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Thermal modelling and optimization of four stages cascade vapor compression refrigeration systems for ultra-low temperature applications

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Abstract

Exergy analysis is a useful way for determining the real thermodynamic losses in terms of exergy destruction in each components and optimizing environmental and economic performances of the four stages vapour compression cascade refrigeration systems using HFO refrigerant in high temperature cycle (HTC) and also HFO-1234yf in medium temperature cycle (MTC) along with HFC-134a in intermediate temperature (ITC) and HFC-404a / Ethylene/ hydrocarbons in ultra-low temperature cycle (LTC). The present study deals with the exergy analysis on a four stages cascade vapour compression refrigeration system using R1234yf, R1234ze, HFC-134a and R404a/Ethylene/HC refrigerants. A computer code is developed by using Engineering Equation Solver (EES-V9.172-3D) software package program. The numerical comparison were made using hydrocarbons / ethylene /HFC-404a in ultra-low temperature cycle. The effects of the temperature overlapping in LTC, ITC, MTC cascade condensers and HTC condenser temperatures have been carried out. The effect of LTC, ITC, MTC & HTC evaporator temperatures on the exergy destruction ratio and first law efficiency (COP_Over_all) and second law efficiency (exergy efficiency) of the system were computed and the optimum values were obtained for such combinations. It was also found that R1234yf and R1234ze, are good alternatives to R12, R22 in view of their environmentally friendly properties for high temperature and medium temperature cycles. Furthermore HFC-404a / ethylene/ hydrocarbons can be used in place of R13 for similar reasons.

Keywords: Thermodynamic Analysis, Energy, Exergy Analysis, Irreversibility Evaluation

1. Introduction

The During World War II, low temperatures were found useful in aeronautical instrument testing, steel alloy treatment, blood plasma desiccation and similar purposes; and these war needs stimulated the development on ultra-low temperatures refrigeration systems, with evaporators from -29^{0}C down to as low as (-140^{0}C). There are many ultra-low temperature cascade refrigeration systems in use today with evaporator temperatures from 5^{0}C to -100^{0}C. In research laboratories. Ultra-low temperature applications require refrigeration in the range of -80°C to -140°C. Single stage vapour compression refrigeration system is not capable to achieve such low temperatures with the use of reciprocating compressor, due to a very high pressure ratios across the compressor. Higher pressure ratios and volumetric efficiency give you an idea about to higher condenser temperatures and for this reason the capacity of the reciprocating compressor drastically reduces. Though multistage or screw compressors can assist excluding the use of single refrigerant at low temperature is limited by solidification temperature of the refrigerant, extremely low pressures in the evaporator, large suction volumes in the evaporator for a high boiling point refrigerant and high condenser pressure for a low boiling refrigerant. This necessitates integrating for other viable options to partially or fully overcome the above shortcomings. The characteristics of any refrigerant to exhibit best performance, when operating in a certain range of temperature and pressure, provide cascade refrigeration systems an edge over single stage and multistage refrigeration systems for low temperature applications. Cascade refrigeration cycles are commonly used in the liquefaction of natural gas, which consists basically of hydrocarbons of the paraffin series, of which methane has the lowest boiling point at atmospheric pressure. Refrigeration down to that temperature can be provided by a ternary cascade

