Use of Hydrocarbons in Low Temperature Circuit in Terms of First Law and Second Law Efficiency of Four Stage Cascade Refrigeration of Semen Preservation

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Abstract

This paper mainly deals with the utility of hydrocarbons , R404a and other ecofriendly refrigerants in the low temperature circuit for semen preservation. The energy-exergy analysis have been carried out to find out the feasibility of above ecofriendly refrigerants in the Four stage cascade refrigeration system using R1234ze in high temperature circuit and R134a in primary intermediate circuit and R410a in secondary intermediate circuit. It was observed that the use of hydrocarbon is feasible for improving thermal performance of the above system by considering safety measures. The best second law performance was observed using R600a and low performance was observed using ethylene in the low temperature evaporator circuit without safety measure the system using R404a in low temperature evaporator circuit gives better performance using ethylene in low temperature circuit.

1. Introduction

Low-temperature refrigeration systems are typically required in the temperature range from –100°C to –140°C for applications in food, pharmaceutical, chemical, and other industries. At such low temperatures, single-stage compression systems with reciprocating compressors are generally not feasible due to high pressure ratios. A high pressure ratio implies high discharge and oil temperatures and low volumetric efficiencies and, hence, low COP values. Cascade refrigeration systems can be used to achieve low temperatures, where series of single-stage units are used that are thermally coupled through evaporator/condenser cascades. Each circuit has a different refrigerant suitable for that temperature. The high-temperature circuit uses high boiling point refrigerants such as R-1234ze, and R1234yf and Intermediate circuits thirteen ecofriendly refrigerants such as R-134a, R123, R125, HFC blends (R-507a), ammonia, propane, propylene, hydrocarbons, etc., whereas the low-temperature circuit uses low boiling refrigerants such as ethane. air, methane etc In a vapour compression cascade refrigeration system where low pressure vapour in the evaporator stage is compressed and then recycled for condensation in the evaporator of a previous stage, the improvement of passing the low pressure refrigerant's vapour from an evaporator stage through a heat exchanger to heated vapour to ambient temperature, compressing said heated vapour, removing the compressor work by passing said compressed vapour through a evaporator, then cooling is by compressed vapour by passing it through heat exchanger in heat exchanger at a low pressure vapour, and condensing it in the evaporator of the next higher temperature cycle of the cascade system and recycling the liquid to the low pressure evaporator stage.

Most of the investigators even did not find out the effect of various approaches on the system performances on three and four stages cascade refrigeration systems and effect of ecofriendly refrigerants in the primary intermediate temperature circuit and secondary intermediate temperature circuit. This paper mainly deals with thermal performances in terms of exergy destruction ratio by thermodynamically analyzing the use of R1234yf and R1234ze in the high temperature circuits and mainly thirteen eco-friendly refrigerants in the intermediates circuits and Ethane in the low temperature applications.

2. Literature Review

Agnew et al [1] explained the performance of a three stage cascade refrigeration systems for low temperature applications. Bansal P.K [3] carried out thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system. Bhattacharyya et al. [4] studied a carbon dioxide–propane (R744–R290) optimum cascade evaporating system to define an evaporating temperature of R744 for application in heating circuits. Lee et al. [5] analyzed a carbon dioxide–ammonia (R744–R717) cascade system thermodynamically to determine the optimum condensing temperature of R744 in the low-temperature circuit. Nikolaidis et.al [6] studied analytically that change in evaporator and condenser temperatures of two stage vapour compression refrigeration plant using R22 add considerable effect on plant irreversibility. They suggested that there is need for optimizing the conditions imposed upon the condenser and evaporator Reddy et al. [7] performed numerical analysis of vapour compression refrigeration system using R134a, R143a, R152a, R404A, R410A, R502 and R507A, and discussed the effect of evaporator temperature, degree of subcooling at condenser outlet, superheating of evaporator outlet, vapour liquid heat exchanger effectiveness and degree of condenser temperature on COP and exergetic efficiency. They reported that evaporator and condenser temperature have significant effect on both COP and exergetic efficiency and also found that R134a has the better performance while R407C has poor performance in all respect Xuan et.al [8] presented in this manuscript about the replacement of R502 by mixture

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of HFC-161 in vapour compression refrigeration system and conducted experimental study it was found that mixture of HFC-161 gives same and higher performance than R404A at lower and higher evaporative temperature respectively on the vapour compression refrigeration system designed for R404A.

