International Journal of Advance Research and Innovation
Vol. 2(4), Oct-Dec 2014, pp. 64-76
Doi: 10.51976/ijari.241411
www.gla.ac.in/journals/ijari

Article Info

Received: 20 Sept 2014 | Revised Submission: 10 Oct 2014 | Accepted: 20 Nov 2014 | Available Online: 15 Dec 2014

Performance Optimization of Four Stage Cascade Refrigeration Systems using Energy-Exergy Analysis in the R1234ze & R1234yf in High Temperature Circuitand Ecofriendly Refrigerants in Intermediate Ciircuits and Ethane in the Low Temperature Circuit for Food, Pharmaceutical, Chemical Industries

*R.S. Mishra**

ABSTRACT

This paper mainly deals with the exergy analysis of Four stages cascade refrigeration systems used for low temperature applications using ecofriendly refrigerants. The effect of performance parameters (i.e. approaches, condenser temperature, and temperature variations in the evaporators) on the thermal performances in terms of second law efficiency of the system (exergetic efficiency) and exergy destruction ratio (EDR) and first law efficiency (i.e. overall coefficient of performance) have been optimized thermodynamically using of R1234yf and R1234ze in the high temperature circuits and mainly thirteen ecofriendly refrigerants in the intermediates circuits and ethane It was observed that in the low temperature (between- 80 oC to -88 oC) applications. It was observed that the best combination in terms of R1234ze-R134a-R410a-ethane gives better thermal performance than using R1234yf-R134a-R410a-ethane.

Keywords: *Four stages Cascade Refrigeration, Energy- Exergy Analysis; First and Second Law Analysis; Low Temperature Applications.*

1.0 Introduction

Low-temperature refrigeration systems are typically required in the temperature range from –30°C to –100°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

**Department of Mechanical Engineering, Delhi Technological University, New Delhi, India*
(E-mail: professor_rsmishra@yahoo.co.in)

thirteen eco-friendly refrigerants in the intermediates circuits and Ethane in the low temperature applications.

2.0 Literature Review

Agnew et al [1] examined the performance of a three stage cascade refrigeration systems. Arora et al [2] analysis of a vapour compression refrigeration system with R502, R404A and R507. Bansal P.K [3] did thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system. Bhattacharyya et al [4] studied the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibility's. Cabell et al [5] Made a simplified steady-state modeling of a single stage vapors compression plant.. Calm [6] reviewed the progression of refrigerants Ecir et al [7] used ten modeling techniques within data mining process for the prediction of thermo-physical properties of refrigerants.

Jain et al [10] showed that carbon dioxide is a potential low temperature refrigerant.

Kilicarslan [12] experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system. Lee et al [13] studied thermodynamically a cascade refrigeration system that uses carbon dioxide and ammonia as refrigerants. Monte [14] calculated thermodynamic properties of R407C Pearson [16] traced the development of the old carbon dioxide systems Samant [18] design and development of two stage cascade refrigearation system using CO2 as LTC refrigerant and Propane as HTC refrigerant. Resat S.

et al [17] exergy based thermo-economic optimization of subcooled and superheated vapour compression refrigeration cycle.

Wang et al [18] potential benefits of compressor cooling. Syed M.

[19] comprehensive investigation of numerical methods in simulating a steady-state vapor compression system. Xudong Wang, [20] Investigated potential benefits of compressor cooling Zubair [21] evaluated the performance of vapour Compression System and experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system.

Experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system.

The 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 ethane in the low temperature circuits and R1234ze and R1234yf in higher temperature circuit.

3.0 Description of four Stage Cascade Systems

The following assumptions have been taken for analyzing four stages cascade vapour compression system for low temperature applications. The cooling load is considered to be 35 ―kW‖ Temperature of condenser is to be 70oC and temperature of ethane evaporator to be -88 oC, The temperature of high temperature evaporator to be 30 oC, temperature of secondary intermediate cascade evaporator is to be -50 oC, temperature of primary intermediate cascade evaporator is to be -10oC, temperature difference between cascade condenser and cascade evaporator is 10 oC in each stage.

4.0 Results and Discussions

Table-1(a) to 1(h) showing the first law efficiency of the four stage cascade refrigeration system usingR1234ze and R1234yf in the high temperature circuit and R-410a in the secondary cascade intermediate temperature circuit which is a lower temperature circuit than primary intermediate cascade circuit and ethane in the lowest temperature circuit with different thirteen ecofriendly refrigerant in primary intermediate cascade circuit. It was observed that the use of R1234ze in higher temperature circuit gives better thermodynamic performance than using R1234yf in high temperature circuit.

