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Thermal performance of HFO refrigerants in two stages cascade refrigeration system for replacing r-134a

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Abstract

The present paper presents thermodynamic performance of two stage cascade vapour compression refrigeration system which circulates a refrigerant comprising a fluoroolefin (R1234ze) in the high temperature circuit .This cascade refrigeration system includes a low temperature refrigeration loop in which fluoroolefin (R1234yf) is circulated. The numerical thermal model have been developed for two stages cascade refrigeration system and thermodynamic performances in terms of and first law efficiency, second law efficiency system exergy destruction ratio, first law efficiency of lower temperature and high temperature circuit have been computed. The effect of low temperature evaporator on the system first and second law performances and system exergy destruction ratio it was found that as low temperature evaporator temperature is decreasing, the first law and second law efficiencies are increasing and exergy destruction ratio is decreasing.

Keywords: Two stages Cascade Refrigeration, Energy-Exergy Performances, Irreversibility Analysis, and HFO Refrigerants

1. Introduction

The refrigeration industry has been working for the past few decades to find replacement refrigerants for the ozone-depleting chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) being phased out as a result of the Montreal Protocol. The solution for most refrigerant producers has been the commercialization of hydrofluorocarbon (HFC) refrigerants. The new HFC refrigerants, HFC-134a being the most widely used at this time, have zero ozone depletion potential and thus are not affected by the current regulatory phase out as a result of the Montreal Protocol. The refrigeration industry has been working for the past few decades to find replacement refrigerants for the ozone-depleting chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) being phased out as a result of the Montreal Protocol.

Global warming potential (GWP) is an index for estimating relative global warming contribution due to atmospheric emission of a kilogram of a particular greenhouse gas compared to emission of a kilogram of carbon dioxide. GWP can be calculated for different time horizons showing the effect of atmospheric lifetime for a given gas. The GWP for the 100 year time horizon is commonly the value referenced. For mixtures, a mass- fraction weighted average can be calculated based on the individual GWPs for each component. Ozone depletion potential (ODP) is a number that refers to the amount of stratospheric ozone depletion caused by a substance. The ODP is the ratio of the impact on stratospheric ozone of a chemical compared to the impact of a similar mass of CFC-11(fluorotrichloromethane).

The new ecofriendly refrigerant (hydrofluoroolefin) HFO-1234ze, has zero ozone-depletion potential and meets EU regulatory requirements for reducing the use of high global-warming-potential (GWP) substances such as R134a etc. This fourth-generation technology is a direct replacement for hydrofluorocarbon R-134a in the low temperature applications (i.e. below -33^{0}C).

Table-1: 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/m3	489	515.3

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Direct contribution of following refrigerants to global warming is lower than that of R134a as shown in Table-2

Table 2: 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

As of today, HFOs found in a number of applications. In refrigeration and heat pump technology HFO-1234yf has been chosen to replace R134a. A number of the refrigerants have been suggested to substitute R134a. R-1234yf, for instance, has very low GWP of 4 and zero ODP. The Thermal performance of R-1234yf in R-134a system have similar coefficient of performance (COP), but R-1234yf provides much lower capacity. Energy conservation and environmental concerns are the main reasons for the development growth of new low GWP refrigerants. While the direct contribution of all the proposed refrigerants to global warming is lower than that of R134a.

2. Literature review

Mishra [1-2] 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 [4] did thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system. Bhattacharyya et al [5] studied the performance of a cascade refrigeration–heat pump system based on a model incorporating both internal and external irreversibility's.
Kilicarslan [6] experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system. Lee et al [7] 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 [9] 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[10] suggested the use of R1234ze(e) for heat pump application to replace R410a.

3. Utility of HFO Refrigerants in Two Stages Cascade Refrigeration Systems

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 40^{0}C to 60^{0}C and evaporator temperature range of -20^{is}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.
The refrigerant R152a is more efficient, where it leads to a system with better COP that alternative refrigerants. Similarly hydrocarbons reach similar or better efficiency shown in Table-3

Table 3 - COP values for different refrigerants [11]

Refrigerant	R152a	R1234ze	R1234yf	R134a
COP Range	3.37- 5.21	3.35-5.0	3.14 -4.94	3.34- 5.01
COP average	4.17	4.10	3.88	4.12

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^{0}C and temperature of R1234yf evaporator to be -50^{0}C, 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 ^{0}C
Table-4 shows 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
Table-5 shows as the variation of condenser temperature with thermal performance parameters. 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 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 20^0C and then decreases rapidly. Table-6.shows as the variation of high temperature evaporator with thermal performance parameters 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 20^0C in both cases using R1234ze in the high temperature circuit. However COP of hot fluid circuit is decreases and COP of low temperature fluid circuit is increases. Table-7.shows as the variation of low temperature evaporator with thermal performance parameters using R1234yf in thelow temperature circuit It was observed that 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 -50^0C and also cop of primary intermediate temperature circuit is decreases and secondary intermediate temperature circuit COP is increases.

