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Modelling of two stages vapour compression cascade refrigeration system using ecofriendly HFO refrigerants for reducing global warming and ozone depletions

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Abstract

This paper mainly deals the performance of two stage (R1234ze-R1234yf) cascade refrigeration system. The effect of condenser temperature of the high temperature circuit on the thermodynamic first law and second law performances of a two stages cascade vapour compression system with refrigerant HFO1234ze as an alternative to HFC134a and HFO 1234yf as an alternative of HFC134a in low temperature circuit is evaluated. The condenser temperature has been varied between 35°C and 60°C to evaluate the effect of system exergy destruction ratio (EDR_system) and exergetic efficiency, overall system coefficient of performance (COP_Overall) and cycle coefficient of performances (COP_HTC_R1234ze &COP_LTC_R1234yf). Similarly the effect of low temperature evaporator (from -40^{0}C to -50^{0}C) and effect of temperature overlapping (from 0 to 10) and temperature variation of cascade evaporator (from -20^{0}C to 20^{0}C) on system performance have been evaluated.

Keywords: HFO Refrigerants, Two stage Cascade refrigeration, First & Second law performances

1. Introduction

The most commonly used refrigerants in recently used are R134a, R410a and R407c which because of their high GWP have been either phased out in 2030, search to find alternative working fluids gained more interest in the recent few years. The HFO1234yf & HFO1234ze were found to be a suitable low GWP ecofriendly refrigerants for replacing R134a because HFC134a has very high GWP which is a matter of environmental concern and is being successfully used in small equipment like domestic refrigerators. This paper mainly deals with the thermodynamic performance of two stage cascade refrigeration system using HFO refrigerantsR-1234ze in high temperature circuit and HFO1234yf in the low temperature circuit.. The effect of temperature overlapping ion the thermodynamic performance is studies in details

1.1 Eco friendly HFO-1234yf

HFO stands for hydrofluoro olefin. HFO-1234yf is a low global warming potential (GWP) refrigerant for use in automotive air-conditioning systems. HFO-1234yf has a chemical structure of CF3CF= CH2

HFO-1234yf is different from HFC-134a due to following reasons.

- HFC-134a is a hydrofluorocarbon refrigerant, while HFO-1234yf is a hydrofluoro-olefin refrigerant. HFC refrigerants are composed of hydrogen, fluorine and carbon atoms connected by single bonds between the atoms.
- HFO refrigerants are composed of hydrogen, fluorine and carbon atoms, but contain at least one double bond between the carbon atoms.

While HFC-134a has been one of the global standard automotive air-conditioning refrigerants, it will not meet the EU F-gas regulation. HFO-1234yf is a low GWP refrigerant for use in automotive air-conditioning. HFO-1234yf has a GWP of 4 based on a 100-year time horizon, and will meet the EU F-gas regulation. HFO-1234yf has physical properties similar to HFC-134a. Therefore, HFO-1234yf has the potential to be used in current HFC-134a systems with minimal system modifications. The potential exists for direct substitution of HFO-1234yf into existing HFC-134a in the automotive air-conditioning systems with minimal modification. HFO-1234yf also has the potential as a retrofit refrigerant in existing HFC-134a in the vapour compression refrigeration systems. Life Cycle results show that HFO-1234yf has improved performance as compared with HFC-134a. It has very low direct contribution to climate change and lower indirect contribution to climate change versus the current refrigerant HFC-134a. With further efficiency improvements, indirect

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contribution to climate change can be reduced further. Table-1-3 show the properties Comparison of HFO 1234yf and R134a.

Table1: Thermal properties Comparison of HFO 1234yf and R134a.

Properties	HFO-1234yf	HFC-134a
Boiling Point, (T_b)	-29°C	-26°C
Critical Point, Tcritical	95°C	102°C
P_{vap}, MPa at (25°C)	0.677	0.665
P_{vap}, MPa at (80°C)	2.44	2.63
GWP (100 ITH)	4	1410
ODP	0	0

Table2: Properties of ecofriendly refrigerants [10-11]

Properties	R1234ze	R134a
Molecular weight, kg/mol	114	102
Boiling point at 101.3 kPa, °C	-18,95	-26,06
Critical temperature,°C	109.4	101,1
Critical pressure, bar	36.4	40.6
Latent heat of vaporization at 30 °C, kJ/kg	162.9	173.1
Critical density, kg/m^3	489	515.3

Direct contribution of following refrigerants to global warming is lower than that of R134a as shown in Table-3

Table 3 – Lifetime and global warming potential of some HFOs [11].

