

COMPARATIVE ANALYSIS OF CASCADE REFRIGERATION SYSTEM BASED ON ENERGY AND EXERGY USING DIFFERENT REFRIGERANT PAIRS

Vipin Kumar^{1,*}, Munawar Nawab Karimi², Sandeep Kumar Kamboj¹

ABSTRACT

In this study a comparative analysis on the basis of energy and exergy of cascade refrigeration system using different refrigerant pair, R13 for low temperature cycle (LTC) and R134a, R290 and R717 for high temperature cycle (HTC) has been done by mathematical simulation using Engineering Equation Solver (EES-V9.224-3D). The analysis of cascade refrigeration system has been carried out at different operating condition and result has been compared with effect of various operating parameters. The range of evaporator temperature of LTC is taken from -53°C to -70°C, which represents the most common operating condition in commercial applications. The range of condenser temperature of LTC is from -11°C to -2°C and evaporator temperature of HTC from -19°C to -10°C. Results show that the refrigerant pair R13-R717 is the best suitable refrigerant pair for proposed cascade refrigeration system in comparison to other used refrigerant pairs and R717 can be a interesting alternative refrigerant to R134a and R290 for high temperature cycle of cascade refrigeration system in commercial applications.

Keywords: Cascade Refrigeration System, High Temperature Circuit, Low Temperature Circuit, COP

INTRODUCTION

Today the demand of energy is increasing day by day in the field of thermal comfort. And to get low temperature, cascade refrigeration system is being widely used in many industrial applications. Cascade refrigeration system is combination of more than one refrigeration systems that works independently.

The low temperature cycle provides the desired refrigeration effect at a relatively low temperature. The condenser in the low temperature cycle is thermally coupled to the evaporator in the high temperature cycle. Thus, the evaporator in the high temperature cycle only serves to extract the heat released by the condenser in the low temperature cycle. Then this heat is rejected to the ambient air or water stream in the condenser of the high temperature cycle. A cascade refrigeration system can operate with a low evaporating temperature, lower compression ratio and high compressor volumetric efficiency in comparison with a single-stage refrigeration system.

Refrigerant in Low temperature cycle enters the compressor as a saturated vapour, after extracting the heat from the space to be cooled and as it gets compressed, the temperature and pressure increases. After exiting from the compressor, the refrigerant passes through the cascade condenser where heat is transferred to the evaporator of the high temperature cycle. Finally, the refrigerant enters the throttling valve, gets expanded and the cycle repeats itself.

LITERATURE REVIEW

In many industrial and medical applications, we need temperature below -40°C for that, a single stage vapour compression system can't be used [1]. Among all the refrigerants, selection of refrigerant is very important. The selected refrigerant must have low global warming potential (GWP) and zero ozone depletion potential (ODP). There are some natural refrigerants like NH₃ and CO₂, which are being widely used in many industrial refrigeration systems [1, 4, 6]. Advance exergy analysis gives the more accurate results which provide the recommendations for refrigeration system improvement. Advanced exergy performance analysis gives better results in comparison to conventional energy analysis [15].

Ehsan G et. al.[1] evaluated a cascade refrigeration system based on advanced exergy analysis and suggested that throttling valve, compressor and cascade heat exchanger needs more improvements. Umesh C.R. [2] evaluated the performance of cascade refrigeration system with refrigerant pair R404a-R23. S Ponsankar et. al.[6]

This paper was recommended for publication in revised form by Regional Editor Erdal Çetkin

¹Vidya College of Engineering, India

²Jamia Millia Islamia, New Delhi, India

*E-mail address: ervipinkumar09@gmail.com

Orcid id: 0000-0003-4530-019X, 0000-0002-9637-6859

Manuscript Received 06 March 2019, Accepted 23 July 2019

performed the irreversibility analysis of cascade refrigeration system with different refrigerant pair and concluded that increment in evaporator temperature will increase COP and decrease the system irreversibility. Refrigerant pair R134a-R23 has minimum irreversibility.