Inspite large number of research have been done by several investigators on single stage vapour compression systems and few investigators on double and double stage systems , there are several problems are to be solved by using more than two stages cascade refrigeration systems for low temperature applications below -90°C for semen preservation. These above investigators did not studies the thermodynamic performances in terms of COP and exergetic efficiency and system exergy destruction ratio (EDR) for very low temperature application using hydrocarbon and other eleven refrigerants used in the low temperature circuits and R1234ze in higher temperature circuit for semen preservation and other applications

3. Results and Discussions

The performance of four stages cascade refrigeration systems using twelve ecofriendly refrigerants of -100 °C in the lower temperature evaporator circuit and R1234ze in HTC (Hiher temperature circuit) and R134a in firsl intermediate temperature circuit and R410a is shown in the table-1 . It was observed that R245fa gives better first law efficiency in terms of overall COP of the system.However second law efficiency of R600a is better inspite by using R245fa and second law efficiency of R507a is lowest and system EDR is highest. EDR of system using R404a is also nearly approaching to EDR using R507a gives more irreversibility occurred in the system components while using these refrigerants. Although circuit first law efficiency of LTC using R114 is highest as shown in Table-1(b) respectively

Table: 1(a). Four Stage Cascade Refrigeration Systems For Low Temperature Applications Using R1234ze in hot fluid circuit-R134a-R410a-Varying Ecofriendly Refrigerants in low temp circuit(T_{eva}= (- 100 °C, T_{cond}= -70 °C, $T_{cascade\ -eva}$= 30 °C, $T_{cascade-eva}$= (- 20 °C, $T_{cascade-va}$= - 70 °C APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

LTC Eco Friendly Refri.	$COP_{overall}$	EDR	Exergetic Efficiency
R290	0.4023	3.201	0.2380
R404A	o.3963	7.143	0.1228
R143A	o.4012	3.957	0.2019
R236fa	0.4032	7.984	0.1113
R142b	0.4002	3.763	0.2099
R600	0.4041	3.208	0.2376
R600A	0.4037	2.879	0.2578
R507A	0.4017	7.179	0.1223
R114	0.4024	9.584	0.09448
R227ea	0.4011	14.37	0.06506
R245fa	0.4032	3.86	0.2058
R125	0.4020	4.42	0.1845

Table: 1(b). Four Stage Cascade Refrigeration Systems For Low Temperature Applications Using R1234ze in hot fluid circuit-R134a-R410a-Varying Ecofriendly Refrigerants in low temp circuit (T_{eva}= (- 100 °C, T_{cond}= -70 °C, $T_{cascade\ -eva}$= 30 °C, $T_{cascade-eva}$= (- 20 °C, $T_{cascade-va}$= - 70 °C) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

LTC Eco Friendly Refri.	COP_H ot fluid circuit	COP_{int} ermediate temperat ure circuit-ii	COP_{in} termedia te temperat ure circuit-II	COP_{low} temperature fluid circuit
R290	4.375	2.279	2.116	2.948
R404A	4.375	2.279	2.116	2.829
R143A	4.375	2.279	2.116	2.927
R236fa	4.375	2.279	2.116	2.968
R142b	4.375	2.279	2.116	2.907
R600	4.375	2.279	2.116	2.987
R600A	4.375	2.279	2.116	2.979
R507A	4.375	2.279	2.116	2.936
R114	4.375	2.279	2.116	3.014
R227ea	4.375	2.279	2.116	2.924