Refrigerant	Chemical formula	Lifetime , days	GWP (100 yr.)
HFO-1234yf	CF3CF=CH2	10.5	<4
HFO-1234ze	trans-CF3CH=CHF	16.4	<6
HFO-1234ze	CF3CH=CHF(Z)	10.0	<1

The main characteristics of HFO-1234yf are:
Low toxicity, Low GWP; GWP = 4, Zero ozone-depletion potential, Low total contribution to climate change, same operating pressures as current HFC-134a system. The environmental properties of HFO-1234yf as follow:
HFO-1234yf has a GWP of 4 based on a 100-year integrated time horizon. More importantly, that HFO-1234yf has lower total contribution to climate change than HFC-134a, because HFO-1234yf has zero ozone-depletion potential. Therefore, HFO-1234yf will not impact the ozone layer**.**

2. Literature Review

Jarall [1] compared the HFO1234yf with HFC134a in a refrigeration plant using 550 W nominal output power of hermetic rotary compressor and found that HFO1234yf gives less(3.4–13.7%) refrigerating capacity, (0.35–11.88%) ,COP, and (0–6.3%) compressor efficiency in comparison to HFC134a. Karber et al. [2] compared energy consumptions of refrigerants HFO1234yf and HFO1234ze for replacement of R134a in domestic refrigerators and found that the HFO1234yf consumes 2.7% and 1.3% higher energy whereas HFO1234ze showed 16% and 5.4% lower energy consumption than HFC134a. Reasor et al. [3] observed that the refrigerant R1234yf has a low GWP of 4 and refrigerant R1234ze has a low GWP of 6 in comparison to 1430 for R134a have similar thermodynamic properties to the R134a which make R1234yf and R1234ze as a replacement for R134a.. Calm [4] in his review, discussed the impact the next generation of refrigerants i.e. fourth-generation refrigerants such as HFO1234yf and HFO1234ze have low GWP and zero ODP. .Lee and Jung [5] studied the performance of HFO1234yf and HFC134a and found that the COP, capacity, and compressor discharge temperature for HFO1234yf are slightly lower 2.7% COP, 4.0% Capacity, and 6.5°Cdischarge temperature. Mishra [6-7] computed 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. Agnew et al [3] examined the performance of a cascade refrigeration systems
Bansal P.K [8] did thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system. Bhattacharyya et al [9] studied the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibility's.
Kilicarslan [10] experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system. Lee et al [11] studied thermodynamically a cascade refrigeration system that uses carbon dioxide and ammonia as refrigerants. Samant [8] design and development of two stage cascade refrigeration system using CO2 as LTC refrigerant and Propane as HTC refrigerant. Zubair [12] 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 S. Fukuda[13] suggested the use of R1234ze(e) for heat pump application to replace R410a. The above investigators have not studies in second law performance on cascade refrigeration system.

3. System Description

In the two stages vapour compression cascade refrigeration systems 1, 3, 3, 3-Tetrafluoropropene (HFO-1234ze) is known as hydrofluoroolefin was used in the high temperature circuit in the condenser temperature range of 40oC to 60^{0}C and evaporator temperature range of -20^{0}C to 20^{0}C. The HFO R1234ze being a stable refrigerant very low global-warming potential (GWP < 7) for high temperature application used as a "fourth generation" refrigerant to replace R-134a. [1] For low temperature applications, ecofriendly refrigerants such as Carbon dioxide, propane, butane, R152a and HFO1234yf has seen as potential candidates to substitute R134a. Finally, HFO1234yf has been chosen due to its properties, which allow replacing R134a ecofriendly. The use of R-134a is being phased out because of its high global-warming potential. HFO-

1234yf has zero ozone-depletion potential (ODP=0) and a very low global-warming potential (GWP < 5), are known for low-temperature refrigeration circuit.

4. Results and Discussions

The following assumptions have been taken for analyzing two stages cascade vapour compression system for low temperature applications. The cooling load is considered to be 70 kW‖ Temperature of condenser is to be 50^0C and temperature of R1234yf evaporator to be -50^0C, The temperature of high temperature evaporator to be 0^0 C, The temperature overlapping in terms of approach (i.e.) temperature difference between cascade condenser using R1234yf and cascade evaporator using R1234ze is known as approach which is equal to 10^0C.

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 is decreases 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 R134a in the high temperature circuit while system EDR increases.

From Table-4(a). 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 increasing up to maximum value at the evaporator temperature of 25^0C 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 25^0C 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

As cascade 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 0^0C and also cop of primary intermediate temperature circuit is decreases and secondary intermediate temperature circuit COP is increases as shown in Tables-4(a)-4(b) respectively.

Table-5(a)-(b) show 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.