Nasruddini et. al. [7] performed the thermodynamic optimization of cascade refrigeration system with environment friendly refrigerant pair and finds the optimum exergy efficiency and its relation with cost. Sertac S.S. et.al. [13] has analyzed exergy for a two stage cascade refrigeration system with flash tank using R600, R290, R152a, and R141b as refrigerants. He has calculated the exergy value of all the components using EES and concluded that the flash tank has minimum exergy loss and with R141a refrigerant, the total irreversibility loss is minimum. Yasin U. A. et. al.[15] analyzed a cascade refrigeration system based on exergetic performance coefficient and finds that refrigerant couple R23-R717 gives the best result.

S.M. H. mohammadi et. al.[17] has analyzed a cascade refrigeration system consisting of a compression and an absorption chillers. He has shown that such a system would increase the efficiency of the energy usage up to 50% compared to a traditional single stage air conditioning system. Bayram K et. al.[19] worked on exergy analysis of two stage refrigeration system and calculated the optimum COP value and optimum irreversibility values. Mohammad I. A. et. al. [21] performed energy and exergy analysis with R744 –R170 and calculated the optimum mass flow rate in terms of evaporator temperature, condenser temperature and cascade condenser temperature.

SYSTEM DESCRIPTION

Fig. 1 shows the diagram of cascade refrigeration system and Fig. 2 , P-h diagram of cascade refrigeration system. This cascade refrigeration system contains two separate refrigeration system.

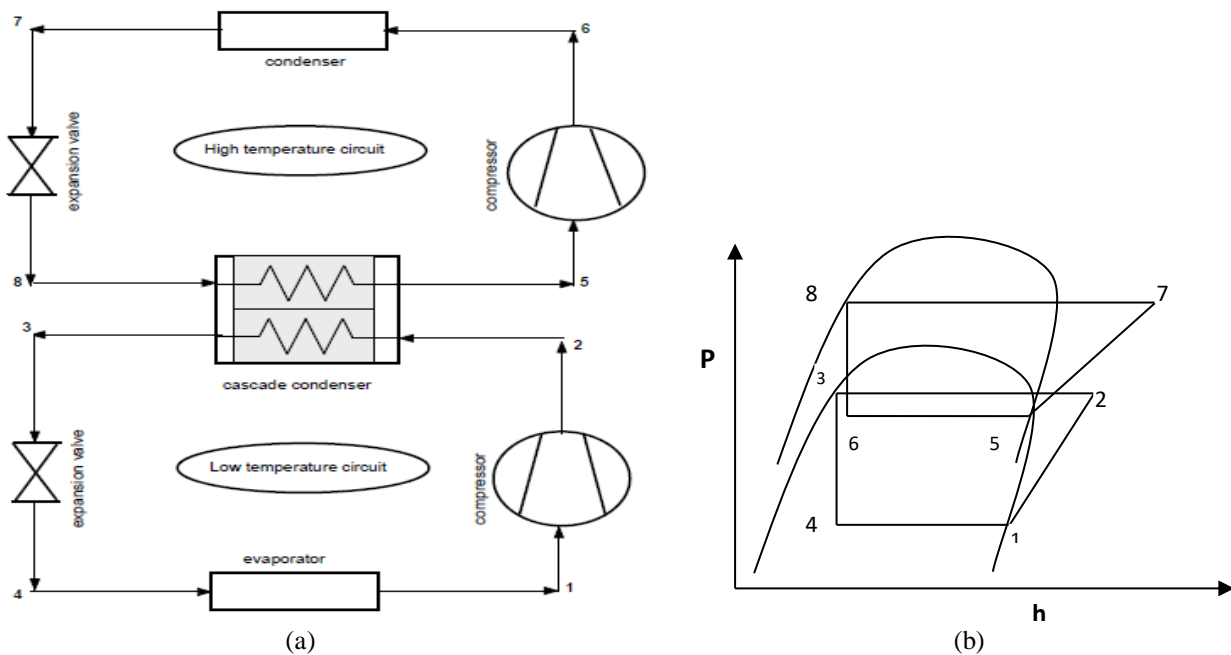


Figure 1. Cascade vapour compression refrigeration system (a) Schematic (b) P-h diagram

In this proposed system the temperature of evaporator in low temperature cycle is ranged between -70°C to -53°C , the temperature of condenser in high temperature cycle is ranged between -11°C to -2°C , and the temperature of evaporator in high temperature cycle is ranged between -19°C to -10°C . The entering refrigerant to the compressor for both low temperature and high temperature cycle are taken as saturated vapour.

