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Exergy analysis of simple and cascade vapor compression refrigeration systems using ultra low GWP, environmental friendly HFO refrigerants

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Abstract

The exergy analysis is a powerful tool for finding irreversibilities (loss work i.e. exergy destruction) occurred in the components as well as complete cascade vapour compression refrigeration system. Global warming and ozone depletion is a big issue for saving our environment. Therefore, ultra-low GWP refrigerants are used in the vapor compression systems. The first law and second law analysis performances have been computed for simple and cascade vapor compression systems and the comparison of low GWP, HFC refrigerants and ultra-low GWP, HFO environmental friendly refrigerants have been carried out and it is found that HFO refrigerants can replace R134a in near future due to its better thermodynamic performances. The exergy destruction in the high temperature cycle of cascade vapor compression system is higher than lower temperature cycle. For components wise, the exergy destruction in condenser is highest while in evaporator is lowest. R1233zd(E) and R-1225ye(Z) gives best thermodynamic (energy-exergy) thermodynamic performances than R134a. However, R 32 gives lowest thermodynamic performances in low temperature cycle. and highest power consumption in the high temperature compressor while R1234ze(Z) gives low power consumption in the high temperature compressor.

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1. Introduction

Currently the highest energy utilized in cooling and air conditioning in industrial as well as for domestic applications. In addition to energy consumption by using refrigerants in cooling and air conditioning have high GWP and ODP, which are accountable for increasing global warming and ozone depletion. The main requirements of ideal refrigerants are having good physical and chemical properties. Due to excellent good physical and chemical properties such as non-corrosiveness, non-toxicity, non- flammability, low boiling point, Chlorofluorocarbons (CFCs) have been used over the last many decades, but hydro chloro fluoro carbons (HCFCs) and Chlorofluorocarbons (CFCs) having large amount of chlorine content as well as high global warming potential and ozone depletion potential, so after 90s refrigerants under these categories these kinds of refrigerants are almost prohibited [1]. In this paper, thermodynamic performances of HFO and HFC refrigerants on simple and cascade refrigeration systems have been presented.

2. Thermodynamic performances of simple & cascade vapour compression refrigeration systems

Refrigeration is a technology which absorbs heat at low temperature and provides temperature below the surrounding by rejecting heat to the surrounding at higher temperature. Simple vapour compression system which consists of four major components compressor, expansion valve, condenser and evaporator in which total cooling load is carried at one temperature by single evaporator but in many applications like large hotels, food storage and food processing plants, food items are stored in different compartment and at different temperatures. Therefore, there is need of HFO and HFC refrigerants on simple a cascade vapour compression refrigeration system for improving thermodynamic performance of system

The utility of exergy analysis (i.e. second law analysis) on vapour compression refrigeration systems is well defined because it gives the idea for improvements in efficiency due to modifications in

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existing design in terms of reducing exergy destructions in the components. In addition to this second law analysis also provides new thought for development in the existing system [2-3].

Most of the study has been carried out for the performance evaluation of CFC, HCFC, HFC refrigerants used in simple & the vapour compression refrigeration systems using energetic analysis. With the help of first law analysis, the irreversibility (exergy destruction) or exergy losses in components of system unable to determined [4], Therefore second law (exergetic) analysis is the progressive approach for computing thermodynamic performances.

3. Results and Discussion

The following input data have been chosen or simple cascade vapour compression refrigeration systems using utra low ecofriendly refrigerants

- Temperature of condenser = 40ºC
- Refrigerant used =HFO Refrigerants
- Temperature of High temperature evaporator = -40ºC
- Cooling Load on low temperature evaporator = 3.5167 kW
- Isentropic efficiency of high temperature compressor = 100%

Table-1 shows, the validation of thermodynamic performances using R12 refrigerant in vapour compression refrigeration cycle an it was found that the results obtained from thermodynamic model well matched.

