)and R1234yf in Intermediate (Medium) temperature circuit (ITC) and R-141b refrigerant in low temperature circuit(LTC) gives highest coefficient of performance ($COP_{\_Overall\_Cascade\ \_System}$) which is also higher than system-1: cascade vapour compression refrigeration system using R1234ze in High temperature circuit (HTC)and R1234yf in Intermediate (Medium) temperature circuit (ITC) and HFC-134a refrigerant in low temperature circuit(LTC) and lowest first law thermodynamic performance was found for system-11 consisting of R1234yf in High temperature circuit (HTC)and R134a in the Intermediate (Medium) temperature circuit (ITC) and R-290 refrigerant in low temperature circuit(LTC). It is also found that system-12 consisting of R1234yf in High temperature circuit (HTC) and R134a in the Intermediate (Medium) temperature circuit (ITC) and R-600a refrigerant in low temperature circuit (LTC is higher first law performance than system11 consisting of R1234yf in High temperature circuit (HTC) and R134a in the Intermediate (Medium) temperature circuit (ITC) and R-290 refrigerant in low temperature circuit (LTC).

Table-3(a) and Table-3(b) shows the comparison of various thermodynamic performance parameters for twelve cascade systems. It is found that exergetic efficiency of system-1 to system-5 containing HFO-1234ze in high temperature circuit is higher than the exergetic efficiency of system-6 to system-12 containing HFO-1234yf in HTC circuit. Similarly Exergy destruction ratio of cascade system and rational exergy destruction ratio of system-1 to system 5 is lower than system 6 to system -12 as shown in Table-3(b).

Table 3(a): Variation of Exergetic law efficiencies and exergy destruction variation of various cascade vapour compression refrigeration systems using HFO-1234ze in HTC and HFO-1234yf in ITC and other ecofriendly refrigerants in the low temperature circuit.

Various systems	$COP_{\_Overall}$	Exergetic Efficiency	Rational $EDR_{\_Cascade}$	$EDR_{\_cascade}$
System1	0.6106	0.3443	0.6557	1.904
System2	0.6001	0.3357	0.6643	1.917
System3	0.6142	0.3544	0.6456	1.970
System4	0.6198	0.3377	0.6623	1.821
System5	0.6081	0.3564	0.6436	1.805

Table 3(b): Variation of Exergetic law efficiencies and exergy destruction variation of various cascade vapour compression refrigeration systems using HFO-1234yf in HTC and HFC-134a in ITC and other ecofriendly refrigerants in the low temperature circuit.

Various systems	$COP_{\_Overall}$	Exergetic Efficiency	Rational $EDR_{\_Cascade}$	$EDR_{\_cascade}$
System6	0.6026	0.3333	0.6667	2.001
System7	0.6062	0.3323	0.6677	2.009
System8	0.5983	0.3522	0.6478	1.839
System9	0.5973	0.3391	0.6609	1.949
System10	0.5844	0.3425	0.6575	1.920
System11	0.5701	0.3409	0.6591	1.934
System12	0.5805	0.3589	0.6411	1.787

Table-4(a) and Table-4(b) shows the variation of various thermodynamic performance parameters for twelve cascade systems. It is found that the second law efficiency of system-1 to system-5 containing HFO-1234ze in high temperature circuit is higher than the second law efficiency of system-6 to system-12 containing HFO-1234yf in HTC circuit. Similarly Exergy destruction ratio of cascade system and rational exergy destruction ratio of system-1 to system 5 is lower than system 6 to system -12 as shown in Table-4(b).