Table-4(a) Performance parameters variations with variation of temperature of HTC Evaporator using R1234ze in HTC Circuit and R1234yf in LTC circuit

T_EVA (^{0}C)	COPOverall	EDRSystem	ETASecond	COP_HTC	COP_LTC	HTC Mass flow rate (Kg/sec)	LTC Mass flow rate (Kg/sec)
-20	1.889	4.296	0.1888	1.86	3.777	0.8884	0.4892
-15	1.631	4.204	0.1921	2.117	3.261	0.8864	0.5115
-10	1.422	4.14	0.1946	2.42	2.844	0.8867	0.5364
-5	1.249	4.102	0.1960	2.78	2.497	0.8895	0.5642
0	1.102	4.094	0.1963	3.215	2.204	0.8951	0.5955
5	0.9753	4.118	0.1954	3.75	1.951	0.9039	0.6312
10	0.8646	4.177	0.1932	4.421	1.729	0.9166	0.6720
15	0.7663	4.337	0.1874	5.287	1.533	0.9338	0.7193
20	0.6781	4.661	0.1768	6.446	1.356	0.9565	0.7747

Table-4(b) Performance parameters variations with variation of temperature of HTC Evaporator using R1234ze in HTC Circuit and R1234yf in LTC circuit

T_EVA (^{0}C)	COP Overall	Total Irreversibility (kW)	Input Exergy (kW)	Irreversibility Ratio	HTC Irreversibility	LTC Irreversibility
-20	1.889	101.1	124.7	0.8112	49.54	51.6
-15	1.631	98.98	122.5	0.8079	45.8	53.19
-10	1.422	97.46	121.0	0.8054	42.35	55.11
-5	1.249	96.58	120.1	0.8040	39.17	57.41
0	1.102	96.38	119.9	0.8037	36.22	23.54
5	0.9753	96.94	120.5	0.8046	33.49	63.45
10	0.8646	98.34	120.9	0.8068	30.94	67.4
15	0.7663	102.1	125.6	0.8126	28.55	73.54
20	0.6781	109.7	133.3	0.8234	26.32	83.42

Table-5(a) Performance parameters variations with variation of temperature of LTC Evaporator using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

T_EVA (^{0}C)	COP Overall	EDR System	ETA Second	COP_HTC	COP_LTC	HTC Mass flow rate (Kg/sec)	LTC Mass flow rate (Kg/sec)
-50	1.102	4.094	0.1963	3.215	2.204	0.8951	0.5955
-45	1.264	4.099	0.1961	3.215	2.529	0.8592	0.5787
-40	1.461	4.123	0.1952	3.215	2.921	0.8264	0.5628
-35	1.702	4.171	0.1934	3.215	3.404	0.7965	0.5479
-30	2.006	4.246	0.1906	3.215	4.011	0.7692	0.5338

Table-5(b) Performance parameters variations with variation of temperature of LTC Evaporator using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

T_EVA (^{0}C)	COP Overall	Total Irreversibility (kW)	Input Exergy (kW)	Irreversibility Ratio	HTC Irreversibility	LTC Irreversibility
-50	1.102	90.38	119.9	0.8037	36.22	60.16
-45	1.264	88.09	109.6	0.8039	34.7	53.32
-40	1.461	80.52	100.0	0.8048	33.45	47.07
-35	1.702	73.6	91.25	0.8066	32.24	41.37
-30	2.006	67.27	83.12	0.8094	31.13	36.14

Table-6(a) Performance parameters variations with variation of temperature of condenser temperature using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

Cond Temp (^{0}C)	COP Overall	EDR System	ETA Second	COP_HTC	COP_LTC	HTC Mass flow rate (Kg/sec)	LTC Mass flow rate (Kg/sec)
60	1.102	4.676	0.1762	2.407	2.204	1.034	0.5955
55	1.102	4.369	0.1862	2.779	2.204	0.9588	0.5955
50	1.102	4.094	0.1963	3.215	2.204	0.8951	0.5955
45	1.102	3.844	0.2065	3.737	2.204	0.840	0.5955
40	1.102	3.613	0.2168	4.379	2.204	0.7922	0.5955

Table-6 (b) Performance parameters variations with variation of temperature of condenser temperature using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

Cond Temp (^{0}C)	COP Overall	Total Irreversibility (kW)	Input Exergy (kW)	Irreversibility Ratio	HTC Irreversibility	LTC Irreversibility
60	1.102	110.10	133.6	0.8238	49.93	60.16
55	1.102	102.9	126.4	0.8138	42.71	60.16
50	1.102	96.38	119.9	0.8037	36.22	60.16
45	1.102	90.4	114.0	0.7975	30.33	60.16
40	1.102	85.06	108.6	0.7832	24.89	60.16

Table-7(a) Performance parameters variations with variation of temperature overlapping in terms of approach of cascade condenser Evaporator temperatures using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

