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Thermodynamic performance of vapour compression refrigeration systems using HFO refrigerants for replacing HFC refrigerants

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Abstract

Due to economic growth, population growth and improved living standards the annual energy consumption behavior and demand is steadily increasing. Presently, major demands of cooling and heating applications are met out by the conventional vapor compression systems.The recent global agreement signed in Kigali to limit the use of hydrofluorocarbons (HFCs) as refrigerants, starting *by* 2019, has promoted an active area of research toward the development of low global warming potential (GWP) new refrigerants. Hydro-fluoro-olefins (HFOs) have been proposed as a low GWP alternative to replace third generation HFC refrigerants. The numerical computations for predicting first law and second law performances for two vapour compression refrigeration systems had been carried out using R1234ze and R1234yf as fourth generation low GWP refrigerants for replacing third generation refrigerant (R134a). The comparison were carried out using HFC-134a for two systems (i.e. System-1 : consisting of condenser, evaporator compressor and throttling valve and System-2 consisting of condenser, evaporator compressor and expander, It was found that system-2 using expander gives best thermodynamic performances around 25.65% higher than system-1 using throttle valve . The comparison were made for using eighteen ecofriendly refrigerants and lowest thermal performance were found using R125 and higher thermal performances were observed by using R123. However thermodynamic performance s using hydro carbons are also comparable.

Keywords: Gas turbine, Retrofitting, EVC, STIG, Exergy

1. Introduction

Refrigeration plays a very important role in industrial, domestic and commercial sectors for cooling, heating and food preserving applications. There are innumerable applications of such systems and they are the major consumer of electricity around the world. Energy consumption is directly proportional to the economic development of any nation, however this area is in great interest now because of increase in the cost of conventional fuels and environmental concerns globally. The scientists are looking for new and renewable sources of energy so as to minimize the costs. Due to the increasing energy demand, degradation of environment, global warming and depletion of ozone layer etc, there is urgent need of efficient energy utilization and waste heat recovery for useful applications. The researchers are concentrating on the alternate and environment friendly refrigerants, especially after the Kyoto and the Montreal protocols. However, in a quest to find out alternate and environment friendly refrigerants, the energy efficiency of the equipment having conventional refrigerants is also very important in the present age of competitive business community. The aim of the scientific community all over the world is to switch to new and renewable energy sources besides, efficient utilization of all conventional sources.

1.1 Use of ecofriendly refrigerants

Currently used third generation hydrofluorocarbon (HFC) refrigerants are known to be Nano zone depleting agents, but are also characterized by their substantial global warming potential (GWP) values. Consequently, the year 2016 marked the launch of a global environmental deal to phase out the production and consumption of HFCs by years 2036 to 2047, starting in 2019. Most of the current effective and proposed regulations target 150 GWP for refrigeration and 750 GWP for air conditioning applications, thus creating an immediate

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demand for developing new fourth generation refrigerants with low GWPs. In response to this need, the National Institute of Standards and Technology recommended a list of new classes of refrigerants that would possess low values of GWPs based on estimates done using data on the chemical structure, the radiative efficiency, and the atmospheric lifetime of these molecules. Hydro-fluoro-olefins (HFOs) were included in the NIST list as one of the best candidates found so far, with GWP values comparable to those of hydrocarbon (HC)-based refrigerants. Furthermore, cycle performance tests carried out for HFOs proved their suitability to act as a replacement for HFCs used in mobile air-conditioners, vending machines, and chillers. As a result, a major shift in the automobile industry is planned to start in the year 2017 to replace 1,1,1,2-tetrafluoroethane (HFC-134a) as a working fluid by 2,3,3,3-tetrafluoropropene (HFO-1234yf), a newly introduced fourth generation refrigerant. Vapour compression refrigeration cycles for carrying out these cycles are well known. In theoretical vapour compression refrigeration, saturated vapour refrigerants at low pressure enter a compressor and undergo isentropic compression. The high pressure vapour enters a condenser and heat is rejected from the fluid at constant pressure from the condenser. The working fluid leaves the condenser as a saturated liquid. An isenthalpic throttling process follows across an expansion valve or capillary tube. The working fluid is then evaporated at constant pressure with the working fluid absorbing heat to complete the cycle. Xiaohui et al [1] presented the performance study of vapour compression system where the expander work recovered during the expansion process was also employed for sub cooling of the system and found higher COP of the system while using R12, R32, R22, R134a refrigerants. Victor et al [2] presented a performance study on automobile air-conditioning based on vapor compression refrigeration cycle with R134a as refrigerant by incorporating an expander and predicted reasonable gains in cycle performance. Alison et al [3] did an economic analysis based on thermodynamic performance by using expander in the refrigeration systems of a medium refrigerating load for ambient temperature of 35 °C, evaporating temperature of 7.2 °C and the condensing temperature of 54.4 °C was considered. Bjorn[4]presented a study by compared properties of hydrocarbons, namely propane, propene and isobutene with R134a, R22 and ammonia and predicted the higher performance of hydrocarbons over R134a and R22 in vapour compassion refrigeration system The present investigation relates generally to the vapour compression refrigeration systems, using expander which utilizes the work expended in direct expansion of a refrigerant to power a turbine which drives a compressor of a refrigeration system in compressing gaseous vapours from evaporator pressure to condenser pressure.