Table 4(a): Variation of second law efficiencies and exergy destruction variation with system of various systems

Various systems	COP_Overall	Second law efficiency	Rational EDR	EDR_System
System-1	0.6106	0.4598	0.5402	1.175
System-2	0.6001	0.4518	0.5482	1.213
System-3	0.6142	0.4625	0.5375	1.162
System-4	0.6198	0.4665	0.5335	1.143
System-5	0.6081	0.4579	0.5421	1.184

Table 4(b): Variation of second law efficiencies and exergy destruction variation with system of various systems

Various systems	COP_Overall	Second law efficiency	Rational EDR	EDR_System
System-6	0.6026	0.4537	0.5463	1.204
System-7	0.6062	0.4564	0.5434	1.191
System-8	0.5983	0.4504	0.5496	1.22
System-9	0.5973	0.4497	0.5503	1.224
System-10	0.5844	0.440	0.560	2.001
System-11	0.5701	0.4293	0.5707	1.329
System-12	0.5805	0.4371	0.5623	1.288

Table 5(a): Percentage variation of exergy losses in various temperature circuit of three stages cascade refrigeration systems

Various systems	COP_Overall	% Exergy Destruction in HTC	% Exergy Destruction in ITC	% Exergy Destruction in LTC
System-1	0.6106	20.47.	17.28	27.82
System-2	0.6001	20.17	17.03	29.23
System-3	0.6142	19.94	16.83	29.56
System-4	0.6198	20.88	17.62	26.05
System-5	0.6081	22.66	16.23	25.89

Table-5(a)and Table-5(b) shows the variation of exergy destruction in HTC circuit (%) ,and exergy destruction in ITC circuit(%) and exergy destruction in LTC circuit(%) for all twelve cascade systems and it is found that Exergy Destruction in HTC (%) of system-1 to system-5 containing HFO-1234ze in high temperature circuit is lower than the second law efficiency of system-6 to system-12 containing HFO-1234yf in HTC circuit. Similarly Exergy destruction in ITC (%) of system-1 to system 5 of cascade system is higher than system-6 to 11 but less than system-12 due to variation of refrigerating properties of low temperature circuit refrigerant. The exergy destruction in low temperature circuit (%) of system-1 to system 5 is slightly less than system 6 to system -12 as shown in Table-5(b).

Table 5(b): Percentage variation of exergy losses in various temperature circuit of three stages cascade refrigeration systems

Various systems	COP_Overall	% Exergy Destruction in HTC	% Exergy Destruction in ITC	% Exergy Destruction in LTC
System-6	0.6026	22.16	15.88	27.71
System-7	0.6062	21.97	15.74	28.20
System-8	0.5983	22.04	15.79	28.26
System-9	0.5973	21.62	15.49	29.66
System10	0.5844	21.98	15.75	28.95
System11	0.5701	23.88	17.11	23.37
System12	0.5805	22.02	18.58	23.05

Table 6 (a): Percentage variation of various systems using energy-exergy concept

Various systems	% (Total) Exergy Destruction in Condensers	% (Total) Exergy Destruction in compressors	% (Total) Exergy Destruction in Valves	% (Total) Exergy Destruction in Evaporators
System-1	27.9543	14.87	13.08	9.1857
System-2	27.391	15.0	13.31	9.839
System-3	28.4024	14.94	13.37	9.2276
System-4	27.5077	14.82	12.6	9.6623
System-5	27.112	14.72	13.03	9.70782

Table 6 (b): Percentage variation of various systems using energy-exergy concept

Various systems	% (Total) Exergy Destruction in Condensers	% (Total) Exergy Destruction in compressors	% (Total) Exergy Destruction in Valves	% (Total) Exergy Destruction in Evaporators
System-6	27.557	14.8	13.77	9.4234
System-7	27.6852	14.8	13.75	9.49477
System-8	27.50	14.84	14.11	9.4486
System-9	27.90	14.87	14.43	9.268
System10	27.02	14.95	14.51	9.7099
System11	24.9244	15.01	14.0	10.2156
System12	26.994	14.82	12.6	10.176

The cumulative sum of exergy destruction in all three compressors, cumulative sum of exergy destruction in all three condensers, cumulative sum of exergy destruction in all three expansion valves and cumulative sum of exergy destruction in all three evaporators are shown in Table-6(a) and Table-6(b) respectively. The Exergy Destruction (%) of all three condensers (of system-1 to system-5 containing HFO-1234ze in high temperature circuit) is slightly higher than the Total exergy destruction in all condensers (of system-6 to system-12 containing HFO-1234yf in HTC circuit). Similarly The Exergy Destruction (%) of all three compressors (of system-1 to system-5 containing HFO-1234ze in high temperature circuit) is similar with small variations (slightly higher) than the Total exergy destruction in all compressors (of system-6 to system-12 containing HFO-1234yf in HTC circuit).

