International Journal of Research in Engineering and Innovation (IJREI)
journal home page: http://www.ijrei.com
ISSN (Online): 2456-6934

Thermal optimization of three stage vapour compression cascade refrigeration system using entropy generation principle for reducing global warming and ozone depletion using ecofriendly refrigerants

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Abstract

Lot of literature review is available on vapour compression cascade refrigeration system so far. But these investigator has not optimized the performance parameters at optimum condition and also not computed optimum second law performances based on optimum performance parameters. In this papers, optimum performance have been predicted for optimum conditions for two cascade refrigeration systems. It was observed that optimum Evaporator temperature in high temperature circuit using R1234ze ecofriendly refrigerant is ranging from 269K to 270K Optimum evaporator temperature in medium (intermediate temperature circuit using (R1234yf) is ranging from 229K to 230K. The optimum evaporator temperature in low temperature circuit is ranging from 183 to 186K using R134a and R404a ecofriendly refrigerants. The thermodynamic performances for these optimum performance parameters for two cascade refrigeration systems have been presented.

Keywords: Low temperature Refrigeration, Cascade system, Energy-Exergy analysis, Parameter optimizations

1. Introduction

Low-temperature refrigeration systems are typically required for low temperature range from –40°C to –100°C for applications chemical, food, pharmaceutical, and other industries. Cascade refrigeration cycles are commonly used in the liquefaction of natural gas, which consists basically of hydrocarbons of the paraffin series, of which methane has the lowest boiling point at atmospheric pressure. Refrigeration down to that temperature can be provided by a ternary cascade refrigeration cycle using propane, ethane and methane, whose boiling points at standard atmospheric pressure .The high-temperature circuit uses high boiling point refrigerants such as R-1234ze, R 717 and R152a and Intermediate circuit's ecofriendly refrigerants such as R-1234yf, etc. are used. Similarly for the low-temperature cascade circuit low boiling refrigerants R134a, 404a, R This paper mainly deals with thermodynamic optimization of three stages cascade vapour compression refrigeration systems using ecofriendly refrigerants used for low temperature applications. The effect of optimum thermal performance parameters (i.e. approaches, condenser temperature, and temperature variations in the evaporators) on the first law thermal performances in terms of the system COP, and also in terms of second law efficiency exergetic Efficiency of the cascade system and System exergy destruction ratio (SEDR) have been computed thermodynamically using entropy generation principle. The utility of R1234ze in the high temperature circuit and R1234yf in the medium (intermediate) temperature circuits and new ecofriendly refrigerants in the intermediates circuits and R134a or R404a in the low temperature cascade circuit between-80oC to -100oC) applications have been optimized.. It was observed that the best combination in terms of R1234ze-R1234yf -R134a gives better thermal performance than using R-1234ze-R1234yf-R404a. The optimum Evaporator temperature in High temperature circuit, and optimum Evaporator temperature in medium temperature circuit and Low temperature evaporator have been predicted and their thermal performance have been presented in this paper.

2. Literature Review

Mishra [1] work carried out critical issue in the field of green technologies is to develop the relationship between ODP and GWP and suggest new and alternative refrigerants which do