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refrigeration cycle using propane, ethane and methane, whose boiling points at standard atmospheric pressure are 231.1 K, 184.5 K and 111.7 K. Cascade refrigeration systems employ series of single stage units which are thermally coupled with evaporator/condenser cascades. In 1974, CFC's were tentatively identified as destructive to the ozone layer. For the next decade, this relationship was investigated and a quantitative statement that tied CFC's to the depletion of ozone was released by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) in 1985. The Montreal Protocol (1987) which was agreed by nearly one hundred and fifty countries froze CFC consumption in 1989 and pledged to cut it in half by 1998. In 1992, the Copenhagen amendments went even farther and halted the production of CFCs in developed countries by 1996.CFCs scheduled to be phased out, hydro chlorofluorocarbons (most notably HCFC22) gained in popularity, while their production levels were controlled by 1992, and they were not scheduled for complete elimination. HCFCs were still damaging to the ozone layer, but much lesser than CFCs. Their average stratospheric lifespan was much shorter and not many of them penetrated into the upper atmosphere. CFC-12 has a stratospheric lifetime of 102 years compared to a lifetime of 13.3 years for HCFC22. Furthermore the ozone depletion potential (ODP) of R22 is only 5.5% of the ODP of R12. To improve the performance of the system and to protect the nature with advanced and increased low temperature application, it is important to go with the cascade systems which handle the low temperature demand with the two different and costlier operations. Zubair [1] simulated thermodynamic performance of an actual single stage vapour compression system using a thermal model to study the performance of a variable-speed refrigeration system in which the evaporator capacity was varied by changing the mass-flow rate of the refrigerant for the constant inlet chilled-water temperature. Cabell et al. [2] developed steady-state model to predict the energy performance of a single stage vapour compression system. Kilicarslan [3] carried out the theoretical and experimental investigation of a two-stage vapor compression cascade refrigeration system using R-134a as the refrigerant. Bhattacharya et al. [4] carried out thermodynamic analysis of an endo-reversible two-stage cascade cycle and obtained optimum intermediate temperature for maximum exergy and refrigeration effect. By developing numerical model of a trans-critical CO_2-C3H8 cascade system to validate the theoretical results. Getu and Bansal [5] carried out the thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system to optimize the design and operating parameters of the system by using multi-linear regression analysis in terms of operating for maximum COP, optimum evaporating temperature and optimum mass flow ratio of R717 to that of R744 in the cascade system. Lee et al.[6] did thermodynamically a cascade refrigeration system that uses carbon dioxide and ammonia as refrigerants, to determine the optimal condensing temperature of the cascade condenser to maximize the COP and minimize the exergy destruction of the system. Bhattacharyya et al. [7] carried out the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibilities. Calm [8] examines the outlook for current options in the contexts of existing international agreements, including the Montreal and Kyoto Protocols to avert stratospheric ozone depletion and global climate change, respectively. Literature shows that several refrigerants have emerged to substitute R12, the most widely used fluorocarbon refrigerant in the world. These include the environmental friendly refrigerants i.e. R717, R290, R744, R404A and R1270. Mishra [9] focused on alternative ecofriendly refrigerants for replacing CFC-12 which contains global warming (GWP=1500) and ozone depleting potential (GWP=0055) containing chlorine sustenance. The main critical issue in the field of green technologies is to develop the relationship between ODP and GWP and suggest new and alternative refrigerants which do not damage ozone layer and not to increase global warming. Different ecofriendly HFOs, HFCs and HCs refrigerants are used in each of the circuit depending on the optimum characteristics shown by the refrigerant for a particular application and also carried out using first and second law thermodynamic analysis (i.e. energy and exergy analysis) of two and three stages cascade vapor refrigeration system of 10 ton capacity for seven eco-friendly refrigerants such as R-1234yf and R-1234ze in high temperature circuit, and R134a ,R-404a, R-407C, R-502, propane(R-290), isobutene(R-600a), butane (R-600)) in lower temperature circuit in two stage and above refrigerants in intermediate circuit in three stage system. The performance parameters such as COP, EDR .Therefore four stage cascade refrigeration systems employ four circuits namely a high temperature circuit (HTC), medium temperature circuit (MTC), intermediate temperature circuit (ITC) and a low temperature circuit (LTC). The high temperature circuit serves to extract heat from the medium temperature circuit and medium temperature circuit serves to extract heat from the intermediate temperature circuit and intermediate temperature circuit serves to extract heat from the low temperature circuit and the desired cooling is achieved at the evaporator of the low temperature circuit. The four circuits are coupled together by a heat exchangers called the cascade condensers, where the refrigerant vapours of LTC are condensed by rejecting heat to the refrigerant in the ITC and similarly the refrigerant vapours of ITC are condensed by rejecting heat to the refrigerant in the MTC. Also the refrigerant vapours of MTC are condensed by rejecting heat to the refrigerant in the HTC. The intermediate temperature between the four circuits is an important design parameters that decide the COP of the entire system. The thermodynamic analysis is carried out to evaluate thermodynamic performances of four stages cascade systems at varying design parameters using a HFO and HFC and HC refrigerants. For this study, HFO-1234ze is selected in the high temperature cycle and other alternatives are R152a and R717 .Similarly HFO-1234yf and other HFC were chosen of medium temperature circuit and also HFC were chosen of intermediate temperature cycle. As the low-temperature refrigerant due to its many inherent advantages. Propane, propylene, R404A, and hydrocarbons are selected as ultra-low temperature refrigerants and comparisons were made. In the present research work, energy and exergy analysis is performed on four stages cascade vapour compression refrigeration system in which high temperature circuit ecofriendly refrigerants (R1234ze/R152a/R717) have been used. In the medium temperature ranges HFO-1234yf and other HFC were used. Similarly In intermediate temperature circuit, HFC are used and in low temperature circuit, HFC-404a, Ethylene, and R600a, R290, R600 were used. The objective of the present study mainly deals with the utility of ecofriendly refrigerants particularly in the intermediate temperature circuit and R1234ze and R1234yf refrigerants. The expressions for the exergy losses (lost works) for the individual processes of the cycle as well as the coefficient of performance (COP) and second law efficiency for the entire cycle has been obtained. Effect of variation of condensing and evaporating temperatures on exergy losses, second law efficiency and COP has been investigated.