The best combination of four stage cascade is system is to be R1234ze-R123-R410a-ethane and R1234ze-R152a-R410a-ethane.

The R123 refrigerants containing chlorine and R152, R600 1nd R290 are also flammable in nature can be considered by adopting safety measures. R717 in toxic in nature. Therefore R1234ze-R134a-R410a- Ethane is most suitable for practical application.

Table 1(a) : R1234ze in hot fluid circuit, R134a in secondary intermediate circuit, R404a in low temperature circuit and Different refrigerant in primary intermediate circuit

Primary Circuit Ecofriendly Refrigerant	$COP_{overall}$	EDR	Exergetic Efficiency
R290	0.4669	5.705	0.1491
R404A	0.4387	6.136	0.1401
R410A	0.4601	5.804	0.1470
R134A	0.4701	5.659	0.1502
R152A	0.4822	5.493	0.1540
R600	0.4799	5.523	0.1533
R600A	0.4698	5.663	0.1501
R407C	0.4385	6.14	0.1401
R507A	0.4428	6.070	0.1415
R113	0.4863	5.437	0.1553
R123	0.4873	5.424	0.1557
R717	0.4838	5.472	0.1545
R125	0.4231	6.399	0.1352

Table 1(b) : R1234ze in Hot Fluid Circuit, R134a in Secondary Intermediate Circuit, R404a in Low Temperature Circuit and Different Refrigerant in Primary Intermediate Circuit

Primary Circuit Ecofriendly Refrigerant	COP_{Hot} fluid circuit	COP_{inte} rmediate temperatur e circuit-ii	COP_{inte} rmediate temperatur e circuit-II	COP_{low} temperature fluid circuit
R290	4.375	2.412	3.829	2.307
R404A	4.375	2.098	3.829	2.307
R410A	4.375	2.332	3.829	2.307
R134A	4.375	2.541	3.829	2.307
R152A	4.375	2.604	3.829	2.307
R600	4.375	2.574	3.829	2.307
R600A	4.375	2.448	3.829	2.307
R407C	4.375	2.096	3.829	2.307
R507A	4.375	2.141	3.829	2.307
R113	4.375	2.659	3.829	2.307
R123	4.375	2.672	3.829	2.307
R717	4.375	2.625	3.829	2.307
R125	4.375	1.944	3.829	2.307

Table 1(c) : R1234yf in Hot Fluid Circuit, R134a in Secondary Intermediate Circuit, R404a in Low Temperature Circuit and Different Refrigerant in Primary Intermediate Circuit

Primary Circuit Ecofriendly Refrigerant	$COP_{overall}$	EDR	Exergetic Efficiency
R290	0.4543	5.891	0.1451
R404A	0.4271	6.330	0.1364
R410A	0.4478	5.991	0.1430
R134A	0.4574	5.844	0.1461
R152A	0.4691	5.674	0.1498
R600	0.4669	5.705	0.1491
R600A	0.4572	5.848	0.1460
R407C	0.4269	6.333	0.1364
R507A	0.4311	6.262	0.1377
R113	0.4731	5.618	0.1511
R123	0.474	5.604	0.1514
R717	0.4706	5.653	0.1503
R125	0.4121	6.598	0.1316

Table 1(d) : R1234yf in Hot Fluid Circuit, R134a in Secondary Intermediate Circuit, R404a in Low Temperature Circuit and Different Refrigerant in Primary Intermediate Circuit

Primary Circuit Ecofriendly Refrigerant	COP_{Hot} fluid circuit	COP_{inte} rmediate temperatur e circuit-ii	COP_{inter} mediate temperature circuit-II	COP_{low} temperature fluid circuit
R290	3.972	2.412	3.829	2.307
R404A	3.972	2.098	3.829	2.307
R410A	3.972	2.332	3.829	2.307
R134A	3.972	2.451	3.829	2.307
R152A	3.972	2.604	3.829	2.307
R600	3.972	2.574	3.829	2.307
R600A	3.972	2.448	3.829	2.307
R407C	3.972	2.096	3.829	2.307
R507A	3.972	2.141	3.829	2.307
R113	3.972	2.659	3.829	2.307
R123	3.972	2.672	3.829	2.307
R717	3.972	2.625	3.829	2.307
R125	3.972	1.944	3.829	2.307

