Thermodynamic Analysis of Two Stage Cascade Refrigeration System

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Abstract— The Montreal protocol and Kyoto protocol underlined the need of substitution of CFCs and HCFCs due to their adverse impact on atmospheric ozone layer which protects earth from U.V rays. The CFCs have been entirely ruled out since 1995 and a long term basis HCFCs must be replaced by 2020. All this events motivated HFC refrigerants which are harmless to ozone layer. In this paper thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R290-R23 and R600A-R23. Effect of various operating parameters i.e. evaporator temperature, condenser temperature, temperature difference in cascade condenser and low temperature cycle condenser temperature on performance parameters viz. COP and exergetic efficiency have been studied. Thermodynamic analysis shows that out of two refrigerant pairs R290-R23 and R600A-R23, the COP of R600A-R23 refrigerant pair is highest.

Keywords: Thermodynamic Analysis, Cascade Refrigeration System, COP, Exergetic Efficiency

I. General

Refrigeration and air conditioning (RAC) play a very important role in modern human life for cooling and heating requirements. This area covers a wide range of applications starting from food preservation to improving the thermal and hence living standards of people. The utilization of these equipment’s in homes, buildings, vehicles and industries provides for thermal comfort in living/working environment and hence plays a very important in increased industrial production of any country. Due to the increasing demand of energy primarily for RAC & HP applications (around 26-30%) this leads to degradation of environment, global warming and depletion of ozone layer etc., to overcome these aspects there is urgent need of efficient energy utilization besides waste heat recovery for useful applications especially after the Kyoto and Montreal protocols. The scientific community is eagerly concentrating on the alternate and environment friendly refrigerants, especially after the Kyoto and the Montreal protocols. However, in a quest to find out the alternate and environment friendly refrigerants, the energy efficiency of this equipment’s while using conventional refrigerants is also very important. The CFCs and HCFCs remain as refrigerant fluids of choice for various applications for many years and now non-ozone depleting HFCs became favoured. The Montreal protocol banned production and consumption of ozone depleting compounds in 1987 and also accelerated the rate of phasing out of CFC and HCFC in order to reduce ozone depletion, and this was only possible by using HFCs in many applications. The Kyoto protocol laid down goals for the reduction of global warming substances in the year 1997 and subsequently the heat pump industry has consequently been forced to look for substitutes of CFCs and HCFCs. In many applications hydrocarbons have been used but this has been limited by safety considerations. Energy saving and climate change is the outcome of system design, which includes the selection of refrigeration cycle, the working fluid (refrigerant), and the minimization of refrigerant quantity and leakage. It also relates to the installation, the service procedures, and the improvement of energy efficiency to reduce the direct emissions of carbon dioxide into the atmosphere.

II. System Modeling

The cascade refrigeration system is constituted by 2 single stage system connected, by a heat exchanger (cascade heat exchanger). The low temperature system with R23 as refrigerant is used for cooling. The high temp system with R290 as the refrigerant is used to condense the R23 of the low temperature system.

In the evaporator, the R23 at the evaporating temperature absorbs the cooling duty Q_{evap}R23 from the cooling space (at T_f temp), then is compressed in the R23 compressor and condensed in the cascade heat exchanger at a condensing temperature of T_{cond}R23 and then sent to the from which evaporator is applied.

In the condenser, the heat flow Q_{cond}R290 is removed from the R290 at condensing temp of T_{cond}R290 to condensing medium (at T_0 temperature). The R290 is expanded, then evaporated at an evaporating temp of T_{evap}R290 in the cascade heat exchanger and then compressed in R290 compressor and discharged into the condenser.

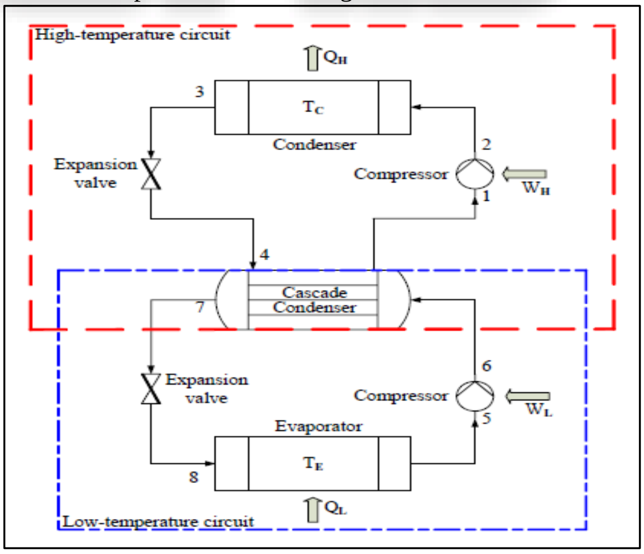

Fig. 1: Schematic diagram of the R23-R290 cascade refrigeration system

Component	Mass	Energy
R23-	$m_2=m_1$	W_{comp}R23=$m_1.(h_{2s}$-
Compressor	$m_6=m_5$	$h_1)$
R290-	$m_4=m_3$	W_{comp}R90=$m_5.(h_{6s}$-
Compressor	$m_8=m_7$	$h_5)$
R23- Exp.	$m_1=m_4$	$h_4=h_3$
Device	$m_7=m_6$	$h_8=h_7$

R290- Exp. Device Evaporator (R23) Condenser (R290) Cascade heat exchanger	$m_3=m_2, m_5=m_8$	$Q_{evap}R23=m_1(h_1-h_4)$ Q_{cond} $R290= m_5(h_7-h_6)$ $m_1.(h_3-h_2)=m_5.(h_5-h_8)$

Table 1: Energy and Mass Balance for CO2/NH3 Cascade System

III. THERMODYNAMIC ANALYSIS

The thermodynamic analysis of R23-R290 and R23-R600A cascade refrigeration system performed based on the following assumptions.

