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Thermodynamic performance evaluation of three stages cascaded vapour compression refrigeration systems using ultralow GWP

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Abstract

In this paper, thermodynamic energetic-exergetic performances of three stage cascaded vapour compression is presented using eco-friendly HFOs & HCFO refrigerants for achieving temperature of -150ºC. have been carried using exergy concept. To identifying irreversiblilities in the cascaded vapour compression refrigeration systems (VCRS), the system performance parameter such as exegetic efficiency (i.e. ratio of actual first law efficiency (COP) to the Carnot COP) and exergy destruction ratio (EDR) to be evaluated using ecofriendly refrigerants. The numerical computations for different configurations of cascaded refrigeration systems have been carried out. It was found that cascaded vapour compression refrigeration system using HFO-1233Zd(E) in high temperature cycle (HTC) at -30ºC & HFO-1336 mzz(Z) in medium temperature cycle(MTC) at -75ºC and HFO-1225ye(Z) in lower temperature cycle(LTC) gives better thermodynamic performances than HFO-1233Zd(E) in high temperature cycle (HTC) at -30ºC & HFO-1225ye(Z) in medium temperature cycle(MTC) at -75ºC and HFO-1336 mzz(Z) in lower temperature cycle(LTC). The effect of temperature over lapping on system performances is also investigated

1. Introduction

The eco-friendly technologies which are receiving more and more attention in the days by day of for solving energy and environmental problems using exergy analysis. For designing and analyzing of a number of thermal systems, the conservation of mass and conservation of energy principles together with the second law of thermodynamics are used for exergy analysis to make effective use of nonrenewable resources such as oil, natural gas and coal etc., the exergy analysis is particularly suited for furthering the goal of more efficient resource use, since it enables the location, types and true magnitudes of waste and loss to be determined. Therefore, the exergy concept is used to design several thermal systems and also a guiding efforts to reduce source of in efficiency in the existing systems [1]. For thermodynamic analysis involving exergy concept, it is necessary to develop thermal model where atmospheric conditions are used This model is also called as exergy reference environmental model because exergy is the maximum theoretical work obtainable from the system and the environment. The use of exergy concept in assessing the effectiveness of energy resource utilization. Therefore, exergetic efficiency is the also known as second law efficiency, if final state of system is brought to be at dead state temperature of 298K.Therefore exergetic efficiency is useful for utilizing fossil fuels that are thermodynamically effective from those that are less so. It can also be used to evaluate the effectiveness of engineering measures taken to improvement

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in the performance of any thermal system. This is done by comparing the efficiency values determined before and after modifications have been made to show that how much improvement has been achieved however the exergetic efficiency can be used to determine the potential for improvement in the system performance by comparing the efficiency of carnot (reversible system). The significance difference between these values will suggest the improved performance is possible improved system value [1]. In the refrigeration systems, the exergetic efficiency is the ratio of actual coefficient of performance to the Carnot COP. in other words, it is a ratio of exergy of product to the exergy of fuel. Therefore, exergy destruction ratio, which is a measure of system irreversibilities can be defined as the ratio of total exergy destruction in the system to the exergy of product. The relationship between exergetic efficiency and exergy destruction ratio can be expressed as

$$\text{Exergetic efficiency}=1/(1+EDR)$$

Where EDR_System is known as system exergy destruction ratio. This paper mainly deals with thermodynamic energetic-exergetic performances of three stage cascaded vapour compression is presented using eco-friendly HFOs and HCFO refrigerants for achieving temperature of -150oC for replacing HFC -134a [2].