Table-1 comparison of thermodynamic performances obtained by model with results obtained with R12 refrigerant in vapour compression refrigeration cycle and with R134a

Performance Parameters	Model	Ref [5]	R134a
First law Efficiency (COP)	1.976	1.970	1.881
Exergetic Efficiency	0.6785	0.676	0.6459
Mass Fow rate (Kg/sec)	0/0370	0/0370	0.0299
Work required to run Compressor WComp "kW"	1.781	1.780	1.869
System Exergy Destruction "kW"	0.5782	0.5735	0.6686
Exergy of Fuel_ "kW"	1.781	1.780	1.869
Exergy_Product_ "kW"	1.207	1.207	1.207
Exergy Destruction Ratio EDR_system)	0.4738	0.4738	0.548
Condenser Heat _ "kW"	5.296	5.298	5.386

Table-2 shows, the variation of thermodynamic performances with different ecofriendly refrigerants in vapour compression refrigeration cycle and using R1234yf in low temperature cycle and it was found that R-1233zd(E) gives best First Law Efficiency (COP)and R1234yf gives lowest thermodynamic First Law Efficiency (coefficient of performances). However, R1234yf gives highest electrical power consumption in the compressor and also higher mass flow rate while R-152a gives lowest power consumption in the compressor and mass flow rate in the evaporator. Similarly, condenser heat rejection is high using R1234yf and have lower exergetic efficiency as compare to higher exergetic efficiency using R-1233zd(E) It clearly seen that HFC-134a (high GWP refrigerant) can be easily replace by using HFO refrigerants which has ultra-low global warming potential

Table 2: Effect of ecofriendly refrigerants in high temperature cycle on the performance of cascade vapour compression refrigeration systems for isentropic efficiencies =100%.

Performance Parameters	R134a	R-1225 ye(Z)	R1233 zd(E)	R1234yf	HFO1336 mzz(Z)	R-245fa	R-152a
First law Efficiency (COP)	1.881	1.801	2.032	1.66	1.896	1.998	2.047
Exergetic Efficiency	0.6459	0.6184	0.6976	0.5701	0.6508	0.6825	0.7026
Mass Fow rate (Kg/sec)	0.0299	0.04091	0.02776	0.0430	0.0346	0.0286	0.0171
Work required to run Compressor W_{Comp} "kW"	1.869	1.953	1.731	2.118	1.855	1.769	1.718
System Exergy Destruction "kW"	0.6686	0.7513	0.5294	0.9165	0.6540	0.5697	0.517
Exergy of Fuel_ "kW"	1.869	1.953	1.731	2.118	1.855	1.769	1.718
Exergy_Product_ "kW"	1.207	1.207	1.207	1.207	1.207	1.207	1.207
Exergy Destruction Ratio ($EDR_{\_system}$)	0.548	0.617	0.4334	0.7541	0.5365	0.4652	0.4229
Condenser Heat _ "kW"	5.386	5.469	5.247	5.635	5.372	5.286	5.25

3.1 *Thermodynamic (energy- exergy) performances with cascade vapour compression refrigeration systems*

The following input data have been chosen or simple cascade vapour compression refrigeration systems using ultra low HFO ecofriendly refrigerants

- Temperature of High temperature condenser = 50°C
- Sub cooling Temperature of High temperature condenser = 5ºC
- Refrigerant used High temperature cycle = R-1234ze(E)
- Temperature of High temperature evaporator = -30°C
- Isentropic efficiency of high temperature compressor = 100%
- Refrigerant used low temperature cycle = ultra-low ecofriendly refrigerants
- Temperature of low temperature evaporator = - 95°C
- Isentropic efficiency of low temperature compressor = 100%
- Cooling Load on low temperature evaporator = 3.5167 kW
- Temperature overlapping between low temperature cascade condenser and High temperature evaporator = 10 ºC

Table-3 shows, the variation of thermodynamic performances with different ecofriendly refrigerants in low temperature cycle and using R-1234ze(E) refrigerant in high temperature cycle for 100%. isentropic efficiency of both compressors and it was found that R1233zd(E) and R-1225ye(Z) gives best thermodynamic performances and R 32 gives lowest thermodynamic performances in low temperature cycle. Similarly, R 32 gives highest power consumption in the high temperature compressor while R1234ze(Z) gives low power consumption in the high temperature compressor. For all ecofriendly refrigerants, exergy destruction in the high temperature cycle is higher than lower temperature cycle similarly exergy destruction in both compressors is larger as compared to expansion valves an evaporator. However, the exergy destruction in evaporators is lowest.