Approach (^{0}C)	COP Overall	EDR System	ETA Second	COP_HTC	COPLTC	HTC Mass flow rate (Kg/sec)	LTC Mass flow rate (Kg/sec)
10	1.104	4.094	0.1963	3.215	2.204	0.8951	0.5955
8	1.158	4.022	0.1991	3.215	2.316	0.8816	0.5825
6	1.217	3.953	0.2019	3.215	2.435	0.8686	0.5702
4	1.281	3.889	0.2045	3.215	2.562	0.8560	0.5584
2	1.349	3.828	0.2071	3.215	2.698	0.8439	0.5471
0	1.422	3.771	0.2096	3.215	2.844	0.8322	0.5364

Table-7(b) Performance parameters variations with variation of temperature overlapping in terms of approach of cascade condenser Evaporator temperatures using low GWP R1234ze in HTC Circuit and low GWP R1234yf in LTC circuit

Approach (^{0}C)	COP Overall	Total Irreversibility (kW)	Input Exergy (kW)	Irreversibility Ratio	HTC Irreversibility	LTC Irreversibility
10	1.104	96.38	119.9	0.8037	36.22	60.16
8	1.158	94.68	118.2	0.8009	35.68	59.0
6	1.217	93.7	116.6	0.7981	35.15	57.92
4	1.281	91.56	115.1	0.7955	34.64	56.92
2	1.349	90.13	113.7	0.7929	34.15	55.98
0	1.422	88.79	112.3	0.7904	33.68	55.11

5. Conclusion

The thermodynamic analysis is carried out to find the first law efficiency in terms of coefficient of performance, exergy destruction ratio and exergetic efficiency and cycle COPs.
As pure substance R1234ze is seen as the R134a replacement. However, its volumetric refrigerating capacity is below that of R134a and It\s boiling point is also higher than that of R134a in the high temperature circuit. The Following conclusions were made:

(i) For high temperature circuit the R1234ze is a better alternative for replacing R134a. and
(ii) For low temperature circuit, HFO1234yf is best alternative for replacing R134a.

References

[1] S. Jarall, “Study of refrigeration system with HFO-1234yf as a working fluid: etude sur un système frigorifique utilisant le HFO-1234yf comme fluide actif,” International Journal of Refrigeration, vol. 35, no. 6, pp. 1668–1677, 2012.

[2] K. M. Karber, O. Abdelaziz, and E. A. Vineyard, “Experimental performance of R-1234yf and R1234ze as drop in replacements for R134a in domestic refrigerator,” in Proceedings of the International Refrigeration and Air Conditioning Conference, Paper no. 1228, Purdue University, West Lafayette, Ind, USA, 2012.

[3] P. Reasor, V. Aute, and R. Radermacher, “Refrigerant R1234yf performance comparison investigation,” in Proceedings of the International Refrigeration and Air Conditioning Conference at Purdue, Paper No. 1085, West Lafayette, Ind, USA, July 2010.

[4] J. M. Calm, “The next generation of refrigerants—historical review, considerations, and outlook,” International Journal of Refrigeration, vol. 31, no. 7, pp. 1123–1133, 2008

[5] Y. Lee and D. Jung, “A brief performance comparison of R1234yf and R134a in a bench tester for automobile applications,” Applied Thermal Engineering, vol. 35, no. 1, pp. 240–242, 2012

[6] R.S. Mishra[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” International Journal of Advance Research and Innovation, ISSN 2347 - 3258 , Volume 2, Issue 4 , page-701-709.

[7] R.S. Mishra[2014] [2014] Use of Hydrocarbons in Low Temperature Circuit in Terms of First Law and Second Law Efficiency of Four Stage Cascade Refrigeration of Semen Preservation” International Journal of Advance Research and Innovation, ISSN 2347 - 3258 , Volume 2, Issue 4, page-725-731.

[8] B. Agnew, et.a.,[2004] A finite time analysis of a cascade refrigeration system using alternative refrigerants, Applied Thermal Engineering, Vol-24 , page. 2557–256.

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

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

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

[12] F. Lee. [2002] 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, , 314– 329.

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

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

[15] DuPont, "DuPont [2012]Fluorochemicals Affirms Confidence that HFO-1234yf Can Be Safely Used as an Automotive Refrigerant," 18 Oct 2012. [Online]. Available: goo.gl/cyyoS

[16] Honeywell, "Honeywell Solstice[2015]Lower-Global-Warming refrigerants approved by leading global compressor suppliers," 18 June 2015. [Online]. Available: bit.ly/1LedeT

[17] S. Fukuda, C. Kondou, N. Takata and S. Koyama, [2014] "Low GWP refrigerants R1234ze(E) and R1234ze(Z) for high temperature heat pumps," International Journal of Refrigeration, vol. 40, pp. 161-173.