METHODOLOGY

- In this analysis a set of equation for energy and exergy balance is prepared.
- EES software is used to solve these equations
- The result is compared by using different refrigerant pair for cascade refrigeration system.

GENERAL ASSUMPTIONS

- The system operates at steady state condition.
- The kinetic and potential energy changes are negligible.
- Pressure and heat loss in pipe network or system components are neglected.
- The mechanical efficiency of each compressor is assumed to be 0.85.
- The cooling demand of refrigeration system is 70kW.
- The ambient temperature is 30°C.

GOVERNING EQUATIONS FOR MATHEMATICAL MODELING

The mass, energy and exergy balance equation are applied for all the components in proposed system.

Mass balance equation

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)$$

where \dot{m} is mass flow rate.

Energy balance equation

$$\dot{Q} + \sum_{in} \dot{m} h = \dot{W} + \sum_{out} \dot{m} h \quad (2)$$

where \dot{Q} is, heat transfer rate and \dot{W} is work transfer rate and h is specific enthalpy

Exergy balance equation

$$\sum \dot{E}_{X_{in}} = \sum \dot{E}_{X_{out}} + \dot{E}_{X_D} \quad (3)$$

where $\dot{E}_{X_{in}}$ and $\dot{E}_{X_{out}}$ are exergy rate at inlet and outlet of system respectively. \dot{E}_{X_D} is exergy destruction rate.

Exergy balance for control volume

$$\dot{E}_{X_D} = \Sigma[(1 - \frac{T_0}{T})\dot{Q}]_{out} - \dot{W} + \Sigma(\dot{m}e)_{in} - \Sigma(\dot{m}e)_{out} \quad (4)$$

Specific equation for each components of cascade refrigeration system:

For high temperature circuit:

i) Compressor

Mass balance:

$$\dot{m}_6 = \dot{m}_5 \quad (5)$$

Energy balance:

$$\dot{W}_{HTC} = \frac{\dot{m}_5(h_{6s} - h_5)}{\eta_{m,HTC}} \quad (6)$$

where \dot{W}_{HTC} is work rate and $\eta_{m,HTC}$ is mechanical efficiency of compressor of high temperature cycle.

Exergy balance:

$$(\dot{E}_{X_D})_{HTC,comp} = \dot{W}_{HTC} - \dot{m}_5[(h_6 - h_5) - T_0(S_6 - S_5)] \quad (7)$$

where $(\dot{E}_{X_D})_{HTC,comp}$ is exergy destruction rate of compressor of high temperature cycle.

ii) Expansion valve

Mass balance:

$$\dot{m}_8 = \dot{m}_7 \quad (8)$$

Energy balance:

$$h_7 = h_8 \quad (9)$$

Exergy balance:

$$(\dot{E}_{X_D})_{HTC,exp} = \dot{m}_8 T_0 (S_7 - S_8) \quad (10)$$

where $(\dot{E}_{X_D})_{HTC,exp}$ is the exergy destruction rate of expansion valve of high temperature cycle.

iii) Condenser

Mass balance:

$$\dot{m}_7 = \dot{m}_6 \quad (11)$$

Energy balance:

$$\dot{Q}_{HTC,con} = \dot{m}_7 (h_6 - h_7) \quad (12)$$

where $\dot{Q}_{HTC,con}$ is the heat rate of condenser of high temperature cycle.

Exergy balance:

$$(\dot{E}_{X_D})_{HTC,con} = \dot{m}_7 [(h_6 - h_7) - T_0 (S_6 - S_7)] \quad (13)$$

where $(\dot{E}_{X_D})_{HTC,con}$ is exergy destruction rate of condenser of high temperature cycle.

iv) Cascade condenser

Mass balance:

$$\dot{m}_5 = \dot{m}_8, \dot{m}_3 = \dot{m}_2 \quad (14)$$

Energy balance:

$$\dot{Q}_{LTC,con} = \dot{m}_5 (h_5 - h_8) = \dot{m}_3 (h_3 - h_2) \quad (15)$$

where $\dot{Q}_{LTC,con}$ is heat rate of condenser of low temperature cycle.