2. Results and Discussions

Following five systems of four stages cascade refrigeration systems have been chosen for numerical computations using HFO and HFC refrigerants

System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC
System-2: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R290 in LTC
System-3: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R600a in LTC
System-4: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R600 in LTC
System-5: R1234ze in HTC, R1234yf in MTC, R134a in ITC & Ethylene in LTC

For above five systems, the following input data have been assumed

- Efficiency of HTC compressor = 0.80,
- Efficiency of MTC compressor = 0.80,
- Efficiency of ITC compressor = 0.80,
- Efficiency of LTC compressor = 0.80,
- Temperature of HTC condenser= 50°C
- Temperature of HTC Evaporator= 10°C
- Temperature of MTC Evaporator= -30°C
- Temperature of ITC Evaporator= -80°C
- Temperature of LTC Evaporator= -135°C
- Temperature overlapping of MTC cascade Condenser =10°C
- Temperature overlapping of ITC cascade Condenser =10°C
- Temperature overlapping of LTC cascade Condenser =10°C
- Load of LTC Evaporator= 175 “kW”

Tables-1, show the variations of HTC condenser temperature with thermal performances of four stages cascade vapour compression refrigeration system. As HTC condenser temperature is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases. Tables-2 show the variations of HTC evaporator temperature with thermal performances of four stages cascade vapour compression refrigeration system. As HTC evaporator temperature is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is increases and reached to an optimum value and then decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also decreases and reached to an optimum value and then increases. Tables-3 show the variations of MTC evaporator temperature with thermal performances of four stages cascade vapour compression refrigeration system. As MTC evaporator temperature is increases, the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is increases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also decreases. Table-5 shows, the variations of ITC evaporator temperature with thermal performances of four stages cascade vapour compression refrigeration system. As ITC evaporator temperature is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases. Tables-5 shows, the variations of LTC evaporator temperature with thermal performances of four stages cascade vapour compression refrigeration system. As LTC evaporator temperature is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is increases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also decreases. Tables-6 show the variations of Temperature Overlapping (^{0}C) in MTC condenser and HTC evaporator with thermal performances of four stages cascade vapour compression refrigeration system. As temperature Overlapping (^{0}C) in MTC condenser and HTC evaporator is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases. Tables-7 shows the variations of temperature overlapping (^{0}C) in ITC condenser and MTC evaporator with thermal performances of four stages cascade vapour compression refrigeration system. As temperature Overlapping (^{0}C) in ITC condenser and MTC evaporator is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases.Tables-9 show the variations of temperature overlapping (°C) in LTC condenser and ITC evaporator with thermal performances of four stages cascade vapour compression refrigeration system. As temperature overlapping (°C) in LTC condenser and ITC evaporator is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases. Table-9(a) shows the effect of ecofriendly Refrigerants in low temperature circuit (LTC) with thermal performances of four stages cascade vapour compression refrigeration system. It is seen, that the overall first law efficiency and exergetc efficiency, is highest and lowest power required to drive four compressors (whole system) by using R600a and lowest by using ethylene. Table-10(a): shows the effect of ecofriendly Refrigerants in low temperature circuit (MTC) with thermal performances of four stages cascade vapour compression refrigeration system. It is seen, that the overall first law efficiency and exergetc efficiency, is highest and lowest power required to drive four compressors (whole system) by using R1234yf and lowest by using R407C. Tables-11 show the variations of Temperature Overlapping (^oC) in LTC condenser and ITC evaporator with thermal performances of four stages cascade vapour compression refrigeration system. As temperature overlapping(^oC) in LTC condenser and ITC evaporator is increases the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is decreases while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is also increases. Tables- 12 shows the variations of Effect of ecofriendly refrigerants in the HTC condenser with thermal performances of four stages cascade vapour compression refrigeration system. And found that using R152a in HTC condenser, the overall first law efficiency, exergetic efficiency and high temperature circuit first law efficiency is maximum while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is minimum as compared to R1234ze in high temperature circuit. The highest thermodynamic performances were achieved by using R717 in high temperature condenser as compared to R152a and R1234ze. Similarly power required by using R717 is lowest. The comparison were made for various systems by using R1234yf in high temperature circuit and HFC in MTC and ITC circuit and results are shown in table-13(a) to table-13(d) respectively. Tables- 12 shows the variations of effect of ecofriendly refrigerants in the MTC condenser with thermal performances of four stages cascade vapour compression refrigeration system and found that using R245a in MTC condenser gives maximum the overall first law efficiency ,exergetic efficiency and high temperature circuit first law efficiency is while exergy destruction ratio of whole system and power required to run whole system (i.e. running of four compressors) is minimum as compared to R227 ea in medium temperature circuit (MTC). The thermodynamic performances were slightly less by using R236fa in medium temperature condenser as compared to R245fa. Similarly power required by using R245fa is lowest. It was also observed that thermal performances of four stages cascade refrigeration system is for better than using HFO-1234yf in high temperature circuit and R134a in ITC and R404a in LTC.