Table 1(e) : R1234ze in Hot Fluid Circuit, R134a in Primary Intermediate Circuit, R404a in Low Temperature Circuit, Different Refrigerant in Primary Intermediate Circuit

Secondary intermediate circuit Ecofriendly Refrigerants	$COP_{overall}$	EDR	Exergetic Efficiency
R290	0.4701	5.659	0.1502
R404A	0.4622	5.773	0.1476
R410A	0.4701	5.659	0.1502
R134A	0.4703	5.657	0.1502
R152A	0.4720	5.633	0.1508
R600	0.4725	5.625	0.1509
R600A	0.4703	5.656	0.1502
R407C	0.4395	6.123	0.1404
R507A	0.4659	5.720	0.1488
R113	0.4742	0.5602	0.1515
R123	0.4737	0.5.609	0.1513
R717	0.4650	5.733	0.1485
R125	0.4629	5.763	0.1479

Table 1(f) : R1234ze in Hot Fluid Circuit, R134a in Primary Intermediate Circuit, R404a in Low Temperature Circuit, Different Refrigerant in Primary Intermediate Circuit

Secondary Intermediate Circuit Ecofriendly Refrigerants	COP_H ot fluid circuit	COP_{in} termediate temperature circuit-ii	COP_{inter} mediate temperature circuit-II	COP_{low} temperature fluid circuit
R290	4.375	2.451	3.828	2.307
R404A	4.375	2.451	3.625	2.307
R410A	4.375	2.451	3.829	2.307
R134A	4.375	2.451	3.822	2.307
R152A	4.375	2.451	3.878	2.307
R600	4.375	2.451	3.894	2.307
R600A	4.375	2.451	3.834	2.307
R407C	4.375	2.451	3.116	2.307
R507A	4.375	2.451	3.717	2.307
R113	4.375	2.451	3.941	2.307
R123	4.375	2.451	3.926	2.307
R717	4.375	2.451	3.695	2.307
R125	4.375	2.451	3.642	2.307

Table 1(g) : R1234yf in Hot Fluid Circuit R134a in Primary Intermediate Circuit, R404a in Low Temperature Circuit and Different Refrigerant in Primary Intermediate Circuit

Secondary Intermediate Ecofriendly Refrigerant	$COP_{overall}$	EDR	Exergetic Efficiency
R290	0.4574	5.844	0.1461
R404A	0.4498	5.959	0.1437
R410A	0.4574	5.844	0.1461
R134A	0.4576	5.842	0.1462
R152A	0.4592	5.817	0.1467
R600	0.4598	5.809	0.1469
R600A	0.4577	5.841	0.1462
R407C	0.4279	6.316	0.1367
R507A	0.4533	5.906	0.1448
R113	0.4614	5.785	0.1474
R123	0.4609	5.792	0.1472
R717	0.4525	5.919	0.1445
R125	0.4505	5.949	0.1439

Table 1(h) : R1234yf in Hot Fluid Circuit R134a in Primary Intermediate Circuit, R404a in Low Temperature Circuit and Different Refrigerant in Primary Intermediate Circuit

Secondary intermediate Ecofriendly Refrigerant	COP_H ot fluid circuit	COP_{inte} rmediate temperature circuit-ii	COP_{inte} rmediate temperature circuit-II	COP_{low} temperature fluid circuit
R290	3.973	2.451	3.828	2.307
R404A	3.973	2.451	3.625	2.307
R410A	3.973	2.451	3.829	2.307
R134A	3.973	2.451	3.832	2.307
R152A	3.973	2.451	3.878	2.307
R600	3.973	2.451	3.894	2.307
R600A	3.973	2.451	3.834	2.307
R407C	3.973	2.451	3.116	2.307
R507A	3.973	2.451	3.717	2.307
R113	3.973	2.451	3.941	2.307
R123	3.973	2.451	3.926	2.307
R717	3.973	2.451	3.695	2.307
R125	3.973	2.451	3.642	2.307

Table 2(a) : To 2(L) Sare Showing the Effect Of Approaches (Differences in Temperature Between Cascade Condenser and Cascade Evaporators in the Various Intermediate Temperature Circuits and Low Temperature Circuit) on the First Law and Second Law Performances on the Four Stage Cascade Refrigeration Systems. It was Observed that as Approach is Decreasing the System First and Second Law Efficiency is Increasing and Exergy Destruction Ratio iDecreases