The Exergy Destruction (%) of all three expansion valves (of system-1 to system-5 containing HFO-1234ze in high temperature circuit) is similar with small variations (slightly higher) than the total exergy destruction in all three expansion valves (of system-6 to system-12 containing HFO-1234yf in HTC circuit). The Exergy Destruction (%) of all three evaporators (of system-1 to system-5 containing HFO-1234ze in high temperature circuit) is similar with small variations (slightly higher) than the total exergy destruction in all three evaporators (of system-6 to system-12 containing HFO-1234yf in HTC circuit). The all three compressors are running on 80% of isentropic compressor efficiency, therefore exergy destruction have been computed by considering 80% of compressor efficiencies. It is found that maximum exergy destruction (%) based on the exergy of input occurred in the condenser and lowest were found in the evaporators. The exergy destruction in the compressors are higher than expansion valves due to expansions valves have international irreversibilities occurred but less than sum of all condensers in the systems.

Case-2: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and ecofriendly Refrigerants in low temperature circuit.

The input data have been taken for computation of thermal performances of following cascade systems.

System-13: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and HFC-134a refrigerant in low temperature circuit.

System-14: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and HFC-404a refrigerant in low temperature circuit.

System-15: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-236fa refrigerant in low temperature circuit.

System-16: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-141b refrigerant in low temperature circuit.

System-17: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-32 refrigerant in low temperature circuit.

System-18: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-123 refrigerant in low temperature circuit.

System-19: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and HFC-143a refrigerant in low temperature circuit.

System-20: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-227ea refrigerant in low temperature circuit.

System-21: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-245fa refrigerant in low temperature circuit.

System-22: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-410a refrigerant in low temperature circuit.

System-23: Vapour compression cascade refrigeration system using R1234ze in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-125 refrigerant in low temperature circuit.

System-24: Vapour compression cascade refrigeration system using R1234yf in HTC (High temperature circuit) and R1234yf in Intermediate (Medium) temperature circuit and R-407c refrigerant in low temperature circuit.
For computation of thermal performances, the following input data have been taken of for cascade system-13 to cascade system-24.

(i) Condenser temperature of High Temperature circuit (ºC)= 50
(ii) Evaporator temperature of High Temperature circuit (ºC)= 0.
(iii) Evaporator temperature of Intermediate Temperature circuit (ºC)= -50.
(iv) Evaporator temperature of Intermediate Temperature Circuit (ºC)= -95
(v) Compressor efficiency of HTC circuit=0.8
(vi) Compressor efficiency of ITC circuit=0.8
(vii) Compressor efficiency of LTC circuit=0.8

Table-7 shows the comparison of various thermodynamic performance parameters such as first law efficiency of whole cascade three stages vapour compression refrigeration systems using HFO-1234ze in high temperature cycle and HFO-1234yf in Intermediate temperature and following ecofriendly refrigerants in the low temperature cycle for twelve cascade systems. It is found that first law efficiency of system-16 (containing HFO-1234ze in high temperature cycle and HFO-1234yf in intermediate (medium) temperature and R-141b in low temperature circuit is higher than system-24 containing HFO-1234ze in high temperature cycle and HFO-1234yf in Intermediate temperature and HFC-407c in LTC circuit. Similarly Low temperature cycle first law efficiency ($COP_{\_LTC}$) using HFC-407c is also found and also no effect on COP_HTC and COP_ITC were observed. Table-8 shows the variation of various thermodynamic performance parameters for twelve cascade systems. It is found that the second law efficiency of system-17 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit is higher and R32in LTC than the system-24 containingR407c in low temperature circuit. . Similarly Exergy destruction ratio of cascade system and rational exergy destruction ratio of system-24 is higher than system 17.