Table 1: Effect of HTC condenser temperature on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants (System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

HTC Condenser Temp (^0C)	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
35	0.3144	4.847	0.1710	7.911	2.983	2.021	1.163	556.7	95.21
40	0.3036	5.055	0.1652	6.374	2.983	2.021	1.163	576.5	95.21
42	0.2992	5.140	0.1628	5.890	2.983	2.021	1.163	588.8	95.21
44	0.2949	5.234	0.1604	5.461	2.983	2.021	1.163	593.5	95.21
45	0.2927	5.181	0.1592	5.264	2.983	2.021	1.163	598.6	95.21
50	0.2816	5.528	0.1532	4.421	2.983	2.021	1.163	621.5	95.21
55	0.2702	5.802	0.1470	3.758	2.983	2.021	1.163	647.6	95.21
60	0.2585	6.111	0.1406	3.209	2.983	2.021	1.163	677.0	95.21

Table 2: Effect of HTC evaporator temperature on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants(System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

HTC Evaporator Temp (^oC)	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
-20	0.2666	5.896	0.1450	1.86	8.961	2.021	1.163	656.5	95.21
-15	0.2719	5.760	0.1479	2.117	6.998	2.021	1.163	643.6	95.21
-10	0.2762	5.654	0.1503	2.42	5.681	2.021	1.163	633.5	95.21
-5	0.2794	5.578	0.1520	2.78	4.731	2.021	1.163	626.3	95.21
0	0.2814	5.531	0.1531	3.215	4.011	2.021	1.163	621.8	95.21
5	0.2822	5.514	0.1535	3.750	3.444	2.021	1.163	620.2	95.21
10	0.2816	5.528	0.1532	4.421	2.983	2.021	1.163	621.5	95.21
15	0.2795	5.576	0.1521	5.287	2.60	2.021	1.163	326.1	95.21
20	0.2759	5.661	0.1501	6.446	2.273	2.021	1.163	634.2	95.21

Table 3: Effect of MTC evaporator temperature on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants (System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

MTC Evaporator Temp (^oC)	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
-20	0.2806	5.552	0.1526	4.421	4.103	1.641	1.163	623.8	95.21
-25	0.2816	5.528	0.1532	4.421	3.479	1.818	1.163	621.5	95.21
-26	0.2817	5.525	0.1532	4.421	3.371	1.856	1.163	621.3	95.21

-27	0.2817	5.525	0.1533	4.421	3.268	1.895	1.163	621.2	95.21
-28	0.2817	5.525	0.1533	4.421	3.144	1.936	1.163	621.2	95.21
-29	0.2817	5.526	0.1532	4.421	3.014	1.978	1.163	621.3	95.21
-30	0.2816	5.528	0.1532	4.421	2.983	2.021	1.163	621.5	95.21
-31	0.2814	5.531	0.1531	4.421	2.896	2.066	1.163	621.8	95.21
-32	0.2813	5.535	0.1530	4.421	2.812	2.112	1.163	622.2	95.21
-33	0.2811	5.54	0.1529	4.421	2.732	2.160	1.163	622.6	95.21
-34	0.2808	5.545	0.1528	4.421	2.654	2.209	1.163	623.2	95.21
-35	0.2805	5.552	0.1526	4.421	2.580	2.260	1.163	623.8	95.21
-40	0.2785	5.60	0.1515	4.421	2.247	2.545	1.163	628.4	95.21
-45	0.2755	5.672	0.1499	4.421	1.967	2.891	1.163	635.2	95.21
-50	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21

Table 4: Effect of ITC evaporator temperature on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants(System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

ITC Evaporator Temp (°C)	COP_{Over_all}	Exergy Destruction Ratio (EDR_{System})	Exergetc Efficiency	COP_{HTC}	COP_{MTC}	COP_{ITC}	COP_{LTC}	Exergy of Fuel (kW)	Exergy of Product (kW)
-70	0.2657	7.041	0.1244	4.421	1.729	4.867	0.9601	658.5	81.90
-75	0.2691	6.359	0.1359	4.421	1.729	3.984	1.055	650.4	88.38
-80	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21
-85	0.2732	5.256	0.1598	4.421	1.729	2.810	1.289	640.6	102.4
-86	0.2734	5.162	0.1623	4.421	1.729	2.721	1.316	640.1	103.9
-87	0.2736	5.07	0.1647	4.421	1.729	2.635	1.345	639.6	105.4
-88	0.2738	4.98	0.1672	4.421	1.729	2.554	1.374	639.3	106.9
-89	0.2739	4.898	0.1697	4.421	1.729	2.476	1.405	639.0	108.4
-90	0.2739	4.809	0.1722	4.421	1.729	2.40	1.436	638.8	110.0
-95	0.2738	4.418	0.1846	4.421	1.729	2.067	1.613	639.2	118.0
-100	0.2737	4.076	0.1970	4.421	1.729	1.790	1.828	641.8	126.4