2. Results and Discussions

The following two systems have been chosen for numerical computation.

System-1: consisting of condenser, evaporator compressor and throttling valve and

System-2 consisting of condenser, evaporator compressor and expander.

2.1 Effect of ecofriendly refrigerants on thermal performances

The numerical values for both systems are as given below:

Compressor Efficiency=0.80

Expander Efficiency=0.80

Condenser temperature=50^{0}C

Evaporator temperature=-10^{0}C

The thermal performance s in terms of first law efficiency (COP) and second law efficiency in terms of exergetic efficiency and exergy destruction ratio are shown in Table-1(a) to Table-1(c) respectively. It was found from Table-1(a) that first law performance in terms of COP of system-2 containing expander gives higher first law efficiency in terms of COP than system-1 and the maximum coefficient of performance is found using R123 and then ecofriendly R245fa refrigerant. However using hydrocarbons in the vapour compression refrigeration systems gives attractive first and second law performance the lowest COP was found using R125 refrigerant. Similarly in system-1, using throttle valve, the maximum COP was observed using R152a and lowest COP was observed using R125 refrigerant. Similarly from table-1(b) & table-1(c) Second law efficiency in terms of exergetic efficiency of system2 containing expander gives better exergetic efficiency and lower exergy destruction ratio than system-1 containing throttle valve. The same trend was also observed in second law performance.

Table-1(a); Comparison of First law efficiency in terms of COP of both systems

Refrigerant	COP_System-I	COP_System-II
R-134a	2.464	3.095
R1234ze	2.42	3.090
R1234yf	2.255	2.981
R-227ea	2.056	2.889
R236fa	2.361	3.052
R245fa	2.634	3.182
R404a	2.009	2.864
R407c	2.084	2.809
R410a	2.259	2.925
R152a	2.652	3.156
R290	2.405	3.067
R600a	2.484	3.11
R600	2.627	3.17
R-125	1.785	2.74
R123	2.744	3.23
R32	2.416	2.917
R717	2.728	2.999
R507a	2.030	2.877

Table-1(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems

Refrigerant	ETA_II_System-I	ETA_II_System-II
R-134a	0.328	0.4118
R1234ze	0.3221	0.4113
R1234yf	0.3001	0.3967
R-227ea	0.2737	0.3845
R236fa	0.3142	0.4061
R245fa	0.3505	0.4232
R404a	0.2673	0.3811
R407c	0.2773	0.3739
R410a	0.3007	0.3892
R152a	0.3529	0.420
R290	0.3201	0.4082
R600a	0.3306	0.4138
R600	0.3496	0.4219
R-125	0.2375	0.3646
R-123	0.3652	0.4298
R32	0.3215	0.3882
R717	0.3630	0.3992
R507a	0.2701	0.3838

Table-1(c): Comparison of rational exergy destruction ratio of both systems

Refrigerant	EDR_System_I	EDR_System_II
R-134a	0.6720	0.5882
R1234ze	0.6779	0.5887
R1234yf	0.6999	0.6033
R-227ea	0.7263	0.6155
R236fa	0.6858	0.5939
R245fa	0.6495	0.5766
R404a	0.7327	0.6189
R407c	0.7227	0.6261
R410a	0.6993	0.6108
R152a	0.6471	0.580
R290	0.6799	0.5918
R600a	0.6694	0.5862
R600	0.6504	0.5781
R-125	0.7625	0.6354
R-123	0.6348	0.5702
R32	0.6785	0.6118
R717	0.6370	0.6008
R507a	0.7299	0.6172

2.2 Effect of evaporator temperature on thermal performances using hfo-1234yf refrigerant

Compressor Efficiency=0.80, Expander Efficiency=0.80, Condenser temperature= 50^{0}C, Refrigerants used: R-1234yf R134a and R-1234yf

The variation of thermal performances in terms of first law efficiency (COP) and II law efficiency in terms of exergetic efficiency and exergy destruction ratio with variation of evaporator temperature using HFO-1234yf, R 134a and HFO-1234ze refrigerants are shown in Table-2(a) to Table-2(c) and using R134a from Table-4(a-c) and also using ecofriendly low GWP and zero ODP HFO -1234ze are shown in Table-6(a-c) respectively. It was found from Table-2(a),Table-(4a) and Table-6(a) that that first law performance in terms of COP of both systems are increased by increasing condenser temperature and exergy destruction ratio is decreased.