Table 7: Variation of First law efficiencies of various systems

Various systems	$COP_{Overall}$	COP_{HTC}	COP_{ITC}	COP_{LTC}
System-13	0.6759	3.027	2.844	2.639
System-14	0.6646	3.027	2.844	2.546
System-15	0.6784	3.027	2.844	2.660
System-16	0.6833	3.027	2.844	2.703
System-17	0.6524	3.027	2.844	2.448
System-18	0.6770	3.027	2.844	2.649
System-19	0.6747	3.027	2.844	2.629
System-20	0.6717	3.027	2.844	2.604
System-21	0.6767	3.027	2.844	2.663
System-22	0.6731	3.027	2.844	2.615
System-23	0.6739	3.027	2.844	2.623
System-24	0.5833	3.027	2.844	1.963

Table 8: Variation of second law efficiencies and exergy destruction variation with system of various systems

Various systems	$COP_{Overall}$	Exergetic Efficiency	Rational $EDR_{Cascade}$	$EDR_{cascade}$
System13	0.6759	0.3307	0.6693	2.024
System14	0.6646	0.3239	0.6761	2.087
System15	0.6784	0.3255	0.6745	2.072
System16	0.6833	0.3377	0.6623	1.961
System17	0.6524	0.3404	0.6596	1.938
System18	0.6770	0.3329	0.6671	2.004
System19	0.6747	0.3285	0.6715	2.044
System20	0.6717	0.3208	0.6792	2.118
System21	0.6767	0.3302	0.6698	2.028
System22	0.6731	0.3367	0.6633	1.970
System23	0.6739	0.3236	0.6764	2.091
System24	0.5833	0.3046	0.6954	2.284

Table-8 shows the comparison of exergetic efficiency (performance parameter) for twelve cascade systems. It is found that exergetic efficiency of system-17 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate temperature circuit and R-32 in low temperature circuit containing is higher than the exergetic efficiency of system-24 (containing HFO-1234ze in HTC circuit HFO-1234yf in ITC circuit and R-407c in low temperature circuit). Similarly Exergy destruction ratio of cascade system and rational exergy destruction ratio of system-24 is higher than system 16 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate temperature circuit and R141b in low temperature circuit. Similarly Exergy destruction ratio of cascade system and rational exergy destruction ratio of system-17 is lower than system 24.

Table 9: Percentage variation of exergy losses in various temperature circuit of three stages cascade refrigeration systems

Various systems	$COP_{Overall}$	% Exergy Destruction in HTC	% Exergy Destruction in ITC	% Exergy Destruction in LTC
System13	0.6759	22.54	17.17	22.27
System14	0.6646	22.3	16.99	28.32
System15	0.6784	22.13	16.86	28.45
System16	0.6833	22.86	17.42	25.95
System17	0.6524	23.69	18.05	24.22
System18	0.6770	22.66	17.26	26.79
System19	0.6747	22.41	17.07	27.67
System20	0.6717	21.94	16.71	29.27
System21	0.6767	22.45	17.1	27.43
System22	0.6731	23.0	17.52	25.81
System23	0.6739	22.09	16.82	28.73
System24	0.5833	22.72	17.31	29.52

Table-9 shows the variation of exergy destruction in HTC circuit (%) ,and exergy destruction in ITC circuit(%) and exergy destruction in LTC circuit(%) for all twelve cascade systems and it is found that Exergy Destruction in HTC (%) of system-1 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (medium) temperature circuit and R125 in low temperature circuit is higher than the % % Exergy Destruction in HTC of system-22 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (medium) temperature circuit and HFO-227ea in LTC circuit.