Table 5: Effect of LTC evaporator temperature on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants (System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

LTC Evaporator Temp (°C)	COP_{Over_all}	Exergy Destruction Ratio (EDR_{System})	Exergetc Efficiency	COP_{MTC}	COP_{MTC}	COP_{ITC}	COP_{LTC}	Exergy of Fuel (kW)	Exergy of Product (kW)
-120	0.3490	4.267	0.1893	4.421	1.729	3.323	1.868	501.5	95.21
-125	0.3224	4.702	0.1754	4.421	1.729	3.323	1.589	542.8	95.21
-130	0.2966	5.198	0.1613	4.421	1.729	3.323	1.358	590.1	95.21
-1355	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21
-140	0.2474	6.431	0.1346	4.421	1.729	3.323	0.9972	707.5	95.21

Table 6: Effect of temperature overlapping between MTC condenser and HTC cascade evaporator on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants(System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

Temp Overlapping (°C) in MTC	COP_{Over_all}	Exergy Destruction Ratio (EDR_{System})	Exergetc Efficiency	COP_{MTC}	COP_{MTC}	COP_{ITC}	COP_{LTC}	Exergy of Fuel (kW)	Exergy of Product (kW)
0	0.3018	5.09	0.1642	4.421	2.204	3.323	1.163	579.8	95.21
2	0.2928	5.214	0.1609	4.421	2.098	3.323	1.163	591.6	95.21
4	0.2897	5.344	0.1576	4.421	1.998	3.323	1.163	604.0	95.21
5	0.2867	5.411	0.1560	4.421	1.951	3.323	1.163	610.4	95.21
6	0.2837	5.479	0.1543	4.421	1.904	3.323	1.163	616.9	95.21
8	0.2776	5.621	0.1510	4.421	1.814	3.323	1.163	630.3	95.21
10	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21
12	0.2654	5.925	0.1444	4.421	1.648	3.323	1.163	659.3	95.21
14	0.2593	6.088	0.1411	4.421	1.57	3.323	1.163	674.9	95.21
15	0.2562	6.173	0.1394	4.421	1.533	3.323	1.163	683.0	95.21

Table 7: Effect of temperature overlapping between ITC condenser and MTC cascade evaporator on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants(System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

Temp Overlapping (°C) in ITC	COP_Over_all	Exergy Destruction Ratio (EDR_System)	Exergetc Efficiency	COP_ HTC	COP_ MTC	COP_ ITC	COP_ LTC	Exergy of Fuel (kW)	Exergy of Product (kW)
0	0.2959	5.212	0.1610	4.421	1.729	4.613	1.163	591.4	95.21
2	0.2908	5.32	0.1582	4.421	1.729	4.291	1.163	601.7	95.21
4	0.2859	5.429	0.1555	4.421	1.729	4.006	1.163	612.1	95.21
5	0.2834	5.485	0.1542	4.421	1.729	3.876	1.163	617.4	95.21
6	0.2810	5.541	0.1529	4.421	1.729	3.753	1.163	622.7	95.21
8	0.2762	5.654	0.1503	4.421	1.729	3.527	1.163	633.5	95.21
10	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21
12	0.2669	5.886	0.1452	4.421	1.729	3.138	1.163	655.6	95.21
14	0.2624	6.006	0.1427	4.421	1.729	2.97	1.163	667.0	95.21
15	0.2601	6.066	0.1415	4.421	1.729	2.891	1.163	672.8	95.21

Table 8: Effect of temperature overlapping between LTC condenser and ITC cascade evaporator on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants(System-1: R1234ze in HTC, R1234yf in MTC, R134a in ITC & R404a in LTC)

Temp Overlapping (°C) in LTC condenser & ITC evap	COP_Over_all	Exergy Destruction Ratio (EDR_System)	Exergetc Efficiency	COP _HTC	COP _MTC	COP _ITC	COP _LTC	Exergy of Fuel (kW)	Exergy of Product (kW)
0	0.3057	5.012	0.1663	4.421	1.729	3.323	1.446	572.4	95.21
2	0.2985	5.158	0.1624	4.421	1.729	3.323	1.374	586.2	95.21
4	0.2915	5.306	0.1586	4.421	1.729	3.323	1.316	600.4	95.21
5	0.288	5.381	0.1557	4.421	1.729	3.323	1.289	607.5	95.21
6	0.2847	5.457	0.1549	4.421	1.729	3.323	1.262	614.8	95.21
8	0.2780	5.612	0.1513	4.421	1.729	3.323	1.211	629.5	95.21
10	0.2715	5.769	0.1477	4.421	1.729	3.323	1.163	644.5	95.21
12	0.2552	5.930	0.1443	4.421	1.729	3.323	1.118	659.8	95.21
14	0.2591	6.094	0.1410	4.421	1.729	3.323	1.075	675.4	95.21
15	0.2561	6.178	0.1393	4.421	1.729	3.323	1.055	683.4	95.21