Table-2(a); Comparison of First law efficiency in terms of COP of both systems using R1234yf

T_Eva (^{0}C)	COP_System_I	COP_System_II
20	6.179	7.129
15	5.047	5.940
10	4.201	5.049
5	3.547	4.358
0	3.027	3.806
-5	2.604	3.355
-10	2.255	2.981
-15	1.962	2.665
-20	1.714	2.396
-25	1.501	2.163
-30	1.317	1.961

Table-2(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234yf

T_Eva (^{0}C)	ETA_II_System_I	ETA_II_System_II
20	0.1055	0.1217
15	0.1752	0.2062
10	0.2227	0.2676
5	0.2552	0.3135
0	0.2772	0.3485
-5	0.2915	0.3756
-10	0.3001	0.3967
-15	0.3042	0.4132
-20	0.3049	0.4261
-25	0.3026	0.4361
-30	0.2981	0.4438

Table-2(c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234yf

T_Eva (^{0}C)	*EDR_System_I*	*EDR_System_II*
20	0.89450.8945	0.8783
15	0.8248	0.7938
10	0.7773	0.7324
5	0.7448	0.6865
0	0.7228	0.6515
-5	0.7085	0.6244
-10	0.6999	0.6033
-15	0.6958	0.5868
-20	0.6951	0.5739
-25	0.6974	0.5639
-30	0.7069	0.5562

Table-3(a); Comparison of First law efficiency in terms of COP of both systems using R1234yf

T_Condenser^{0}C	COP_System_I	COP_System_II
30	4.171	4.814
35	3.551	4.214
40	3.044	3.728
45	2.619	3.324
50	2.255	2.981
55	1.937	2.683
60	1.653	2.42

Table-3(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234yf

T_Condenser ^{0}C	ETA_II_System_I	ETA_II_System_II
30	0.5551	0.6406
35	0.4725	0.5608
40	0.4051	0.4961
45	0.3486	0.4424
50	0.3001	0.3967
55	0.2577	0.3571
60	0.220	0.322

Table-3 (c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234yf

T_Condenser ^{0}C	*EDR_System_I*	*EDR_System_II*
30	0.4449	0.3594
35	0.5275	0.4392
40	0.5948	0.5039
45	0.6514	0.5576
50	0.6999	0.6033
55	0.7423	0.6429
60	0.780	0.6780

Table-4(a); Comparison of First law efficiency in terms of COP of both systems using R134a

T_Eva (^{0}C)	COP_System_I	COP_System_II
20	6.429	7.278
15	5.286	6.08
10	4.433	5.182
5	3.772	4.485
0	3.246	3.928
-5	2.819	3.473
-10	2.464	3.095
-15	2.167	2.775
-20	1.914	2.502
-25	1.696	2.267
-30	1.508	2.061

Table-4(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Eva (^{0}C)	ETA_II_System_I	ETA_II_System_II
20	0.1097	0.122
15	0.1836	0.2111
10	0.2350	0.2747
5	0.2714	0.3226
0	0.2973	0.3597
-5	0.3155	0.3887
-10	0.328	0.4118
-15	0.3359	0.4303
-20	0.340	0.4451
-25	0.3020	0.4570
-30	0.3413	0.4665

Table-4(c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Eva (^{0}C)	*EDR_System_I*	*EDR_System_II*
20	0.8903	0.8758
15	0.8164	0.7889
10	0.765	0.7253
5	0.7286	0.6774
0	0.7027	0.6403
-5	0.6845	0.6113
-10	0.6720	0.5882
-15	0.6641	0.5697
-20	0.6596	0.5549
-25	0.6580	0.5430
-30	0.6587	0.5335

Table-5(a); Comparison of First law efficiency in terms of COP of both systems using R134a

T_Condenser ^{0}C	COP_System_I	COP_System_II
30	4.326	4.904
35	3.718	4.308
40	3.224	3.8270
45	2.814	3.43
50	2.464	3.095
55	2.162	2.807
60	1.895	2.555

Table-5(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Condenser ^{0}C	ETA_II_System_I	ETA_II_System_II
30	0.5757	0.6526
35	0.4947	0.5733
40	0.4291	0.5093
45	0.3744	0.4565
50	0.3280	0.4118
55	0.2877	0.3735
60	0.2523	0.340