Table-10: Percentage variation of exergy destruction of various components in the three stages cascade vapour compression refrigeration systems

Various systems	% Exergy Destruction in Condensers	% (Total) Exergy Destruction in compressors	% (Total) Exergy Destruction in Valves	% (Total) Exergy Destruction in Evaporators
System13	27.94	14.57	13.10	10.66
System14	27.61	14.7	13.22	10.98
System15	28.50	14.66	13.29	10.40
System16	27.82	14.52	12.45	10.82
System17	26.39	14.68	13.12	11.13
System18	27.94	14.58	12.92	10.66
System19	28.14	14.63	13.24	10.54
System20	28.60	14.76	13.71	10.28
System21	28.09	14.57	13.05	10.60
System22	27.57	14.60	12.76	10.79
System23	28.34	14.67	13.55	10.43
System24	20.18	15.0	12.37	16.29

Table-10 shows Exergy Destruction (%) of all three compressors (of system-12 to system-24 and it is found that the system-20 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit and R227ea in low temperature is higher condenser exergy destruction (%) than the system-14 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit and R407c in low temperature circuit. The all three compressors are running on 80% of isentropic compressor efficiency, therefore exergy destruction have been computed by considering 80% of compressor efficiencies. It is found that maximum exergy destruction (%) based on the exergy of input occurred in the condenser and lowest were found in the evaporators. The exergy destruction in the compressors are higher than expansion valves due to expansions valves have international irreversibility occurred but less than sum of all condensers in the systems

The Exergy Destruction (%) of all three expansion valves (of system-1 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit) and R227ea is higher than the system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit) and R-407c. The Exergy Destruction (%) of all three compressors (of system-16 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R141b in lower temperature circuit is lower than system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R407c in lower temperature circuit. The Exergy Destruction (%) of all three evaporators (of system-20 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R227ea in lower temperature circuit is lower than system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R407c in lower temperature circuit.

8. Conclusions

The following conclusions were made from present investigation

- The thermal performance of three stage cascade refrigeration system using HFO-1234ze in HTC and HFO-1234yf in ITC and HFC-134a in LTC gives better thermodynamic performance.
- The numerical computed results of developed model were compared to validate results obtained from developed models using R12 in the high temperature circuit and R22 in intermediate (medium)at -60ºC temperature circuit and R13 in the low temperature circuit at -90ºC and found that our model validates results well in terms of 1.67 % (higher) first law efficiency of cascade refrigeration system and 1.667% (lower) total power required to run the whole cascade systems (containing all three running compressors) , 10.96% (higher) circuit high temperature cycle first law efficiency (COP_{HTC}) , 1.27% (lower) intermediate circuit (Medium) temperature cycle first law efficiency (COP_{ITC}) and 0.615% (higher) Low temperature circuit first law efficiency (COP_{LTC}).
- The developed thermal model predicts thermodynamic performance parameters for all twenty four systems.
- Exergetic efficiency of system-17 (containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate temperature circuit and R-32 in low temperature circuit) is higher than the exergetic efficiency of system-24 (containing HFO-1234ze in HTC circuit HFO-1234yf in ITC circuit and R-407c in low temperature circuit.
- The Exergy Destruction (%) of all three evaporators of all cascade refrigeration systems are lower and highest exergy destruction is found in the condensers.
- The Exergy Destruction (%) of all three compressors is higher than Exergy Destruction (%) of all three expansion valves in the all cascade systems
- The Exergy Destruction (%) of all three expansion valves (of system-1 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit) and R227ea is higher than the system-24 (containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit) and R-407cin lower temperature circuit.
- The Exergy Destruction (%) of all three condensers (of system-16 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R141b in lower temperature circuit is lower than system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R407c in lower temperature circuit
- The Exergy Destruction (%) of all three compressors of system-20 (containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit and R227ea in low temperature) is higher exergy destruction (%) than the system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in ITC circuit and R407c in low temperature circuit.
- The Exergy Destruction (%) of all three evaporators (of system-20 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R227ea in lower temperature circuit is lower than system-24 containing HFO-1234ze in high temperature circuit and HFO-1234yf in intermediate (Medium) temperature circuit and R407c in lower temperature circuit

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Cite this article as: R.S. Mishra, Exergy destruction computation in three stages cascade vapour compression refrigeration systems for low temperature applications, International Journal of Research in Engineering and Innovation Vol-3, Issue-3 (2019), 187-194.