Exergy balance:

$$(\dot{E}_{X_D})_{LTC,con} = \dot{m}_5 [(h_5 - h_8) - T_0 (S_5 - S_8)] - \dot{m}_3 [(h_3 - h_2) - T_0 (S_3 - S_2)] \quad (16)$$

where $(\dot{E}_{X_D})_{LTC,con}$ is exergy destruction rate of condenser of low temperature cycle.

For low temperature circuit

v) Compressor

Mass balance:

$$\dot{m}_1 = \dot{m}_2 \quad (17)$$

Energy balance:

$$\dot{W}_{LTC} = \frac{\dot{m}_1(h_{2s}-h_1)}{\eta_{m,LTC}} \quad (18)$$

where \dot{W}_{LTC} is work transfer rate of compressor of low temperature circuit.

Exergy balance:

$$(\dot{E}_{XD})_{LTC,comp} = \dot{W}_{LTC} + \dot{m}_1[(h_2 - h_1) - T_0(S_2 - S_1)] \quad (19)$$

where $(\dot{E}_{XD})_{LTC,comp}$ is exergy destruction rate of compressor of low temperature cycle.

vi) Expansion valve

Mass balance:

$$\dot{m}_4 = \dot{m}_3 \quad (20)$$

Energy balance :

$$h_4 = h_3 \quad (21)$$

Exergy balance:

$$(\dot{E}_{XD})_{LTC,exp} = \dot{m}_3 T_0(S_3 - S_4) \quad (22)$$

where $(\dot{E}_{XD})_{LTC,exp}$ is exergy destruction rate of expansion valve of low temperature cycle.

vii) Evaporator

Mass balance:

$$\dot{m}_1 = \dot{m}_4 \quad (23)$$

Energy balance:

$$\dot{Q}_{LTC,evap} = \dot{m}_1(h_1 - h_4) \quad (24)$$

where $\dot{Q}_{LTC,evap}$ is heat transfer rate of evaporator of low temperature cycle.

Exergy balance:

$$(\dot{E}_{XD})_{LTC,evap} = (1 - \frac{T_0}{T_E})\dot{Q}_{LTC,evap} + \dot{m}_1[(h_4 - h_1) - T_0(S_4 - S_1)] \quad (25)$$

where $(\dot{E}_{XD})_{LTC,evap}$ is the exergy destruction rate of evaporator of low temperature cycle.

The COP of high temperature cycle has been calculated by the following equations:

$$COP_{HTC} = \frac{\dot{Q}_{HTC,evap}}{\dot{W}_{HTC}} \quad (26)$$

And for low temperature cycle

$$COP_{LTC} = \frac{\dot{Q}_{LTC,evap}}{\dot{W}_{LTC}} \quad (27)$$

The cascade system total COP is calculated by the following equation:

$$COP_{total} = \frac{\dot{Q}_{LTC,evap}}{W_{HTC} + W_{LTC}} \quad (28)$$

And the Carnot COP is calculated by

$$COP_{carnot} = \frac{T_E}{T_C + T_E} \quad (29)$$

Second law efficiency is calculated by:

$$\eta_{II} = \frac{COP_{total}}{COP_{carnot}} \quad (30)$$

Total Exergy destruction rate is calculated by:

$$\begin{aligned} (\dot{E}_{X_D})_{Total} = & (\dot{E}_{X_D})_{HTC,comp} + (\dot{E}_{X_D})_{HTC,exp} + (\dot{E}_{X_D})_{HTC,con} + (\dot{E}_{X_D})_{LTC,con} \\ & + (\dot{E}_{X_D})_{LTC,comp} + (\dot{E}_{X_D})_{LTC,exp} + (\dot{E}_{X_D})_{LTC,evap} \end{aligned} \quad (31)$$

Table 1. Thermodynamic and environmental properties of refrigerant used [4,5,23]

Refrigerant	Molecular Weight (g/mol)	Boiling Point at 1 atm (°C)	Critical Temperature (°C)	Critical Pressure (kPa)	Ozone Depletion Potential (ODP)	Global Warming Potential (GWP)
R13	104.5	-114.6	29.22	3914.84	1	14400
R717	17.02	-33.33	132.41	1135.7	0	0
R290	44.097	-44	96.67	4240	0	3
R134a	102	-26.1	101.1	4060	0	1300

RESULTS AND DISCUSSION

The effect of evaporator temperature, cascade condenser temperature and cascade evaporator temperature on actual COP, second law efficiency and total exergy loss has been calculated. In order to compare exergy performance of the system, different refrigerant pair has been used.