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not damage ozone layer and not to increase global warming. The Numerical computation have been carried out using energy - exergy Analysis of two and three stages cascade vapour refrigeration system of 10 ton capacity for seven eco-friendly refrigerants such as R-1234yf and R-1234ze in high temperature circuit, and R134a , R-404a, R-407C, R-502, propane(R-290), isobutene (R-600a), butane (R-600)) in lower temperature circuit in two stage and above refrigerants in intermediate circuit in three stage system. The performance parameters such as COP, EDR, exegetic efficiency, have been predicted. Lima et.al. [2] studied thermodynamic performance of a cascade refrigeration system using the refrigerant R22 as the working fluid in the high temperature circuit (HT) and the refrigerant R404a as the working fluid in the low temperature circuit (LT) and developed thermodynamic analysis to obtain the evaporation temperature in high temperature cycle , ,condensing temperature of the LT and effect of temperature overlapping (effect of approach) which provides the optimal value for first law efficiency in terms of coefficient of performance (COP) of the cycle and compared with experimental results obtained from a prototype which showed closed agreement and found that by increasing the intermediate temperature varied COP of the system. Messineo et.al.[3] presented thermodynamic analysis of a cascade refrigeration system working at TE=-35^{0}C and TC= 35^{0}C using six different refrigerants in the HTC,in which three were natural refrigerants (R717, R290 and R600), and three were synthetic refrigerants (R404A, R410A and R134a).along with carbon dioxide In the Low temperature circuit, and concluded that , the results obtained show that a cascade refrigeration system using natural refrigerants is an interesting alternative to systems as compared to the synthetic refrigerants for energetic, security and environmental reasons. Prasanna et.al [4] studied comparison of synthetic and natural refrigerants in cascade refrigeration system for low temperature application. Synthetic refrigerants have been used in all refrigeration systems and comparison of various refrigerant pairs such as R507-R23, R717-R23, R290-N2O, and R717- N_2O. The System performance was predicted with the variation in evaporator temperature, condensing temperature, isentropic efficiency of compressor, temperature overlap in cascade condenser. The computed Results shows that, COP of the system with R717-N_2O is higher than other pairs and it can also be used as alternative refrigerant for low temperature application in vapour compression cascade refrigeration system. M. Idrus Alhamid et.al [5] builds a prototype cascade refrigeration machine using the environmentally friendly hydrocarbon refrigerants (propane, ethane and CO and compared thermal performances in terms of COP with experimental COP. Nimai et.al [6] developed theoretical model of solar-assisted cascade refrigeration system in cold storage. The system consists of electricity-driven vapor compression refrigeration system and solar-driven vapour absorption refrigeration system. The vapour compression refrigeration system was connected in series with vapour absorption refrigeration system. The computed results shows higher COP as compared with the conventional vapour compression refrigeration system. Parmar et.al [7] studied thermodynamic analysis of eco-friendly/natural fluids used in cascade refrigeration systems. He used R744 is used in Low-temperature cycle whereas R134a, R290, R717 and R404a (R125 (44%)/R143a (52%)/R134a (4%)) are used in the High-temperature cycle. The effects of evaporator temperature, condenser temperature and temperature overlapping (in terms of temperature difference in cascade condenser and low temperature cycle condenser temperature) on the thermal performance parameters in terms of . COP and refrigerant mass flow ratio have been computed. Dopazo et.al [8] used statistical procedure to analyse the parameters of design and operation of a CO cascade cooling system and their effect on the system's COP and exergetic efficiency. The analysis was carried through his mathematical model the first law efficiency in terms of system's COP and its second law efficiency in terms of exergetic efficiency. Heobtained functional relationship between six design/operating parameters using statistical procedure and obtained parametric results. Rawat et.al [9] developed thermodynamic model for cascade refrigeration system using NH3 in high temperature circuit (HTC) and CO2 in low temperature circuit (LTC) at different operating conditions to find out the effect of various designs and operating parameters on the thermal performance of the cycle. These design and operating parameters include: condenser temperature; evaporator temperature; coupling temperature; compressor isentropic efficiency and temperature difference in cascade heat exchanger and observed that the use of internal heat exchanger has undesirable effect on the performance of the R744-R717 cascade system and also advisable that, internal heat exchanger should be never used for this pair of refrigerants in cascade system. However, degree of sub cooling always desirable feature in R744-R717 cascade system. Messineo [10] developed thermodynamic model of a cascade refrigeration system using as refrigerant carbon dioxide in low-temperature circuit and ammonia in high-temperature circuit. The operating parameters include condensing, evaporating, superheating and sub cooling temperatures in the ammonia (R717) high temperature circuit and in the carbon dioxide (R744) low-temperature circuit. The computed Results show that a carbon dioxide-ammonia cascade refrigeration system is an interesting alternative toR404A two-stage refrigeration system for low evaporating temperatures (–30°C to –50(°C) in commercial refrigeration for energy, security and environmental reasons. Winkler et.al [11] developed component-based simulation model for vapour compression cascade systems and predicted COP. Gami et.al [12] developed thermodynamic energy and exergy analysis for two cascade refrigeration systems using refrigerants pairs R134a R23and R290-R23 to optimize the operating parameters of the system. The computed results show that COP and exergetic efficiency decreases when degree of superheating increases in LT system and increases when degree of superheating increases in HT system and also be remain constant when degree of superheating increases in HT and LT system and founds that COP and exergetic efficiency increases when degree of sub cooling increases in all two systems B. Agnew, et.al [13] conducted finite time analysis of a cascade refrigeration system using alternative refrigerants. Bansal P.K [14] used thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system.

3. Modelling Three Stage Vapour Compression Cascade Refrigeration Systems using ecofriendly Refrigerants

The following assumptions have been taken for analyzing three stages cascade vapour compression system for low temperature applications. The cooling load in the low temperature evaporator is considered to be 70 [kW]. Temperature of condenser using R1234ze is to be 50^0C and temperature of high temperature circuit evaporator to be 0^0C, The temperature of low temperature evaporator to be -100^0C, temperature of secondary intermediate cascade evaporator using R1234yf is to be -50^0C, The effect of temperature overlapping (approach means temperature difference between cascade condenser and cascade evaporator is 10^0C in each stage is considered

4. Result and Discussion

Three stages cascade vapour compression refrigeration have been considered and following optimum values have been found were shown in Table-1-8 respectively.