Table-3 Effect of ecofriendly refrigerants in Low temperature cycle on the thermodynamic performances of cascade vapour compression refrigeration systems using R-1234ze(E) refrigerant in high temperature cycle for isentropic efficiency of compressors =100%.

Performance Parameters	R-1225 ye(Z)	HFO1336 mzz(Z)	R1233 zd(E)	R-245fa	R-134a	R32
Over all COP_LTC	0.7781	0.7662	0.7785	0.7763	0.7707	0.7359
Cascaded Exergy Destruction Ratio (EDR_$_{LTC}$)	3.352	3.394	3.347	3.339	3.472	3..598
Cascaded Exergetic Efficiency_	0.2298	0.2276	0.230	0.2304	0.2236	0.2175
First law Efficiency (COP_$_{HTC}$)	1.81	1.81	1.81	1.81	1.81	1.81
First law Efficiency (COP_$_{LTC}$)	2.199	2.063	2.093	2.111	2.084	1.926
Exergy of Fuel_Cascade "kW"	4.520	4.59	4.552	4.530	4.563	4.779
Exergy_Product_LTC"kW"	2.371	2.371	2.371	2.371	2.371	2.371
Work required to run HT Compressor W_{Comp_HTC}"kW"	2.86	2.885	2.872	2.864	2.876	2.953
Work required to run low temp Compressor W_{Comp_LTC}"kW"	1.659	1.704	1.68	1.666	1.687	1.826
Total work required to run whole system W_{Comp_Total}"kW"	4.520	4.59	4.552	4.530	4.563	4.779
Cascaded Exergy Destruction Ratio (EDR_$_{MTC}$)	0.9064	0.9359	0.9202	0.9109	0.9247	1.016
Cascaded Exergetic Efficiency_MTC	0.5245	0.5166	0.5208	0.5233	0.5156	0.4961
Exergy_input "kW"	10.32	10.42	10.31	10.29	10.28	9.983
Total Exergy Consumption in HT cycle (%)	30.72	30.44	30.92	30.89	31.05	33.71
Total Exergy Consumption in LT cycle (%)	26.83	27.86	26.54	26.49	26.29	21.15
Total Exergy Consumption in system (%)	57.55	58.3	57.46	57.38	57.34	54.86
Total Exergy Consumption_Cond (%)	28.8	28.8	28.66	28.68	28.45	25.97
Total Exergy Consumption_Comp (%)	0.0	0.0	0.0	0.0	0.0	0.0
Total Exergy Consumption_Eva (%)	4.3320	4.3282	4.3216	4.401	4.406	4.3572
Total Exergy Consumption_Valve (%)	24.32	24.17	24.48	24.30	24.49	24.53
Exergy Consumption_Cond_$_{HTC}$ (%)	10.20	10.10	10.27	10.26	10.32	11.29
Exergy Consumption_Comp_$_{HTC}$ (%)	0.0	0.0	0.0	0.0	0.0	0.0
Exergy Consumption_Eva__$_{HTC}$ (%)	1.2425	1.2403	1.2440	1.2439	1.2451	1.2660
ExergyConsumption_Valve__$_{HTC}$ (%)	18.28	18.10	18.40	18.39	18.48	20.16
Exergy Consumption_Cond_$_{LTC}$ (%)	18.69	18.70	18.39	18.41	18.13	14.68
Exergy Consumption_Comp_$_{LTC}$ (%)	0.0	0.0	0.0	0.0	0.0	0.0
Exergy Consumption_Eva_$_{LTC}$ (%)	3.08949	3.08781	3.07756	3.1571	3.1609	3.0911
Exergy Consumption_Valve_$_{LTC}$ (%)	6.044	6.086	6.077	5.915	6.004	4.373

Table-4 shows, the variation of thermodynamic performances with different ecofriendly refrigerants in low temperature cycle and using R-1234ze(E) refrigerant in high temperature cycle for 80% isentropic efficiency of both compressors and it was found that R1233zd(E) and R-1225ye(Z) gives best thermodynamic performances and R 32 gives lowest thermodynamic performances in low temperature cycle. Similarly, R 32 gives highest power consumption in the high temperature compressor while R1234ze(Z) gives low power consumption in the high temperature compressor. For all ecofriendly refrigerants, exergy destruction in the high temperature cycle is higher than lower temperature cycle similarly exergy destruction in both compressors is larger as compared to expansion valves an evaporator. However, the exergy destruction in evaporators is lowest.