Table 2(a) : R1234ze in High Temperature Circuit Effect of Approach-1

Effect of Approach-1	$COP_{overall}$	EDR	Exergetic Efficiency
10	0.4701	5.659	0.1502
5	0.4953	5.321	0.1582
0	0.5207	5.013	0.1663

Table 2(b) : R1234ze in High temperature circuit Effect of Approach-1

Effect of Approach-1	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	4.375	2.451	3.829	2.307
5	4.375	2.783		2.307
0	4.375	3.175		2.307

Table 2(c) : R1234ze in High temperature circuit Effect of Approach-2

Effect of Approach -2	$COP_{overall}$	EDR	Exergetic Efficiency
10	0.4701	5.659	0.1502
5	4920	5.364	0.1571
0	5207	5.083	0.1644

Table 2(d) : R1234ze in High temperature circuit Effect of Approach-2

Effect of Approach -2	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	4.375	2.451	3.829	2.307
5	4.375	2.451	4.482	2.307
0	4.375	2.451	5.349	2.307

Table 2(e) : R1234ze in High temperature circuit Effect of Approach-3

Effect of Approach -3	$COP_{overall}$	EDR	Exergetic Efficiency
10	0.4701	5.659	0.1502
5	0.4920	5.303	0.1587
0	0.5247	4.966	0.1676

Table 2(f) : R1234ze in High temperature circuit Effect of Approach-3

Effect of Approach -3	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	4.375	2.451	3.829	2.307
5	4.375	2.451	3.829	2.623
0	4.375	2.451	3.829	3.013

Table 2(g) : R1234yf in High temperature circuit Effect of Approach-1

Effect of Approach-1	$COP_{overall}$	EDR	Exergetic Efficiency
10	0.4574	5.844	0.1461
5	0.4817	5.499	0.1539
0	0.5062	5.185	0.1617

Table 2(h) : R1234yf in High temperature circuit Effect of Approach-1

Effect of Approach-1	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	3.973	2.451	3.829	2.307
5	3.973	2.783	3.829	2.307
0	3.973	3.175	3.829	2.307

Table 2(i) : R1234yf in High temperature circuit Effect of Approach-2

Effect of Approach-2	$COP_{overall}$	EDR	Exergetic Efficiency
10	0.4574	5.844	0.1461
5	0.4817	5.499	0.1539
0	0.5062	5.185	0.1617

Table 2(j) : R1234yf in High temperature circuit Effect of Approach-2

Effect of Approach-2	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	3.973	2.451	3.829	2.307
5	3.973	2.783	3.829	2.307
0	3.973	3.175	3.829	2.307

Table 2(k) : R1234yf in High temperature circuit Effect of Approach-3

Effect of Approach-3	$COPoverall_t$	EDR	Exergetic Efficiency
10	0.4574	5.844	0.1461
5	0.4831	5.481	0.1543
0	0.5103	5.138	0.1629

Table 2(l) : R1234yf in High temperature circuit Effect of Approach-3

Effect of Approach-3	COP_H ot fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
10	3.973	2.451	3.829	2.307
5	3.973	2.451	3.829	2.623
0	3.973	2.451	3.829	3.013

Table 3(a) : Performance Variation with Condenser Temperature of Four Stage Cascade Vapours Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tcond (°C)	$COP_{overall}$	EDR	Exergetic Efficiency
80	0.4204	6.447	0.1343
75	0.4459	6.02	0.1424
70	0.4701	5.659	0.1502
65	0.4933	5.347	0.1576
60	0.5157	5.07	0.1647
55	0.5378	4.822	0.1718
50	0.5595	4.595	0.1787
45	0.5812	4.387	0.1856
40	0.6029	4.193	0.1926

Table 3(b) : Performance Variation with Condenser Temperature of Four Stage Cascade Vapours Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tcond (°C)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
80	3.054	2.451	3.829	2.307
75	3.651	2.451	3.829	2.307
70	4.375	2.451	3.829	2.307
65	5.282	2.451	3.829	2.307
60	6.467	2.451	3.829	2.307
55	8.10	2.451	3.829	2.307
50	10.52	2.451	3.829	2.307
45	14.52	2.451	3.829	2.307
40	22.47	2.451	3.829	2.307