T_Eva2=-43 (oC),T_eva3=-89^0C T_Cond=50^0C, Approach_1=Approach_2=10 and Q_Eva3=70”kW”
Compressor Efficiency-1= Compressor Efficiency-2= Compressor Efficiency-3=0.8

Table- 1: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-134a refrigerants.

T_EVA_1 (oC)R134a	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-3	0.6029	1.68	0.3732	2.944	2.90	2.098
-4	0.6018	1.682	0.3729	2.861	2.979	2.098

T_Eva2=-43 (oC),T_eva3=-89^0C, T_Cond=50^0C Approach_1=Approach_2=10 and Q_Eva3=70”kW”

Table-2: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-404a refrigerants.

T_EVA_1 (oC)R404a	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-3	0.5966	1.744	0.3644	2.944	2.51	2.333
-4	0.5964	1.745	0.3643	2.861	2.575	2.333
-5	0.5962	1.746	0.3641	2.78	2.643	2.333

.T_Eva2=-44 (oC),T_eva3=-89^0C, T_Cond=50^0C Approach_1=Approach_2=10 and Q_Eva3=70”kW”

Table-3: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-407c refrigerants

T_EVA(oC)	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-3	0.6019	1.681	0.3729	2.944	2.815	2.147
-4	0.6015	1.683	0.3727	2.861	2.892	2.147

T_Eva2=-43 (oC),T_eva3=-89^0C, T_Cond=50^0C Approach_1=Approach_2=10 and Q_Eva3=70”kW”

Table-4: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R404a refrigerants.

T_EVA3 (oC)	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-88	0.6104	1.682	0.3729	2.861	2.892	2.21
-89	0.6015	1.683	0.3727	2.861	2.892	2.147
-90	0.5927	1.685	0.3725	2.861	2.892	2.086

T_Eva2=-43 (oC),T_eva1=-3^0C T_Cond=50^0C Approach_1=Approach_2=10 and Q_Eva3=70”kW

Table- 5: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-134a refrigerants.

T_EVA3 (oC)	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-87	0.6053	1.744	0.3645	2.944	2.51	2.405
-88	0.5966	1.744	0.3644	2.944	2.51	2.333
-89	0.5879	1.745	0.3643	2.944	2.51	2.264

T_Eva1=-4 (oC),T_eva3=-89^{0}C T_Cond=50^{0}C Approach_1=Approach_2=10 and Q_Eva3=70"kW

Table- 6: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-134a refrigerants.

T_EVA(oC) R134a	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-43	0.6018	1.682	0.3729	2.861	2.979	2.098
-44	0.6015	1.683	0.3727	2.861	2.892	2.147

T_Eva1=-4 (oC),T_eva3=-89^{0}C T_Cond=50^{0}C Approach_1=Approach_2=10 and Q_Eva3=70"kW

Table- 7: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-134a refrigerants.

T_EVA (oC)R404a	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-47	0.5970	1.742	0.3647	2.944	2.582	2.2768
-48	0.5966	1.744	0.3644	2.944	2.51	2.333
-49	0.5960	1747	0.3640	2.944	2.441	2.392

T_Eva1=-4 (oC),T_eva3=-89^{0}C, T_Cond=50^{0}C Approach_1=Approach_2=10 and Q_Eva3=70"kW

Table- 8: Optimum Performance of three stages Cascade Refrigeration Systems using ecofriendly R1234ze-R1234yf-R-134a refrigerants.

T_EVA(oC) R134a	COP_Overall	EDR_Overall	ETA_Second	COP_HTC	COP_MTC	COP_LTC
-43	0.6023	1.68	0.3732	2.944	2.90	2.098
-44	0.6019	1.681	0.3729	2.944	2.815	2.147

Table-1 showing the optimum first law efficiency of the three stage cascade refrigeration system usingR1234ze in the high temperature circuit and R1234yf in the secondary cascade intermediate temperature circuit and R134a in a lower temperature circuit. It was observed that the use of R1234ze in higher temperature circuit gives better thermodynamic performance than using R1234yf in high temperature circuit up to temperature range of -30oC. However for low temperature applications. The best combination of three stage cascade is system is to be R1234ze-R1234yf-R134a as compared to R1234ze-R1234yf-R404a. Therefore R1234ze-R1234yf-R134a is most suitable for practical applications. Because of The other refrigerants such as R123 and hydrocarbons containing chlorine and R152a, R600a , R290and R600 are also flammable in nature can be considered by adopting safety measures while R717 in toxic in nature.

5. Conclusions

The following conclusions were drawn while optimizing performance parameters in the three stages cascade refrigeration systems.

(i) The use of R1234ze has replaced in high temperature circuit of three stages cascade refrigeration systemas compared to R717 which is toxic in nature.

(ii) There is significant performance improvements using R1234yf in the intermediate temperature circuit as compared with R407c.

(iii) The second law efficiency using R134a in the low temperature evaporator circuit gives better performance as compared with R404a in low temperature circuit.

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