Table-4: Effect of temperature overlapping (approach) on thermal performance of two stages cascade refrigeration systems using HFO refrigerants for replacing R134a (T_Cond=50^0C, T_EVA_HTC=0^0C, T_EVA_LTC =-50 oC, ETA_COMP_HTC= ETA_COMP_LTC=0.80

Approach	Overall_COP	EDR_System	ETA_Second	COP_HTC	COP_LTC	ED_RATIO	Eff_Second
0	1.509	1.0	0.5075	3.215	2.844	0.1497	5.682
2	1.467	1.027	0.4934	3.215	2.638	0.1505	5.647
4	1.426	1.085	0.4795	3.215	2.562	0.1512	5.614
6	1.386	1.146	0.466	3.215	2.435	0.1519	5.584
8	1.346	1.209	0.4527	3.215	2.316	0.1525	5.558
10	1.307	1.274	0.4397	3.215	2.204	0.1530	5.535

Table-5: Thermal performance of two stages cascade refrigeration systems using HFO refrigerants for replacing R134a (T_EVA_HTC=0^0C, T_EVA_LTC =-50 ^{0}C, Temperature Overlapping (Approach= (T_COND_LTC - T_EVA_HTC)=10)

T_Cond (oC)	Overall_COP	EDR_System	ETA_Second	COP_HTC	COP_LTC	ED_RATIO	Eff_Second
40	1.466	1.028	0.493	4.379	2.204	4.642	0.1773
45	1.386	1.145	0.4662	3.737	2.204	5.062	0.1650
50	1.307	1.274	0.4397	3.215	2.204	5.535	0.1530
55	1.229	1.419	0.4134	2.779	2.204	6.073	0.1414
60	1.151	1.584	0.3869	2.407	2.204	6.694	0.130

Table-6: effect of cascade evaporator temperature thermal performance of two stages cascade refrigeration systems using HFO refrigerants for replacing R134a (T_Cond=50^0C, T_EVA_LTC =-50 ^{0}C, Temperature Overlapping (Approach= (T_COND_LTC - T_EVA_HTC)=10)

T_EVA_HTC (oC)	Overall_COP	EDR_System	ETA_Second	COP_HTC	COP_LTC	ED_RATIO	Eff_Second
-10	1.307	1.274	0.4397	2.42	2.844	6.299	0.1370
-5	1.316	1.260	0.4425	2.78	2.497	5.887	0.1452
0	1.307	1.274	0.4397	3.215	2.204	5.535	0.1530
5	1.283	1.317	0.4315	3.75	1.951	5.242	0.1602
10	1.243	1.392	0.4180	4.421	1.729	5.0	0.1664

Table-7: Effect of low temperature evaporator temperature on thermal performance of two stages cascade refrigeration systems using HFO refrigerants for replacing R134a (T_Cond=50^0C, T_EVA_HTC=0^0C, Temperature Overlapping (Approach= (T_COND_LTC - T_EVA_HTC)

T_EVA_LTC (oC)	Overall_COP	EDR_System	ETA_Second	COP_HTC	COP_LTC	ED_RATIO	Eff_Second
-35	1.653	1.399	0.4168	3.215	3.404	6.319	0.1366
-40	1.531	1.342	0.427	3.215	2.921	6.003	0.1428
-45	1.415	1.301	0.4346	3.215	2.529	5.745	0.1483
-50	1.307	1.274	0.4397	3.215	2.204	5.535	0.1530

5. Conclusions and Recommendation

The following conclusions were made during experimental investigation.

(1) Ecofriendly HFO R1234ze is suitable for replacing R134a. Although it's 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 of cascade refrigeration system in the range of HTC Circuit from 60^0C to -20^0C.

(2) Ecofriendly HFO R1234yf is suitable for replacing R134a in the low temperature circuit of cascade refrigeration system in the range of HTC Circuit from 20^0C to -50^0C.

(3) Increasing evaporator temperature overall cop is increases while System EDR first decreases while second law efficiency is increases. The maximum efficiency was obtained at -45^0C and then decreases as increasing evaporator temperature.

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