Table 3(c) : Performance Variation with Condenser Temperature of Four Stage Cascade Vapours Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tcond (^{0}C)	COP $_{\_overall}$	System EDR	Exergetic Efficiency
80	0.3945	6.935	0.1260
75	0.4279	6.316	0.1367
70	0.4574	5.844	0.1461
65	0.4844	5.463	0.1547
60	0.5096	5.143	0.1628
55	0.5337	4.866	0.1705
50	0.5569	4.622	0.1779
45	0.5796	4.401	0.1851
40	0.6021	4.20	0.1923

Table 3(d) : Performance Variation with Condenser Temperature of Four Stage Cascade Vapours Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tcond (^{0}C)	COP_{Hot} fluid circuit	COP_{inte} rmediate temperatur e circuit-ii	COP_{inte} rmediate temperatur e circuit-II	COP_{low} temperature fluid circuit
80	2.573	2.451	3.829	2.307
75	3.216	2.451	3.829	2.307
70	3.973	2.451	3.829	2.307
65	4.904	2.451	3.829	2.307
60	6.106	2.451	3.829	2.307
55	7.748	2.451	3.829	2.307
50	10.17	2.451	3.829	2.307
45	14.14	2.451	3.829	2.307
0.1923	22.02	2.451	3.829	2.307

From Tables-3: it was observed that as condenser temperature decreases overall COP of system (First law efficiency of system) increases and System EDR is decreases and also second law efficiency (exergetic efficiency) increases. While First law efficiency of hot fluid circuit is increases. There will not be effect on other circuit first law efficiencies. The exergetic efficiency and Overall COP of system using R1234ze is higher than using R1234yf in the high temperature circuit while system EDR increases. As decreasing High temperature evaporator temperature, the first law efficiency (i.e. overall cop of system) and second law efficiency (i.e. exergetic efficiency of whole system) is is increasing up to maximum value at the evaporator temperature of 25oC and then decreases rapidly.

As decreasing High temperature evaporator temperature the system EDR first decreasing up to decreasing evaporator temperature and then further constant and then increasing and optimum becomes at evaporator temperature at 25oC in both cases using R1234yf and R1234ze in the high temperature circuit. However Cop of hot fluid circuit is decreases and COP of primary intermediate fluid circuit is increases.

Table 4(a) : Performance Variation with Evaporator Temperature in the High Temperature Circuit of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator High temp circuit (^{0}C)	COP $_{Overall}$	System EDR	Exergetic Efficiency
50	0.4331	6.229	0.1383
45	0.4476	5.995	0.1430
40	0.4584	5.829	0.1464
35	0.4659	5.720	0.1488
30	0.4701	5.659	0.1502
25	0.4713	5.642	0.1505
20	0.4696	5.666	0.150
15	0.4652	5.729	0.1486
10	0.4583	5.831	0.1464
5	0.4489	5.974	0.1434
0	0.4375	6.158	0.1397

Table 4(b) : Performance Variation with Evaporator Temperature in the High Temperature Circuit of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator High temp circuit (°C)	COP Hot fluid circuit	COP_{inte} rmediate temperature circuit-ii	COP_{interm} ediate temperature circuit-II	COP_{low} temperature fluid circuit
50	10.53	1.489	3.829	2.307
45	8.06	1.61	3.829	2.307
40	6.417	1.914	3.829	2.307
35	5.248	2.165	3.829	2.307
30	4.375	2.451	3.829	2.307
25	3.699	2.783	3.829	2.307
20	3.161	3.175	3.829	2.307
15	2.723	3.646	3.829	2.307
10	2.361	4.229	3.829	2.307
5	2.056	4.97	3.829	2.307
0	1.791	5.951	3.829	2.307

Table 4(c) : Performance Variation with Evaporator Temperature in the High Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator High temp circuit (°C)	COP_Overall	EDR	Exergetic Efficiency
50	0.4291	6.295	0.1371
45	0.4419	6.085	0.1412
40	0.4507	5.946	0.1440
35	0.4559	5.868	0.1456
30	0.4574	5.844	0.1461
25	0.4557	5.870	0.1456
20	0.4507	5.946	0.1440
15	0.4428	6.070	0.1414
10	0.4321	6.245	0.1380
5	0.4189	6.474	0.1338
0	0.4033	6.762	0.1288