2. Cascaded vapour compression refrigeration systems

Refrigeration technology plays an important role in human production and life; it is widely used in daily lives, business, and manufacturing. The traditional single-stage compression refrigeration system and absorption refrigeration system are two basic forms of the refrigeration technology. The single-stage compression refrigeration system is used in air conditioning, human life, food storage, and transportation. However, some applications, e.g., rapid freezing and the storage of frozen food, require rather low temperatures in the evaporator (ranging from −30 to −40 ◦C), Mishra [5] found the use of R1234ze(E) gives better thermal performance than R1234yf in the higher temperature circuit of four stage cascade refrigeration system. When the temperature difference between cold energy and heat source increases, the first law efficiency (COP) is decreased; therefore, the application of refrigeration system at a low evaporation temperature is seriously limited. Therefore, Cascaded vapour refrigeration system is to be used to achieve the lower refrigerating evaporator temperature., Normally two circuits mainly high-temperature cycle (HTC) and low-temperature cycle (LTC) are connected to each other through a heat exchanger in the cascaded vapour compression two-staged refrigeration system The cascade absorption refrigeration system is an another type of cascaded vapour refrigeration system that can operate with two or more different refrigerants; the performance of Cascaded vapour refrigeration system with R744 and R717 as working fluids has been analyzed to realize the cold energy production at lower temperatures and found that the cascaded absorption refrigeration system is very appropriate for low heat source temperature and low refrigeration temperature system. Sun et al., [6] found higher COP and thermodynamic performance for evaporation temperatures above −60 °C in the combination of R41/R161 pairs in two stage cascade arrangement is better than using R170. Ming zhang Pan et al., [4] carried out a literature review of the cascade refrigeration system and found−170 °C the evaporator temperature. Wang et al. [7] obtained the influence of thermodynamic system performance parameters of two stage cascaded VCRS working on the R744/R717 as refrigerants and found the increase of COP of cascaded VCRS by increasing the evaporator temperature. Also cooling capacity and COP of CO2 cycle decreased sharply by increase of condenser temperature. Therefore, to obtain a larger cooling capacity by reducing the condenser temperature of CO_2 cycle. With the increase of the CO_2 evaporator temperature and NH_3 condenser temperature, the CO2 the optimum value of condenser temperature is increased Dopazo, J.A. et.al [8] carried out optimization based on the optimum CO_2 condenser temperature and developed correlation of condensation temperature to determined optimal condenser temperature of CO_2 cycle as follows

$$T_{\_Cond\_Opt\_R744} = [-218.78+0.3965*T_{\_Evap\_R744}+0.39064*T_{\_Cond\ R717} + 0.670747*\Delta T] \quad (1)$$

Similarly, Park et al. [9] found the temperature difference in cascade heat exchanger increases, the first law efficiency (COP) is decreased and obtained correlation for the optimal condenser temperature of the cascaded condenser by considering three design parameters (such as T_{Eva}, T_{Cond}, and ΔT,) for computing the maximum COP and optimal condenser temperature of the cascade–condenser as

$$T_{\_Cond\_OPT\ \_LTC}= [40.63 + 0.4*T\_Cond + 0.4*T\_Eva + \Delta T] \quad (2)$$

$$COP_{\_max} = [1.0818 - 0.0221*T\_Cond + 0.0315*T\_Eva - 0.0283*\Delta T] \quad (3)$$

By increasing $T_{\_Cond}$, T_{Eva}, and ΔT, the optimal condensation temperature of a cascade condenser is increased. And the maximum COP is also increased with increasing T_{Eva} while decreases as $T_{Cond,}$ or ΔT is increased Many different refrigerants are used in the vapour compression cycle. Mishra [11] used the zero ODP and low GWP refrigerants including HFO 1234yf, HFO¬1234ze(E), and R1233zd(E) in the vapour compression section. The vapour absorption refrigeration system using Li/Br¬H_2O, cascaded with vapour compression refrigeration using HFO1234yf obtained a less COP as compared to vapour absorption refrigeration system using Li/Br¬H_2O, and vapour compression systems using R1234ze(E) a higher COP. Jain et al. [10] computed the size and cost estimation of Cascaded vapour absorption compression refrigeration system using R410A in compression cycle and Li/Br¬H_2O as working fluid in the absorption refrigeration cycle

3. Results and Discussion

The following vapour compression cascaded refrigeration's have been considered to get - 150ºC of low temperature evaporator temperature using HFO and HCFO refrigerants.

System-1: Cascaded VCRS using R1233zd(E), in HTC andR-1225ye(Z) in MTC and R1336mzz(Z) in LTC

System-2: Cascaded VCRS using R1233zd(E), in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC

System-3: Cascaded VCRS using R1243zf, in HTC and R1233zd(E), and R1336mzz(Z)in LTC

System-4: Cascaded VCRS using R1243zf, in HTC and R1233zd(E), in MTC and R1225ye(Z) in LTC

System-5: Cascaded VCRS using R1234ze(E), in HTC and R1233zd(E) in MTC, and R-R1336mzz(Z)in LTC

System-6: Cascaded VCRS using R-1234ze(E) in HTC, and R1233zd(E), in MTC and R-1225ye(Z) in LTC

System-7: Cascaded VCRS using R1234yf, in HTC and R-1225ye(Z) in MTC, and R1336mzz(Z)in LTC

System-8: Cascaded VCRS using R1234yf, in HTC and R1336mzz(Z) in MTC, and R-1225ye(Z) in LTC.