Similarly the variation of system performance with hydrocarbon and R404a and Ethylene in the LTC(lower temperature evaporator circuit evaporator temperature) varying form -160 °C to -130 °C and R1234ze in HTC (Hiher temperature circuit) and R134a in firsl intermediate temperature circuit and R410a in second intermediate temperature circuit is also shown in Table 2(a) to 2(e) and circuit performance s in terms of first law efficiency of each temperature circuit is also shown in Table 3(a) to 3(e) respectively. It was observed that using R1234ze in high temperature circuit gives better thermal performance than using R1234yf in HTC. It was also observed that interchanging Refrigerants in the intermediate temperature circuits do not affect system overall second law performances also there is a slightly variation in the system exergy destruction ratio. The second law efficiency in terms of exergetic efficiency of R600a is better than alR290 and R40a and lowest performance obtained using ethylene in the LTC. IT was also observed that One can used R600 hydrocarbon below 136°C only but theoretically the performance is also shown in Table 2(e) and 3(e) respectively.

Table: 2(a). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade\ -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and

Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$EVA_{\_Temp}$	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1436	3.255	0.2350
-155	0.1582	3.145	0.2413
-150	0.1730	3.063	0.2461
-145	0.1879	3.006	0.2496
-140	0.2029	2.972	0.2518
-135	0.2179	2.959	0.2526
-130	0.2328	2.963	0.2523

Table: 2(b). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R290 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade}$ $-_{eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$Eva_{\_Temp}$	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1385	3.411	0.2267
-155	0.1539	3.259	0.2348
-150	0.1696	3.144	0.2413
-145	0.1853	3.063	0.2461
-140	0.2110	3.011	0.2494
-135	0.2165	2.983	0.2511
-130	0.2319	2.978	0.2514

Table: 2(c). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R404a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade}$ $-_{eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$Eva_{\_Temp}$	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1369	3.461	0.2242
-155	0.1672	3.203	0.2379
-150	0.1520	3.313	0.2318
-145	0.1826	3.124	0.2425
-140	0.1979	3.073	0.2455
-135	0.2132	3.046	0.2472
-130	0.2283	3.040	0.2475

Table: 2(d). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly ethylene refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade}$ $-_{eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$Eva_{\_Temp}$	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1366	3.472	0.2236
-155	0.1524	3.302	0.2325
-150	0.1684	3.175	0.2395
-145	0.1843	3.085	0.2448
-140	0.2002	3.026	0.2484
-135	0.2160	2.994	0.2504
-130	0.2315	2.985	0.2509

Table: 2(e). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade}$ $-_{eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$Eva_{\_Temp}$	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1418	3.308	0.2321
-155	0.1568	3.182	0.2391
-150	0.1719	3.088	0.2446
-145	0.1872	3.022	0.2486
-140	0.2024	2.982	0.2511
-135	0.2176	2.964	0.2523
-130	0.2326	2.966	0.2521

Table: 3(a). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade}$ $-_{eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

$EVA_{\_Temp}$	COP_{HTC}	COP_{ICT_1}	COP_{ICT-2}	COP LTC
-160	1.797	1.784	1.212	1.255
-155	1.797	1.784	1.212	1.784
-150	1.797	1.784	1.212	1.889

-145	1.797	1.784	1.212	2.349
-140	1.797	1.784	1.212	2.966
-135	1.797	1.784	1.212	3.834
-130	1.797	1.784	1.212	5.138

Table: 3(b). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R290 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade\ -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_temp	COP_{HTC}	COP_{ICT-1}	COP_{ICT-ii}	COP_{LTC}
-160	1.797	1.784	1.212	1.170
-155	1.797	1.784	1.212	1.447
-150	1.797	1.784	1.212	1.80
-145	1.797	1.784	1.212	2.259
-140	1.797	1.784	1.212	2.875
-135	1.797	1.784	1.212	3.742
-130	1.797	1.784	1.212	5.046

Table: 3(c). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R404a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade\ -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	COP_{HTC}	COP_{ICT-1}	COP_{ICT-ii}	COP_{LTC}
-160	1.797	1.784	1.212	1.145
-155	1.797	1.784	1.212	1.741
-150	1.797	1.784	1.212	1.409
-145	1.797	1.784	1.212	2.168
-140	1.797	1.784	1.212	2.737
-135	1.797	1.784	1.212	3.524
-130	1.797	1.784	1.212	4.685