Table 4(d) : Performance Variation with Evaporator Temperature in the High Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator High temp circuit (°C)	COP_H ot fluid circuit	COP_{inte} rmediate temperature circuit-ii	COP_{inte} rmediate temperature circuit-II	COP_{low} temperature fluid circuit
50	9.804	1.489	3.829	2.307
45	7.462	1.690	3.829	2.307
40	5.906	1.914	3.829	2.307
35	4.799	2.165	3.829	2.307
30	3.973	2.451	3.829	2.307
25	3.333	2.783	3.829	2.307
20	2.825	3.175	3.829	2.307
15	2.413	3.646	3.829	2.307
10	2.072	4.229	3.829	2.307
5	1.786	4.970	3.829	2.307
0	1.544	5.951	3.829	2.307

As evaporator temperature decreases, the first law efficiency (overall COP) and second law efficiency (exergetic efficiency) of the system is increases and maximum efficiency is obtained at evaporator temperature of -10 oC and also cop of primary intermediate temperature circuit is decreases and secondary intermediate temperature circuit COP is increases.

Tablex 5(a) : Performance Variation with Cascade Evaporator Temperature in the Primary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (°C)	$COP_{overall}$	EDR	Exergetic Efficiency
20	0.4436	6.057	0.1417
15	0.4546	5.886	0.1452
10	0.4633	5.757	0.1480
5	0.4696	5.666	0.150
0	0.4738	5.607	0.1513
-5*	0.4758	5.579	0.1520
-10*	0.4759	5.579	0.1520
-15	0.4739	5.609	0.1514
-20	0.4701	5.659	0.1502
-25	0.4646	5.739	0.1484
-30	0.4573	5.485	0.1461
-35	0.4485	5.980	0.1433
-40	0.4383	6.143	0.140

Table 5(b) : Performance Variation with Cascade Evaporator Temperature in the Primary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (°C)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
20	4.375	10.33	1.460	2. .307
15	4.375	7.951	1.629	2. .307
10	4.375	6.367	1.818	2. .307
5	4.375	5.239	2.032	2. .307
0	4.375	4.396	2.278	2. .307
-5*	4.375	3.744	2.565	2. .307
-10*	4.375	3.224	2.905	2. .307
-15	4.375	2.801	3.317	2. .307
-20	4.375	2.451	3.829	2. .307
-25	4.375	2.157	4.482	2. .307
-30	4.375	1.907	5.349	2. .307
-35	4.375	1.691	6.559	2. .307
-40	4.375	1.505	8.368	2. .307

Table 5(c) : Performance Variation with Cascade Evaporator Temperature in the Primary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (°C)	$COP_{overall}$	EDR	Exergetic Efficiency
20	0.4319	6.249	0.1379
15	0.4425	6.075	0.1413
10	0.4509	5.944	0.1440
5	0.4570	5.851	0.1460
0	0.4610	5.791	0.1473
-5*	0.4630	5.762	0.1479
-10*	0.4630	5.762	0.1479
-15	0.4611	5.789	0.1473
-20	0.4574	5.844	0.1461
-25	0.4521	5.925	0.1444
-30	0.4451	6.034	0.1422
-35	0.4366	6.170	0.1395
-40	0.4267	6.336	0.1363

Table 5(d) : Performance Variation with Cascade Evaporator Temperature in the Primary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (°C)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
20	4.375	10.33	1.460	2. .307
15	4.375	7.951	1.629	2. .307
10	4.375	6.367	1.818	2. .307
5	4.375	5.239	2.032	2. .307
0	4.375	4.396	2.278	2. .307
-5*	4.375	3.744	2.565	2. .307
-10*	4.375	3.224	2.905	2. .307
-15	4.375	2.801	3.317	2. .307
-20	4.375	2.451	3.829	2. .307
-25	4.375	2.157	4.482	2. .307
-30	4.375	1.907	5.349	2. .307
-35	4.375	1.691	6.559	2. .307
-40	4.375	1.505	8.368	2. .307

Table 6(a) : Performance Variation with Cascade Evaporator Temperature in the Secondary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (°C)	$COP_{overall}$	EDR	Exergetic Efficiency
-70	0.4631	5.76	0.1479
-65	0.4674	5.697	0.1493
-60	0.4701	5.66	0.1502
-55***	0.4710	5.647	0.1504
-50	0.4701	5.659	0.1502
-45	0.4675	5.696	0.1493
-40	0.4631	5.760	0.1479
-35	0.4569	5.851	0.1460
-30	0.4490	5.973	0.1434