Effect of parameters on total COP

Fig. 2 and 3 shows the effect of evaporator temperature of LTC , evaporator temperature of HTC respectively on total COP of cascade refrigeration system for all the refrigerant pairs. It has been seen that the total COP is increasing at all the points and for all the refrigerant pairs with increase in evaporator temperature of LTC and the total COP is maximum for refrigerant pair R13-R717. Similar behavior is observed on total COP with increase in evaporator temperature of HTC. This is due to the reason that the value of $\dot{Q}_{HTC,evap}$ is maximum for refrigerant R717^[21]. Because of high latent heat of vaporization, R717 will extract the more heat from cascade condenser and will produce more refrigeration effect.

Fig. 4 shows the effect of condenser temperature of LTC on total COP. It can be seen from figure that with increase in condenser temperature, the COP is decreasing.

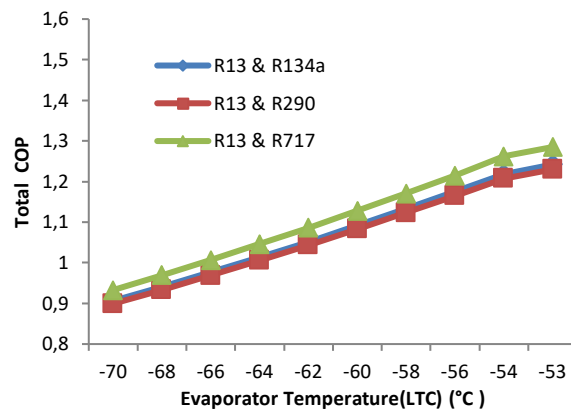


Figure 2. Variation of total COP with evaporator temperature (LTC)

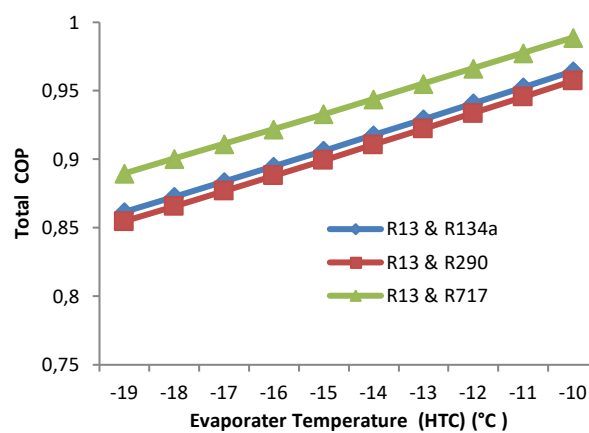


Figure 3. Variation of total COP with evaporator temperature (HTC)

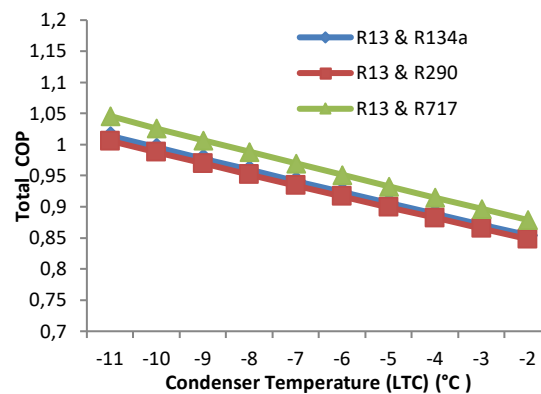


Figure 4. Variation of total COP with condenser temperature (LTC)

Effect of parameters on second law efficiency

The effect of evaporator temperature of LTC on second law efficiency can be seen from figure 5. During the variation of evaporator temperature of LTC, other operating conditions were as follows : condenser temperature of HTC was 40°C, evaporator temperature of HTC was -15°C, condenser temperature of LTC was -5°C. it can be seen from figure 5 that the second law efficiency is increasing with increase in evaporator temperature of LTC and it is maximum at all the points for refrigerant pair R13-R717 because, a higher evaporating temperature would lower the difference (ambient and cooling medium), so thermodynamically, it makes the system more efficient. Thus, the second law efficiency of the cascade system would increase due to increase in evaporator temperature. The similar effect can be seen in figure 6, in which second law efficiency is linearly increasing with increase in evaporator temperature of HTC.