Table 9(a): Effect of ecofriendly refrigerants in low temperature circuit (LTC) on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants

Ecofriendly Refrigerants in LTC	COP_Over_all	Exergy Destruction Ratio (EDR_System)	Exergetc Efficiency	COP_ HTC	COP_ MTC	COP_ ITC	COP_ LTC	Exergy of Fuel (kW)	Exergy of Product (kW)
R404a	0.2715	5.679	0.1477	4.421	2.204	3.323	1.163	644.9	95.21
R290	0.2761	5.658	0.1502	4.421	2.098	3.323	1.196	633.9	95.21
R600a	0.2811	5.539	0.1529	4.421	1.998	3.323	1.234	622.6	95.21
R600	0.2802	5.559	0.1525	4.421	1.951	3.323	1.228	624.6	95.21
Ethylene	0.2651	5.935	0.1442	4.421	1.904	3.323	1.117	660.2	95.21

Table 9(b): Effect of ecofriendly refrigerants in low temperature circuit (LTC) on the power consumed by the compressors and total power consumed by whole system using four stages cascading vapour compression refrigeration cycle.

Ecofriendly Refrigerants in LTC	Total power consumed by whole system (kW)	Work done by HTC compressor W_Comp (kW)	Work done by MTC compressor W_Comp (kW)	Work done by ITC compressor W_Comp (kW)	Work done by LTC compressor W_Comp (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R404a	644.9	151.2	244.9	97.95	150.5	644.9	95.21
R290	633.9	149.2	241.7	96.69	146.3	633.9	95.21
R600a	622.6	147.1	238.3	95.33	141.8	622.6	95.21
R600	624.6	147.5	238.9	95.56	142.5	624.6	95.21
Ethylene	660.2	154.1	249.6	99.83	156.7	660.2	95.21

Table 10(a): Ecofriendly Refrigerants in *medium temperature circuit (*MTC) on *the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants*

Ecofriendly Refrigerants in MTC	COP_Over_all	Exergy Destruction Ratio (EDR_System)	Exergetc Efficiency	COP_ HTC	COP_ MTC	COP_ ITC	COP_ LTC	Exergy of Fuel (kW)	Exergy of Product (kW)
R1234yf	0.2959	5.212	0.1610	4.421	1.729	4.613	1.163	591.4	95.21
R32	0.2908	5.32	0.1582	4.421	1.729	4.291	1.163	601.7	95.21
R152a	0.2859	5.429	0.1555	4.421	1.729	4.006	1.163	612.1	95.21
R410a	0.2834	5.485	0.1542	4.421	1.729	3.876	1.163	617.4	95.21
R407c	0.2810	5.541	0.1529	4.421	1.729	3.753	1.163	622.7	95.21

Table 10(b): Effect of Ecofriendly Refrigerants in medium temperature circuit (MTC) on the power consumed by the compressors and total power consumed by whole system using four stages cascading vapour compression refrigeration cycle

Ecofriendly Refrigerants in MTC	Total power consumed by whole system (kW)	Work done by HTC compressor $W_{\_Comp}$ (kW)	Work done by MTC compressor $W_{\_Comp}$ (kW)	Work done by ITC compressor $W_{\_Comp}$ (kW)	Work done by LTC compressor $W_{\_Comp}$ (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R1234yf	624.5	147.5	238.9	95.56	142.5	624.5	95.21
R32	609.9	144.8	227.1	95.56	142.5	609.9	95.21
R152a	594.0	141.9	214.1	95.56	142.5	594.0	95.21
R410a	610.0	144.8	227.2	95.56	142.5	610.0	95.21
R407c	649.9	152.2	259.6	95.56	142.5	649.9	95.21

Table 11(a): Effect of Ecofriendly Refrigerants in ITC on the first and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants

Ecofriendly Refrigerants in ITC	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
R134a	0.2802	5.559	0.1525	4.421	1.729	3.323	1.228	624.5	95.21
R410a	0.280	5.585	0.1523	4.421	1.729	3.313	1.228	625.0	95.21
R407c	0.2568	6.158	0.1397	4.421	1.729	3.539	1.228	681.5	95.21
R125	0.2787	5.595	0.1516	4.421	1.729	3.262	1.228	627.9	95.21
R507a	0.2793	5.581	0.1520	4.421	1.729	3.286	1.228	626.6	95.21
R236fa	0.2803	5.559	0.1525	4.421	1.729	3.323	1.228	624.4	95.21
R245fa	0.2805	5.553	0.1526	4.421	1.729	3.333	1.228	623.9	95.21

Table 11(b): Effect of Ecofriendly Refrigerants in intermediate temperature circuit (ITC) on the power consumed by the compressors and total power consumed by whole system using four stages cascading vapour compression refrigeration cycle.