Table 6(b) : Performance Variation with Cascade Evaporator Temperature in the Secondary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (^{0}C)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
-70	4.375	2.451	2.116	4.161
-65	4.375	2.451	2.426	3.508
-60	4.375	2.451	2.798	3.013
-55***	4.375	2.451	3.255	2.603
-50	4.375	2.451	3.829	2.307
-45	4.375	2.451	4.568	2.046
-40	4.375	2.451	5.556	1.825
-35	4.375	2.451	6.942	1.636
-30	4.375	2.451	9.022	1.42

As increasing evaporator temperature overall cop is increases while System EDR first decreases while second law efficiency is increases. The maximum efficiency was obtained at -55 oC and then decreases as increasing evaporator temperature. Secondary intermediate circuit COP is increases while low temperature circuit COP is decreases. Table-6(b):

Performance variation with cascade evaporator temperature in the secondary intermediate temperature circuit temperature of four stage cascade vapour compression refrigeration system using R1234yf in High temperature circuit and R404a in the low temperature circuit

Table 6(c) : Performance Variation with Cascade Evaporator Temperature in the Secondary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (^{0}C)	$COP_{overall}$	EDR	Exergetic Efficiency
-70	0.4507	5.946	0.1440
-65	0.4549	5.883	0.1453
-60	0.4574	5.845	0.1461
-55***	0.4583	5.831	0.1464
-50	0.4574	5.844	0.1461
-45	0.4949	5.882	0.1453
-40	0.4507	5.946	0.1440
-35	0.4447	6.039	0.1421
-30	0.4370	6.163	0.1396

Table 6(d) : Performance Variation with Cascade Evaporator Temperature in the Secondary Intermediate Temperature Circuit Temperature of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (^{0}C)	COP_{Hot} fluid circuit	COP_{inter} mediate temperature circuit-ii	COP_{inter} mediate temperature circuit-II	COP_{low} temperature fluid circuit
-70	0.3973	2.451	2.116	4.161
-65	0.3973	2.451	2.426	3.508
-60	0.3973	2.451	2.798	3.013
-55*	0.3973	2.451	3.255	2.603
-50	0.3973	2.451	3.829	2.307
-45	0.3973	2.451	4.568	2.046
-40	0.3973	2.451	5.556	1.825
-35	0.3973	2.451	6.942	1.636
-30	0.3973	2.451	9.022	1.42

Table 7(a) : Performance Variation with Low Temperature Evaporator Temperature in the Of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (^oC)	$COP_{overall}$	EDR	Exergetic Efficiency
-90	0.4701	5.659	0.1502
-85	0.5024	5.14	0.1629
-80	0.5358	4.676	0.1762
-75	0.5701	4.259	0.1902
-70	0.6056	3.884	0.2048
-65	0.6421	3.546	0.220
-60	0.6796	3.239	0.2359
-55	0.7181	2.962	0.2524

Table 7(b) : Performance Variation with Low Temperature Evaporator Temperature in the Of Four Stage Cascade Vapour Compression Refrigeration System Using R1234ze in High Temperature Circuit and R404a in the Low Temperature Circuit

Tevaporator (^oC)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
-90	4.375	2.451	3.829	2.307
-85	4.375	2.451	3.829	2.697
-80	4.375	2.451	3.829	3.185
-75	4.375	2.451	3.829	3.812
-70	4.375	2.451	3.829	4.645
-65	4.375	2.451	3.829	5.804
-60	4.375	2.451	3.829	7.525
-55	4.375	2.451	3.829	10.35

Table 7(c) : Performance Variation with Low Temperature Evaporator Temperature in the Of Our Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit And R404a in the Low Temperature Circuit

Tevaporator (^oC)	$COP_{overall}$	EDR	Exergetic Efficiency
-90	0.4574	5.844	0.1461
-85	0.4881	5.314	0.1584
-80	0.5207	4.840	0.1712
-75	0.5538	4.415	0.1847
-70	0.5878	4.032	0.1987
-65	0.6228	3.686	0.2134
-60	0.6587	3.373	0.2287
-55	0.6956	3.09	0.2445

Table 7(d) : Performance Variation with Low Temperature Evaporator Temperature in the of Four Stage Cascade Vapour Compression Refrigeration System Using R1234yf in High Temperature Circuit And R404a in the Low Temperature Circuit

Tevaporator (^oC)	COP_{Hot} fluid circuit	$COP_{intermediate}$ temperature circuit-ii	$COP_{intermediate}$ temperature circuit-II	COP_{low} temperature fluid circuit
-90	3.972	2.451	3.829	2.307
-85	3.972	2.451	3.829	2.697
-80	3.972	2.451	3.829	3.185
-75	3.972	2.451	3.829	3.812
-70	3.972	2.451	3.829	4.645
-65	3.972	2.451	3.829	5.804
-60	3.972	2.451	3.829	7.525
-55	3.972	2.451	3.829	10.35

Table-7(a) to 7(d) are showing the effect of low temperature evaporator on the system first and second law performances and system exergy destruction ratio and various circuit first law performances . as low temperature evaporator temperature is decreasing , the first law and second law efficiencies are increasing and exergy destruction ratio is decreasing and high temperature circuit first law performances in increasing.