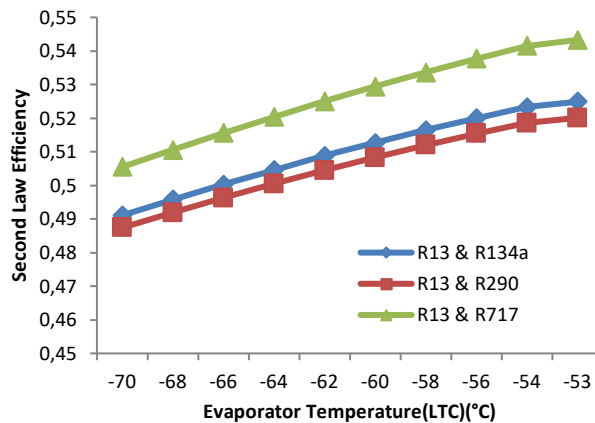


Figure 5. Variation of second law efficiency with evaporator temperature (LTC)

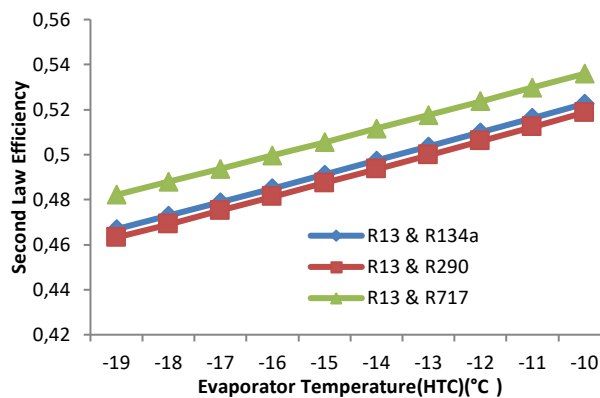


Figure 6. Variation of second law efficiency with evaporator temperature (HTC)

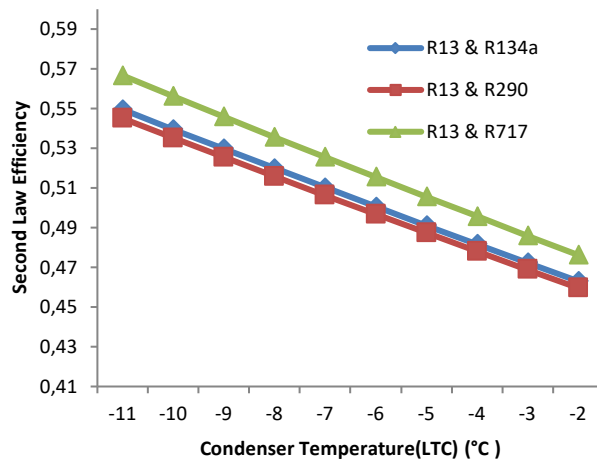


Figure 7. Variation of second law efficiency with condenser temperature (LTC)

Figure 7 shows the change in second law efficiency of cascade refrigeration system with respect to condenser temperature of LTC. In this figure evaporator temperature of LTC, evaporator temperature of HTC and condenser temperature of HTC are kept constant. It has been seen from the figure 8 that the second law efficiency is decreasing with increase in condenser temperature of LTC. In the considered temperature range, R13-R717 has the highest second law efficiency values while R13-R290 and R13-R134a have lowest one.

Effect of parameters on total exergy loss

The variation of total exergy loss with respect to evaporator temperature of LTC, evaporator temperature of HTC and condenser temperature of LTC has been shown in figure 8, 9 and 10 respectively. The total exergy loss of cascade system for all the considered refrigerant couple decrease when evaporator temperature of LTC

increases. The similar effect has been seen in figure 9 with evaporator temperature of HTC. In the given set of conditions, R13-R717 has the minimum total exergy loss. As it was stated earlier, R13-R717 has maximum COP values, the increase of COP of cascade system decrease the power consumption, decrease the waste heat which thus, decrease the total exergy loss of cascade refrigeration system.

It has been seen from figure 10 that the total exergy loss is increasing with increase in condenser temperature of LTC.