Table-5 (c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Condenser ^{0}C	*EDR_System_I*	*EDR_System_II*
30	0.4243	0.3474
35	0.5053	0.4267
40	0.5709	0.4909
45	0.6255	0.5436
50	0.6720	0.5882
55	0.7123	0.6265
60	0.7477	0.660

Table-6(a); Comparison of First law efficiency in terms of COP of both systems using R1234ze

T_Eva (^{0}C)	COP_System_I	COP_System_II
20	6.446	7.308
15	5.287	6.10
10	4.421	5.196
5	3.75	4.493
0	3.215	3.931
-5	2.78	3.472
-10	2.42	3.09
-15	2.117	2.768
-20	1.860	2.493
-25	1.639	2.255
-30	1.448	2.048

Table-6(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234ze

T_Eva (^{0}C)	ETA_II_System_I	ETA_II_System_II
20	0.110	00.1247
15	0.1836	0.2118
10	0.2349	0.2754
5	0.2697	0.3232
0	0.2944	0.360
-5	0.3112	0.3887
-10	0.3227	0.4113
-15	0.3283	0.4292
-20	0.3308	0.4434
-25	0.3305	0.4546
-30	0.3277	0.4635

Table-6(c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R1234yf

T_Eva (^{0}C)	*EDR_System0.6692_I*	*EDR_System_II*
20	0.890	0.8753
15	0.8164	0.7882
10	0.7657	0.7246
5	0.7303	0.7246
0	0.7056	0.6768
-5	0.6888	0.640
-10	0.6779	0.6113
-15	0.6717	0.5887
-20	0.6692	0.5708
-25	0.6695	0.5566
-30	6723	0.5454

2.3 Effect of condenser temperature on thermal performances using hfo-1234yf refrigerant

Compressor Efficiency=0.80
Expander Efficiency=0.80
Condenser temperature= 50^{0}C
Refrigerants used: R-1234yf, R134a and R1234ze

The variation of thermal performances in terms of first law efficiency (COP) and second law efficiency in terms of exergetic efficiency and exergy destruction ratio with variation of condenser temperature using HFO-1234yf refrigerant are shown in Table-2 (a-c) respectively and using R134a are shown in Table-5(a) to Table-Table-5(c) and using Low GWP and zero ODP are shown in Table-7(a-b) respectively It was found from Table-2(a) that first law performance in terms of COP is reduced by increasing condenser temperature and exergy destruction ratio is also increased.

Table-7(a); Comparison of First law efficiency in terms of COP of both systems using R134a

T_Condenser ^{0}C	COP_System_I	COP_System_II
30	4.308	4.923
35	3.691	4.32
40	3.191	3.833
45	2.774	3.43
50	2.42	3.09
55	2.113	2.798
60	1.843	2.543

Table-7(b); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Condenser ^{0}C	ETA_II_System_I	ETA_II_System_II
30	0.5733	0.6551
35	0.4912	0.5749
40	0.4246	0.5101
45	0.3692	0.4565
50	0.3221	0.4113
55	0.2812	0.3724
60	0.2453	0.3384

Table-7 (c); Comparison of second law efficiency in terms of Exergetic Efficiency of both systems using R134a

T_Condenser ^{0}C	EDR_System_I	EDR_System_II
30	0.4267	0.3449
35	0.5088	0.4251
40	0.5754	0.4899
45	0.6308	0.5435
50	0.6779	0.5887
55	0.7188	0.6276
60	0.7547	0.6616

3. Conclusion

(i) The first law performance in terms of COP of system -2 containing expander is higher than system -1 containing throttle valve.

(ii) The higher COP was found usng R123 refrigerant and is higher than R245fa and lower COP is found by using R125.

(iii) Thermal performances in terms of first law efficiency (COP) and second law efficiency in terms of exergetic efficiency decreases with variation of condenser temperature using HFO-1234yf refrigerant. Similarly exergy destruction ratio of both systems are increased with increasing condenser temperature.

(iv) The thermal performances in terms of first law efficiency (COP) and second law efficiency in terms of exergetic efficiency increases with increasing evaporator temperature using HFO-1234yf refrigerant and exergy destruction ratio decreases with increasing evaporator temperature for both systems.

(v) The thermal performances in terms of first law efficiency (COP) and second law efficiency in terms of exergetic efficiency of both systems using R134a is higher than using R1234ze and R1234yf. However first law efficiency of R1234ze is also higher than R1234yf and also slightly lesser than using R134a. It is clear that both HFO refrigerants (i.e. R1234ze and R1234yf) will replace R134a in near future for domestic applications.

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