Table: 3(d). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly ethylene refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade\ -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	COP_{HTC}	COP_{ICT-1}	COP_{ICT-ii}	COP_{LTC}
-160	1.797	1.784	1.212	1.14
-155	1.797	1.784	1.212	1.417
-150	1.797	1.784	1.212	1.769
-145	1.797	1.784	1.212	2.226
-140	1.797	1.784	1.212	2.84
-135	1.797	1.784	1.212	3.703
-130	1.797	1.784	1.212	5.001

Table: 3(d). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R404a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade\ -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	COP_{HTC}	COP_{ICT-1}	COP_{ICT-ii}	COP_{LTC}
-160	1.797	1.784	1.212	1.225
-155	1.797	1.784	1.212	1.505
-150	1.797	1.784	1.212	1.861
-145	1.797	1.784	1.212	2.322
-140	1.797	1.784	1.212	2.942
-135	1.797	1.784	1.212	3.813
-130	1.797	1.784	1.212	5.121

Similarly system performance in terms of first law efficiency (overall system COP) and system exergy Destruction ratio (EDR) and second law efficiency in terms of exergetic efficiency (rational efficiency) using hydrocarbons in the lower temperature circuit and R1234yf in High temperature circuit and R134a in first intermediate temperature circuit and R410a in second intermediate evaporator temperature circuit is also shown in Table 4 and circuit first law performances in Table 5 respectively. It has lower performance than R1234ze in HTC. Following observations using hydrocarbons and R404a and ethylene in lower temperature evaporator circuit in the four stages cascade refrigeration systems have been drawn.

Use of hydrocarbons in the lower temperature circuit gives better first law performance in terms of overall system coefficient of performance and second law system performance in terms of exergetic efficiency By using Hydrocarbons in lower temperature evaporators circuit safety precautions must be taken because these refrigerants also having flammable properties.R600a hydrocarbon gives best first law and second law performance than using R404a in LTC Ecofriendly refrigerant R1234yf using high temperature circuit gives lower performances than R1234ze but it has lower global warming potential (approximately

Four) than R1234ze (GWP is six). This is a advantage using R1234yf in the high temperature circuit.

Table: 4(a). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade\ -eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_{Temp}	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1345	3.541	0.2202
-155	0.1481	3.426	0.2259
-150	0.1619	3.342	0.2303
-145	0.1757	3.286	0.2333
-140	0.1895	3.253	0.2351
-135	0.2033	3.242	0.2358
-130	0.2171	3.250	0.2353

Table: 4(b). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R290 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade\ -eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	COPoverall	EDR	Exergetic Efficiency
-160	0.1298	3.706	0.2125
-155	0.1442	3.547	0.2199
-150	0.1587	3.439	0.2258
-145	0.1733	3.346	0.2301
-140	0.1878	3.293	0.2329
-135	0.2021	3.267	0.2343
-130	0.2163	3.266	0.2344

Table: 4(c). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R404a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade\ -eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1284	3.759	0.2101
-155	0.1424	3.605	0.2171
-150	0.1565	3.491	0.2227
-145	0.1707	3.411	0.2267
-140	0.1849	3.360	0.294
-135	0.1990	3.334	0.2307
-130	0.2130	3.332	0.2309

Table: 4(d). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly ethylene refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade\ -eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1280	3.771	0.2096
-155	0.1427	3.593	0.2177
-150	0.1576	3.461	0.2242
-145	0.1724	3.369	0.2289
-140	0.1870	3.309	0.2321
-135	0.2016	3.279	0.2337
-130	0.2159	3.273	0.2340

Table: 4(e). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}= 70 ^oC, $T_{cascade\ -eva2}$= -60 ^oC, $T_{cascade-eva3}$= - 120 ^oC,) APPROACH1=APPROACH2=APPROACH3= 10 (^oC) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	$COP_{overall}$	EDR	Exergetic Efficiency
-160	0.1329	3.596	0.2176
-155	0.1468	3.466	0.2239
-150	0.1609	3.369	0.2289
-145	0.1750	3.303	0.2324
-140	0.1891	3.263	0.2346
-135	0.2031	3.247	0.2354
-130	0.2161	3.253	0.2351