Table-1: Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva_LTC=35.167 kW, T_Cond=50ºCT_ambient=25ºC,T_Eva=-30ºC, Approach_MTC=10, Approach_LTC=10, Compressor efficiency$_{_HTC}$=80%,T_Eva_MTC= - 95ºC, Eva_LTC= - 150ºC , Compressor efficiency$_{_LTC}$=80% Compressor efficiency$_{_LTC}$=80%)

Performance Parameter	System1	System2	System-3	System-4	System-5	System6	System7	System8
First Law efficiency (COP $_{Cascade}$)	0.2804	0.2887	0.2804	0.2887	0.2804	0.2887	0.2804	0.2887
Exergy Destruction Ratio (EDR $_{Cascade}$)	2.256	2.201	2.455	2.397	2.483	2.401	2.684	2.623
Cascade Exergetic Efficiency	0.3071	0.3124	0.2894	0.2944	0.2871	0.292	0.2714	0.2761
Cascade Exergy of Fuel "kW"	162.7	159.9	172.7	169.7	174.1	171.1	184.1	181.1
Cascade Exergy of Product "kW"	49.97	49.97	49.97	49.97	49.97	49.97	49.97	49.97
HTC Mass flow Rate (Kg/sec)	1.022	1.088	1.174	1.158	1.337	1.319	1.684	1.66
MTC Mass flow Rate (Kg/sec)	0.5737	0.5055	0.5737	0.5055	0.5737	0.5055	0.5737	0.5055
LTC Mass flow Rate (Kg/sec)	0.1882	0.2157	0.1882	0.2157	0.1882	0.2157	0.1882	0.2157
Q_Cond_HTC"kW"	197.9	195.1	207.8	204.9	209.2	206.3	219.3	216.2
Q_Cond_MTC"kW"	123.8	122.0	123.8	122.0	123.8	122.0	123.8	122.0
Q_ Cond _LTC"kW"	71.99	70.14	71.99	70.14	71.99	70.14	71.99	70.14
Q_ EVA _LTC"kW"	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law efficiency(COP$_{_HTC}$)	1.022	1.008	1.472	1.472	1.448	1.448	1.295	1.295
Exergy Destruction Ratio (EDR_ $_{HTC}$)	1.649	1.649	2.004	2.004	2.054	2.054	2.413	2.413
HTC Exergetic Efficiency_	0.3776	0.3776	0.3329	0.3329	0.3275	0.3275	0.2930	0.2930
HTC Exergy of Fuel "kW"	74.14	73.10	84.09	82.9	85.49	84.49	95.53	94.18
HTC Exergy of Product"kW"	27.99	27.6	27.99	27.6	27.99	27.6	27.99	27.6
First Law efficiency COP$_{_MTCascade}$	0.5718	0.5613	0.5299	0.5205	0.5245	0.5152	0.4888	0.4888
Exergy Destruction Ratio (EDR $_{MTCascade}$)	1.596	1.645	1.801	1.852	1.83	1.882	2.037	2.091
Exergetic Efficiency_ MTCascade	0.3851	0.3781	0.357	0.3506	0.3533	0.347	0.3292	0.3235
Exergy of Fuel _ $_{MTCascade}$ "kW"	125.9	125.0	135.9	134.8	137.3	136.2	147.3	146.1
Exergy of Product ($_{MTCascade}$) "kW	48.49	47.49	48.49	47.49	48.49	47.49	48.49	47.49
First Law efficiency COP$_{_MTC}$	1.391	1.352	1.391	1.352	1.391	1.352	1.391	1.352
First Law efficiency COP$_{_LTC}$	0.955	1.005	0.955	1.005	0.955	1.005	0.955	1.005
HTC compressor Work"kW	74.14	73.10	84.09	82.9	85.49	84.49	95.53	94.18
MTC compressor Work"kW"	51.77	51.87	51.77	51.87	51.77	51.87	51.77	51.87
LTC compressor Work"kW"	36.83	34.97	36.83	34.97	36.83	34.97	36.83	34.97