Ecofriendly Refrigerants in ITC	Total power consumed by whole system (kW)	Work done by HTC compressor $W_{\_Comp}$ (kW)	Work done by MTC compressor $W_{\_Comp}$ (kW)	Work done by ITC compressor $W_{\_Comp}$ (kW)	Work done by LTC compressor $W_{\_Comp}$ (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R134a	624.5	147.5	238.9	95.95	142.5	624.5	95.21
R410a	625.0	147.6	239.1	95.85	142.5	625.0	95.21
R407c	681.5	158.0	256.0	125.0	142.5	681.5	95.21
R125	627.9	148.1	239.9	97.33	142.5	627.9	95.21
R507a	626.6	147.9	239.5	96.64	142.5	626.6	95.21
R236fa	624.4	147.5	238.9	95.54	142.5	624.4	95.21
R245fa	623.9	147.4	238.7	95.26	142.5	623.9	95.21

Table 12(a) : Effect of HTC condenser ecofriendly refrigerants on the first and second law thermal performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants

Ecofriendly Refrigerants in HTC	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
R1234ze	0.2715	5.769	0.1477	4.421	1.729	3.323	1.228	644.5	95.21
R152a	0.2749	5.687	0.1494	4.661	1.729	3.313	1.228	636.7	95.21
R717	0.2764	5.649	0.1504	4.782	1.729	3.539	1.228	633.0	95.21

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Table 12(b): Effect of Ecofriendly Refrigerants in high temperature circuit (HTC) on the power consumed by the compressors and total power consumed by whole system using four stages cascading vapour compression refrigeration cycle

Ecofriendly Refrigerants in HTC	Total power consumed by whole system (kW)	Work done by HTC compressor $W_{\_Comp}$ (kW)	Work done by MTC compressor $W_{\_Comp}$ (kW)	Work done by ITC compressor $W_{\_Comp}$ (kW)	Work done by LTC compressor $W_{\_Comp}$ (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R1234ze	644.5	151.2	244.9	97.95	150.5	644.5	95.21
R152a	636.7	143.4	244.9	97.95	150.5	636.7	95.21
R717	633.0	139.8	244.9	244.9	150.5	633.0	95.21

Table 13: Thermal performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants HFO-1234yf in HTC ecofriendly refrigerants in MTC & R134a in ITC and R404a in LTC for evaporator temperature of -135°C

Eco Friendly Refrigerants	$COP_{\_Over\_all}$	Exergy Destruction Ratio ($EDR_{\_System}$)	Exergetc Efficiency	$COP_{\_HTC}$	$COP_{\_MTC}$	$COP_{\_ITC}$	$COP_{\_LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
R227ea	0.2563	6.171	0.1395	4.2019	1.572	3.323	1.163	682.7	95.21
R236fa	0.2688	5.837	0.1463	4.2019	1.737	3.323	1.163	650.9	95.21
R245fa	0.2798	5.569	0.1522	4.2019	1.898	3.323	1.163	625.4	95.21

Table 13(b): Thermal performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants R1234yf in HTC-Eco friendly Ref in MTC –R134a in ITC –R404a in LTC

Eco Friendly Refrigerants	Total power consumed by whole system (kW)	Work done by HTC compressor W_{Comp} (kW)	Work done by MTC compressor W_{Comp} (kW)	Work done by ITC compressor W_{Comp} (kW)	Work done by LTC compressor W_{Comp} (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R227ea	682.7	164.9	269.4	97.95	150.5	682.7	95.21
R236fa	650.9	158.8	243.7	97.95	150.5	650.9	95.21
R245fa	625.4	158.9	223.1	97.95	150.5	625.4	95.21

Table 13(c): Thermal performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants HFO-1234ze in HTC-Eco friendly Ref in MTC –R134a in ITC –R404a in LTC

Eco Friendly Refrigerants	COP_{Over_all}	Exergy Destruction Ratio (EDR_{System})	Exergetc Efficiency	COP_{HTC}	COP_{MTC}	COP_{ITC}	COP_{LTC}	Exergy of Fuel (kW)	Exergy of Product (kW)
R227ea	0.2594	6.085	0.1412	4.421	1.572	3.323	1.163	682.7	95.21
R236fa	0.2721	5.754	0.1481	4.421	1.737	3.323	1.163	650.9	95.21
R245fa	0.2833	5.489	0.1541	4.421	1.898	3.323	1.163	625.4	95.21