Table-4. Effect of ecofriendly refrigerants in high temperature cycle on the performance of cascade vapour compression refrigeration systems for isentropic efficiencies =80%.

Performance Parameters	R-1225ye(Z)	R1336mzz(Z)	R1233zd(E)	R245fa	R134a	R-32
Over all COP_LTC	0.5924	0.5831	0.5880	0.5910	0.5866	0.5592
Cascaded Exergy Destruction Ratio (EDR_$_{LTC}$)	1.920	1.976	1.903	1.901	1.980	2.087
Cascaded Exergetic Efficiency_LTC	0.3424	0.3361	0.3445	0.3448	0.3355	0.3239
First law Efficiency (COP_$_{HTC}$)	1.448	1.448	1.448	1.448	1.448	1.448
First law Efficiency (COP_$_{LTC}$)	1.695	1.651	1.674	1.689	1.667	1.541
Exergy of Fuel_Cascade "kW"	5.936	6.031	5.981	5.951	5.995	6.861
Exergy_Product_LTC	2.371	2.371	2.371	2.371	2.371	2.371
Work required to run whole system W_{Comp_HTC}"kW"	3.862	3.901	3.880	3.868	3.886	4.006
Work required to run whole system W_{Comp_LTC}"kW"	2.074	2.13	2.10	2.083	2.109	2.283
Total work required to run whole system W_{Comp_Total}"kW"	5.936	6.031	5.981	5.951	5.995	6.861
Cascaded Exergy Destruction Ratio (EDR_$_{MTC}$)	1.504	1.544	1.523	1.510	1.529	1.653
Cascaded Exergetic Efficiency_MTC	0.3994	0.3931	0.3964	0.3984	0.3954	0.3770
Total Exergy Consumption_Cond (%)	24.74	24.69	24.38	24.45	24.10	20.94

Total Exergy Consumption_Comp (%)	16.25	16.27	16.19	16.19	16.21	16.58
Total Exergy Consumption_Eva (%)	4.3112	4.3111	4.3110	4.3113	4.3114	4.3115
Total Exergy Consumption_Valve (%)	20.48	20.16	20.71	20.54	20.73	21.21
Exergy Consumption_Cond_$_{HTC}$ (%)	9.75	9.66	9.87	9.85	9.92	9.03
Exergy Consumption_Comp_$_{HTC}$ (%)	10.16	10.08	10.27	10.25	10.32	11.37
Exergy Consumption_Eva__$_{HTC}$ (%)	1.2113	1.2095	1.2136	1.2132	1.2146	1.2365
ExergyConsumption_Valve__$_{HTC}$ (%)	14.8	14.65	15.98	15.95	16.06	16.8
Exergy Consumption_Cond_$_{LTC}$ (%)	14.98	14.03	14.51	14.59	14.23	9.93
Exergy Consumption_Comp_$_{LTC}$ (%)	6.09	6.192	5.193	5.942	5.886	5.204
Exergy Consumption_Eva_$_{LTC}$ (%)	3.07215	3.07080	3.06280	3.1271	3.1303	3.07456
Exergy Consumption_Valve_$_{LTC}$ (%)	5.683	5.503	4.731	4.595	4.674	4.398

4. Conclusions

Following conclusions were drawn in cascade vapour compression refrigeration systems using HFO refrigerants

- HFO refrigerants can replace R134a in near future due to its thermodynamic performances
- Exergy destruction in the high temperature cycle is higher than lower temperature cycle
- For components wise, the exergy destruction in condenser is highest while in evaporator is lowest
- R1233zd(E) and R-1225ye(Z) gives best thermodynamic (energy-exergy) performances than R134a and R 32 gives lowest thermodynamic performances in low temperature cycle.
- R 32 gives highest power consumption in the high temperature compressor while R1234ze(Z) gives low power consumption in the high temperature compressor.

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