Table: 5(a). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234yf in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 ^oC, T_{cond}=

70 °C, $T_{cascade -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	**COP_{HTC}**	**COP_{ICT-1}**	**COP_{ICT-ii}**	**COP_{LTC}**
-160	1.544	1.784	1.212	1.255
-155	1.544	1.784	1.212	1.535
-150	1.544	1.784	1.212	1.889
-145	1.544	1.784	1.212	2.349
-140	1.544	1.784	1.212	2.966
-135	1.544	1.784	1.212	3.834
-130	1.544	1.784	1.212	5.138

Table: 5(b). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R290 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	**COP_{HTC}**	**COP_{ICT-1}**	**COP_{ICT-ii}**	**COP_{LTC}**
-160	1.544	1.784	1.212	1.170
-155	1.544	1.784	1.212	1.447
-150	1.544	1.784	1.212	1.80
-145	1.544	1.784	1.212	2.259
-140	1.544	1.784	1.212	2.875
-135	1.544	1.784	1.212	3.742
-130	1.544	1.784	1.212	5.046

Table: 5(c) Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R404a refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficie2.349ncy1= Compressor-Efficiency2= Comp2.966ressor-Efficiency3= Compressor-Efficiency4=83.8340%

EVA_Temp	**COP_{HTC}**	**COP_{ICT-1}**	**COP_{ICT-ii}**	**COP_{LTC}**
-160	1.544	1.784	1.212	1.145
-155	1.544	1.784	1.212	1.409
-150	1.544	1.784	1.212	1.784
-145	1.544	1.784	1.212	2.168
-140	1.544	1.784	1.212	2.737
-135	1.544	1.784	1.212	3.524
-130	1.544	1.784	1.212	5.685

Table: 5(d). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly Ethylene refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	**COP_{HTC}**	**COP_{ICT-1}**	**COP_{ICT-ii}**	**COP_{LTC}**
-160	1.544	1.784	1.212	1.140
-155	1.544	1.784	1.212	1.417
-150	1.544	1.784	1.212	1.769
-145	1.544	1.784	1.212	2.226
-140	1.544	1.784	1.212	2.840
-135	1.544	1.784	1.212	3.703
-130	1.544	1.784	1.212	5.001

Table: 5(e). Variation of low temperature evaporator temperature with thermal performance of four stage cascade refrigeration system using R1234ze in hot fluid circuit and R134a in first cascade intermediate circuit and R410a- in second cascade intermediate circuit and Ecofriendly R600 refrigerant in low temp circuit for ($T_{Cascade\_eva1}$= 0 °C, T_{cond}= 70 °C, $T_{cascade -eva2}$= -60 °C, $T_{cascade-eva3}$= - 120 °C,) APPROACH1=APPROACH2=APPROACH3= 10 (°C) and Compressor-Efficiency1= Compressor-Efficiency2= Compressor-Efficiency3= Compressor-Efficiency4=80%

EVA_Temp	**COP_{HTC}**	**COP_{ICT-1}**	**COP_{ICT-ii}**	**COP_{LTC}**
-160	1.544	1.784	1.212	1.255
-155	1.544	1.784	1.212	1.535
-150	1.544	1.784	1.212	1.889
-145	1.544	1.784	1.212	2.349
-140	1.544	1.784	1.212	2.966
-135	1.544	1.784	1.212	3.834
-130	1.544	1.784	1.212	5.138

4. Conclusions

The following conclusions were drawn while analyzing four stages cascade refrigeration systems.

(i) The use of R1234ze has Global warming potential potential (GWP) = 6 gives better thermal performance than R1234yf of 4GWP in the higher temperature circuit of four stage cascade refrigeration system.

(ii) There is not much performance improvements using R134a as compared with R410a in the first intermediate temperature circuit.

(iii) The second law efficiency using R600a in the low temperature evaporator circuit gives better performance than using R290 and R404a refrigerant in lower temperature circuit (LTC).

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