Table 13(d): Thermal performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants R1234ze in HTC-Eco friendly Ref in MTC –R134a in ITC –R404a in LTC

Eco Friendly Refrigerants	Total power consumed by whole system (kW)	Work done by HTC compressor W_{Comp} (kW)	Work done by MTC compressor W_{Comp} (kW)	Work done by ITC compressor W_{Comp} (kW)	Work done by LTC compressor W_{Comp} (kW)	Exergy of Fuel (kW)	Exergy of Product (kW)
R227ea	674.5	156.7	269.4	97.95	150.5	682.7	95.21
R236fa	674.5	150.9	243.7	97.95	150.5	650.9	95.21
R245fa	617.8	146.3	223.1	97.95	150.5	625.4	95.21

Table 14: First and second law thermal Performance of four stages cascade vapour compression refrigeration using eco-friendly refrigerants

Systems	COP_{Over_all}	Exergy Destruction Ratio (EDR_{System})	Exergetc Efficiency	COP_{HTC}	COP_{MTC}	COP_{ITC}	$COP\ _{LTC}$	Exergy of Fuel (kW)	Exergy of Product (kW)
System-1	0.2816	5.528	0.1532	4.421	2.983	2.021	1.163	621.5	95.21
System-2	0.2863	5.420	0.1558	4.421	2.983	2.021	1.196	611.2	95.21
System-3	0.2916	5.304	0.1586	4.421	2.983	2.021	1.234	600.2	95.21
System-4	0.2907	5.324	0.1581	4.421	2.983	2.021	1.228	602.1	95.21
System-5	0.2748	5.689	0.1495	4.421	2.983	2.021	1.117	636.8	95.21

Table-14: shows the First and second law thermal Performance of four stages cascade vapor compression refrigeration using eco-friendly refrigerants and found that system-3 is better systems than system-5.

3. Conclusions

The following conclusions were drawn from present investigations.

- The system-3 (using R1234ze in HTC, R1234yf in MTC, R134a in ITC & R600a in LTC) gives better first law efficiency and system-5 gives lowest thermodynamic performance system -5 using R1234ze in HTC, R1234yf in MTC, R134a in ITC & ethylene in LTC.
- Thermodynamic performances of system-1 using R1234ze in HTC, R1234yf in MTC, R134a in ITC &R404a in LTC is slightly less than the system-3 (using R1234ze in HTC, R1234yf in MTC, and R134a in ITC &R600a in LTC).
- Thermodynamic performances using HFO-1234yf in HTC is lower than using HFO-1234ze in high temperature condenser and HFC in MTC & ITC circuits.
- R245fa gives better thermodynamic performance as compared to HFC-134a and HFO-1234yf.

References

[1] S. M. Zubair [1999] "Performance Evaluation of Vapour Compression System", International Journal of Refrigeration, vol. 22, pp. 235-243,

[2] R. Cabello, J. Navarro, E. Torrella , [2005]" Simplified Steady-State Modelling of a Single Stage Vapour Compression Plant. Model Development and Validation", Applied Thermal Engineering, vol. 25, pp. 1740–1752, 2005

[3] A. Kilicarslan, [2004] "An Experimental Investigation of a Different Type Vapor Compression Cascade Refrigeration System", Applied Thermal Engineering, vol. 24, pp. 2611–2626..

[4] S. Bhattacharyya, S. Bose, J. Sarkar, [20087] "Exergy Maximization of Cascade Refrigeration Cycles and Its Numerical Verification for a Transcritical CO2-C3H8 System", International Journal of Refrigeration, vol. 30, pp. 624-632,

[5] H.M. Getu, P.K. Bansal, [2008] "Thermodynamic Analysis of an R744–R717 Cascade Refrigeration System", International Journal of Refrigeration, vol. 31, pp. 45-54,

[6] T.S. Lee, C.H. Liu, T.W. Chen, [2006] "Thermodynamic Analysis of Optimal Condensing Temperature of Cascade-Condenser in CO2/NH3 cascadeRefrigeration Systems", International Journal of Refrigeration, vol. 29, pp. 1100-1108,

[7] S. Bhattacharyya, S. Mukhopadhyay, J. Sarkar, [2008] "CO2–C3H8 Cascade Refrigeration–Heat Pump System: Heat Exchanger Inventory Optimization and Its Numerical Verification", International Journal of Refrigeration, vol. 31, pp. 1207-1213,

[8] J. M. Calm, (2008) "The Next Generation of Refrigerants – Historical Review, Considerations, and Outlook", International Journal of Refrigeration, vol. 31, pp. 1123-1133.

[9] R.S. Mishra [2013] Thermodynamic analysis of three stages cascade vapour compression refrigeration system for biomedical applications, Journal of Multi Disciplinary Engineering Technologies Volume 7 No.1, page-27-35.

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