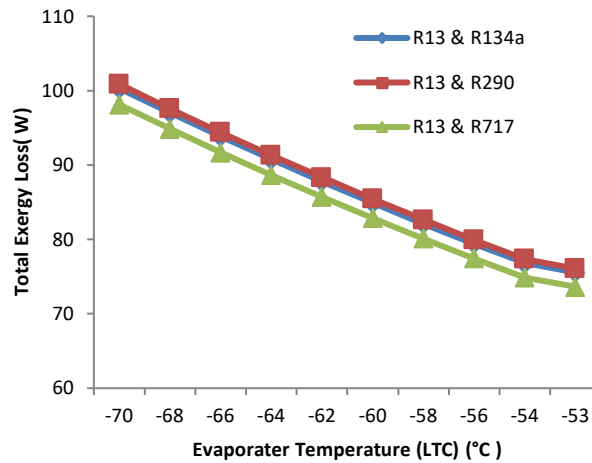


Figure 8. Variation of total exergy loss with evaporator temperature (LTC)

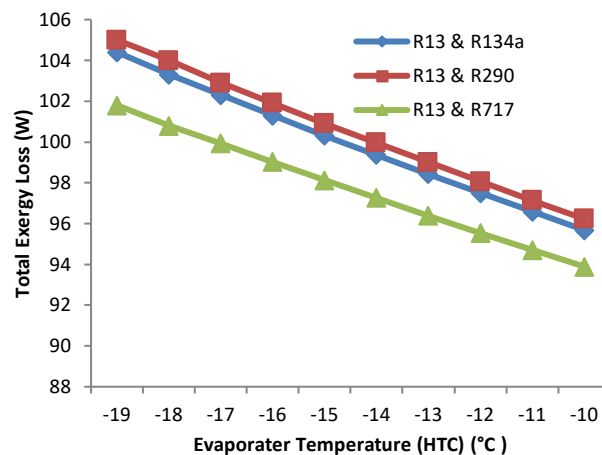


Figure 9. Variation of total exergy loss with evaporator temperature (HTC)

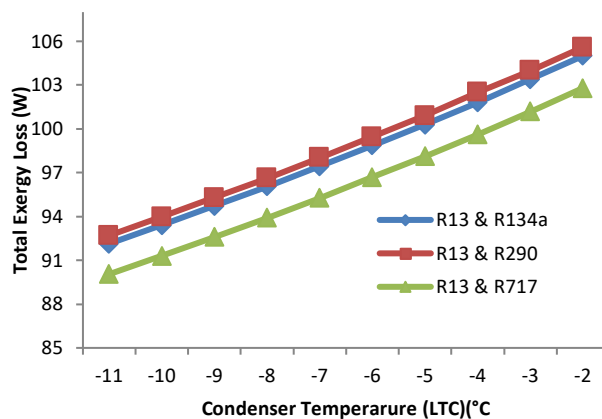


Figure 10. Variation of total exergy loss with condenser temperature (LTC)

CONCLUSION

In this paper a novel two stage cascade refrigeration system has been proposed and the result has been compared using different refrigerant pairs. The effects of evaporator temperature of LTC, evaporator temperature of HTC and condenser temperature of LTC have been studied. The following are the conclusions resulted from this study:

- Results show that, with decrease in evaporator temperature of LTC, the COP and second law efficiency of cascade system decreases whereas total exergy loss increases. The similar results have been found with decrease in evaporator temperature of HTC.
- Results show that with increase in condenser temperature of LTC, the COP and second law efficiency decreases whereas total exergy loss increases.
- In the considered all the refrigerant pairs, the cascade system was found most efficient with refrigerant pair R13-R717.

NOMENCLATURE

\dot{m}	Mass flow rate, kg/s
h	Enthalpy, kJ/kg
W	Work, kW
E	Exergy Rate, kW
Q	Cooling Capacity, kW
S	Entropy, kJ/kg-K
COP	Coefficient of Performance
η	Efficiency
η_{II}	Second law efficiency
η_m	Mechanical Efficiency
o	Atmospheric condition
LTC	Low temperature cycle
HTC	High temperature cycle
evap	Evaporator
comp	Compressor
con	Condenser
cas	Cascade
Ex_D	Exergy destruction

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