The thermodynamic performance of several systems mentioned above have been numerically computed it was was found that the best combination of system is the cascaded vapour compression refrigeration systems using R1233zd(E),in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC, in which less electrical power consumptions required for running the whole cascaded VCRS as compared to other seven cascaded VCRS. The thermodynamic performance of several systems mentioned above have been numerically computed it was was found that the best combination of system is the cascaded VCRS using R1233zd(E), in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC, in which less electrical power consumptions required for running the whole cascaded vapour compression refrigeration system as compared to other seven cascaded VCRS. The following vapour compression cascaded refrigeration have been considered to get - 135ºC of low temperature evaporator temperature using HFO and HCFO.

System-1: Cascaded VCRS using R1224yd(Z), in HTC andR-1225ye(Z) in MTC and R1336mzz(Z) in LTC

System-2: Cascaded VCRS using R1224yd(Z), in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC

System-3: Cascaded VCRS using R1234ze(E), in HTC and R1233zd(E) in MTC, and R-R1336mzz(Z)in LTC

System-4: Cascaded VCRS using R-1234ze(E) in HTC, and R1233zd(E), in MTC and R-1225ye(Z) in LTC.

System-5: Cascaded VCRS using R1243zf, in HTC and R1233zd(E), and R1336mzz(Z)in LTC

System-6: Cascaded VCRS using R1243zf, in HTC and R1233zd(E), in MTC and R1225ye (Z) in LTC.

System-7: Cascaded VCRS using R1233zd(E), in HTC andR-1225ye(Z) in MTC and R1336mzz(Z) in LTC.

System-8: Cascaded VCRS using R1233zd(E), in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC

System-9: Cascaded VCRS using R1234yf, in HTC and R-1225ye(Z) in MTC, and R1336mzz(Z)in LTC

System-10: Cascaded VCRS using R1234yf, in HTC and R1336mzz(Z) in MTC, and R-1225ye(Z) in LTC

The thermodynamic performance of several systems mentioned above have been numerically computed it was was found that the best combination of system is the cascaded VCRS using R1224yd(Z),in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC, in which less electrical power consumptions required for running the whole cascaded vapour compression refrigeration system as compared to other nine cascaded VCRS as shown in Table-2 respectively .

Table-2: Thermodynamic performances of cascaded vapour compression refrigeration system using ecofriendly low GWP refrigerants (Q_Eva_LTC=35.167 kW, T_Cond=50ºCT_ambient=25ºC, T_Eva=-10ºC, Approach_MTC=10, Approach_LTC=10, Compressor efficiency_$_{HTC}$=80%, T_Eva_MTC= - 75ºC, Eva_LTC= - 135ºC, Compressor efficiency_$_{LTC}$=80% Compressor efficiency_$_{LTC}$=80%)