References

[1] B. Agnew, et.a., A finite time analysis of a cascade refrigeration system using alternative refrigerants, Applied Thermal Engineering, 24, 2004, 2557–2565

[2] Akhilesh Arora et.al, Theoretical analysis of a vapour compression refrigeration system with R502, R404A and R507A, International Journal of Refrigeration, 31, 2008, 1–8

[3] P. K. Bansal, Thermodynamic analysis of an R744–R717 cascade refrigeration system, international journal of refrigeration 31, 2008, 45-54.

[4] Souvik Bhattacharyya, Exergy maximization of cascade refrigeration cycles and its numerical verification for a trans critical CO2-C3H8 system, International Journal of Refrigeration, 30, 2007, 624-632

[5] R. Cabello, Simplified steady-state modelling of a single stage vapour compression plant. Model development and validation, Applied Thermal Engineering, 25, 2005, 1740–1752

[6] James M. Calm, The next generation of refrigerants – Historical review, considerations, and outlook, International Journal of Refrigeration, 31, 2008, 1123-1133.

[7] Ecir Ugˇur Küçüksille, Data mining techniques for thermophysical properties of refrigerants, Energy Conversion and Management, 2008

[8] J. Guilpart, Comparision of the performance of different ice slurry types depending on the application temperature, International Journal of Refrigeration, 29, 2006, 781-788

[9] M. Herbert et.al, On the Performance of R22 and A HfC/HC Refrigerant Mixture over A Range of Charge Quantity In A Window Air conditioner, Acre-conf, 2009

[10] P. K. Jain, Cascade Systems: Past, Present, and Future, 2007 ASHRAE Trans. 113(1), 245-252(DA-07-027)

[11] Jonathan Winkler, Comprehensive investigation of numerical methods in simulating a steady-state vapor compression system, International Journal of Refrigeration, 31, 2008, 930-942

[12] A. Kilicarslan, An experimental investigation of a different type vapor compression cascade refrigeration system, Applied Thermal Engineering, 24, 2004 2611–2626

[13] F. De. Monte, Calculation of thermodynamic properties of R407C and R410A by the Martin–Hou equation of state — part II: technical interpretation, International Journal of Refrigeration, 25, 2002, 314–329

[14] F. Monte, de Calculation of thermodynamic properties of R407C and R410A by the Martin–Hou equation of state - part I: theoretical development, International Journal of Refrigeration, 25, 2002, 306–313.

[15] Mukhopadhyay, CO2–C3H8 cascade refrigeration–heat pump system: Heat exchanger inventory optimization and its numerical verification, international journal of refrigeration, 31, 2008, 1207-1213

[16] D. Peter, Refrigeration of the Future for Air Conditioning, Air conditioning and Refrigeration Journal, 8, 2008, 20-27

[17] Reşat Selbaş, Önder Kızılkan, Arzu Şencan, Thermoeconomic optimization of subcooled and superheated vapor compression refrigeration cycle, Energy, 31, 2006, 2108–2128.

[18] Samant Maj, Design and Development of two stage cascade refrigeration system, Mechanical Engineering Deparment, IIT Delhi, 2006

[19] Tzong-Shinge.al, Thermodynamic analysis of optimal condensing temperature of cascade-condenser in CO2/NH3 cascade refrigeration systems, International Journal of Refrigeration, 29, 2006, 1100-1108

[20] Xudong Wang, Yunho Hwang, Reinhard Radermacher, Investigation of potential benefits of compressor cooling, Applied Thermal Engineering, 28, 2008, 1791–1797

[21] S. M. Zubair, Performance evaluation of Vapour Compression System, International Journal of Refrigeration, 22, 1999, 235-243

[22] C. P. Arora, Refrigeration and Airconditioning, Second edition, New Delhi: Tata McGraw Hill, 2002