Performance Parameter	System 1	System 2	System-3	System-4	System-5	System 6	System 7	System 8	System 9	System 10
COP_$_{Cascade\ three\ staged\ VCRS}$)	0.3178	0.3309	0.3178	0.3309	0.3178	0.3309	0.3178	0.3309	0.3178	0.3309
EDR_ $_{Cascade\ three\ staged\ VCRS}$	1.952	1.86	2.04	1.946	2.038	1.944	1.964	1.886	2.141	2.045
Exergetic Efficiency_ $_{Cascade}$	0.3387	0.3496	0.3289	0.3394	0.3291	0.3396	0.3374	0.3465	0.3183	0.3284
Exergy of Fuel $_{Cascade\ three\ staged\ VCRS}$	120.2	116.50	123.80	120.0	123.80	199.90	120.70	117.50	127.90	124.0
Exergy of Product $_{Cascade\ 3\ stage\ VCRS}$	40.73	40.73	40.73	40.73	40.73	40.73	40.73	40.73	40.73	40.73
HTC Mass flow Rate (Kg/sec)	1.005	0.9804	1.054	1.029	0.9449	0.9222	0.8397	0.8226	1.296	1.265
MTC Mass flow Rate (Kg/sec)	0.4497	0.4389	0.4497	0.4389	0.4497	0.4389	0.4497	0.4389	0.4497	0.4389
LTC Mass flow Rate (Kg/sec)	0.2065	0.2325	0.2065	0.2325	0.2065	0.2325	0.2065	0.2325	0.2065	0.2325
Q_Cond_HTC“kW”	120.2	151.7	159.0	155.2	158.9	155.1	155.9	152.7	163.1	159.2
Q_Cond_MTC“kW”	112.5	109.8	112.5	109.8	112.5	109.8	112.5	109.8	112.5	109.8
Q_ Cond _LTC“kW”	68.49	66.84	68.49	66.84	68.49	66.84	68.49	66.84	68.49	66.84
Q_ EVA _LTC“kW”	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167	35.167
First Law efficiency COP_HTC	2.622	2.622	2.42	2.42	2.424	2.424	2.691	2.691	2.223	2.223
HTC Exergy Destruction Ratio	1.867	1.867	1.618	2.107	2.102	2.102	1.794	1.794	2.382	2.382
Exergetic Efficiency HTC	0.3488	0.3488	0.3219	0.3219	0.3223	0.3223	0.3579	0.3579	0.2957	0.2957
Exergy of Fuel _HTC “kW”	42.9	41.87	46.49	45.37	46.42	45.30	42.23	41.37	50.61	49.39
Exergy of Product _HTC “kW”	14.96	14.6	14.96	14.96	14.96	14.96	15.12	14.81	14.86	14.6
Cascaded COP_$_{MTCascade}$	0.788	0.788	0.7567	0.7567	0.7573	0.7573	0.7836	0.7783	0.7238	0.7238
Cascaded EDR	1.515	1.515	2.107	1.618	1.617	1.617	1.794	1.546	1.738	1.738
Exergetic Efficiency $_{MTCascade}$	0.3977	0.3977	0.3819	0.3819	0.3822	0.3822	0.3955	0.3928	0.3653	0.3653
Cascaded Exergy of Fuel “kW”	86.92	84.82	90.5	88.32	90.44	88.26	87.4	85.87	94.62	92.34
Cascaded Exergy of Product “kW	34.56	33.73	34.56	33.73	34.56	33.73	34.56	33.73	34.56	33.73
First Law efficiency COP_$_{MTC}$	1.556	1.556	1.556	1.556	1.556	1.556	1.556	1.556	1.556	1.556
First Law efficiency COP_$_{LTC}$	1.055	1.11	1.055	1.11	1.055	1.11	1.055	1.11	1.055	1.11
HTC compressor Work “kW	42.9	41.87	46.49	45.37	46.42	45.30	42.23	41.37	50.61	49.39
MTC compressor Work “kW”	44.02	42.95	44.02	42.95	44.02	42.95	44.02	42.95	44.02	42.95
LTC compressor Work“kW”	33.32	31.67	33.32	31.67	33.32	31.67	33.32	31.67	33.32	31.67

4. Conclusions

Following conclusions were drawn from present investigation.

(i) For Getting ultra-low evaporator temperature of (-150ºC) using R1225ye(Z) in LTC and -95ºC in medium evaporator temperature cycle using R-1336mzz(Z) and -30ºC using R1233yd(Z) of high temperature evaporator with 10ºC temperature overlapping in temperature between MTC condenser and HTC evaporator (Approach_MTC) and temperature overlapping in temperature between LTC condenser and 10ºC of MTC evaporator (Approach_LTC) using 80% of all three compressor's efficiency for a 35.167 kw of cooling load capacity, the best combination of system is the cascaded vapour compression refrigeration systems using R1233zd(E),in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC, in which less electrical power consumptions required for running the whole cascaded vapour compression refrigeration system as compared to other seven cascaded VCRS.

(ii) For Getting ultra-low evaporator temperature of (-135ºC), using R1225ye(Z) and -75ºC in medium evaporator temperature cycle using R-1336mzz(Z) and -10ºC using R1233yd(Z) of high temperature evaporator with 10ºC temperature overlapping in temperature between MTC condenser and HTC evaporator (Approach_MTC) and temperature overlapping in temperature between LTC condenser and 10ºC of MTC evaporator (Approach_LTC) using 80% of all three compressor's efficiency for a 35.167 kw of cooling load capacity the best combination of system is the cascaded vapour compression refrigeration systems using R1233zd(E),in HTC and R1336mzz(Z)in MTC and R-1225ye(Z) in LTC, in which less electrical power consumptions required for running the whole cascaded vapour compression refrigeration system as compared to other seven cascaded Vapour compression refrigeration systems.

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