1) Compression process is adiabatic with an isentropic efficiency of 0.7 in both HTC and LTC;
2) The expansion process is isenthalpic;
3) Negligible heat interaction in the cascade heat exchanger with surrounding;
4) Negligible changes in kinetic and potential energy;
5) The system is at steady state condition. All processes are steady flow processes.
6) Temperature difference in the cascade heat exchanger is -3°C.

The calculation for the two stage cascade system is initiated by assigning certain fixed values for the evaporator and condenser temperature. Subsequently, the saturation pressure, the liquid and vapour enthalpies, the entropies, specific heats are computed from EES. The evaporator is assumed to take heat from the cooling space. For this, the evaporator temperature of low temp circuit is initiated by assuming T_E=-80°c and then varied as $T_E=T_E+5$ with 5^0C interval, the T_C= 25°c and then varied as $T_C=T_C+5$ with 5°C interval. Low temperature cycle condenser temperature (T_{casL}) = -5°c. Then the optimal condensing temperature has been designed under different evaporating temperature corresponding to the minimum energy required. Mass flow rate of the Refrigerant through the cascade condenser (m_1) and condenser (m_2) are selected as 1Kg/s. Thus, the other parameter, W_{Total}, COP, η_{Exergy} and $X_{Total\ loss}$ are evaluated for each set of operating temperature.

IV. RESULTS AND DISCUSSION

In the present work thermodynamic model has been developed in Engineering Equation Solver software and results of the analysis have been given in the following sections.

A. Effect of Evaporator Temperature

The effect on COP, exergetic efficiency and total exergetic loss, when evaporator temperature varied from -80°C to -60°C in the interval of 5°C keeping other parameters constant is shown in Figs. 3 (a), (b), and (c) respectively. For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases.

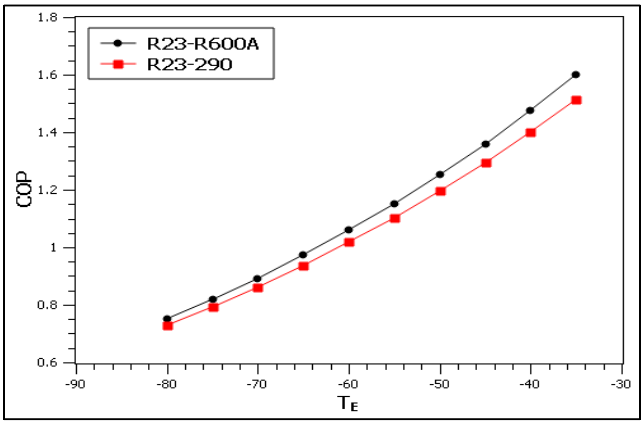

Fig. 2: Effect of evaporator temperature on COP

Fig. 2 shows that as evaporator temperature increases the COP increases. COP increases for R23-R600A and R290-R23 respectively. Among two pair R23-R600A shows maximum change in COP followed by R290-R23.

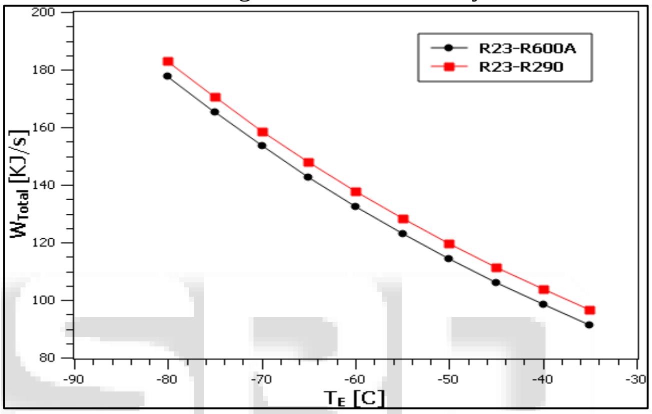

Fig. 3: Effect of evaporator temperature on total compressor work

Fig. 3 shows that as evaporator temperature increases the total compressor work decreases. The total compressor work decreases for R23-R600A followed by R290-R23 respectively. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.

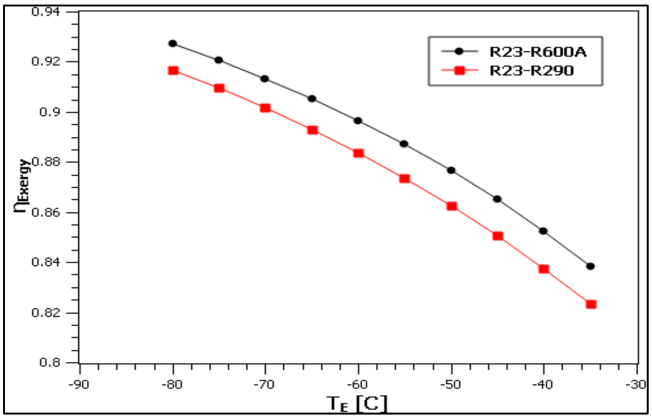

Fig. 4: Effect of evaporator temperature on exergetic efficiency

Fig. 4 shows that as evaporator temperature increases the exergetic efficiency decreases. Among two pair R23-R600A shows maximum change in exergetic efficiency followed by R290-R23.

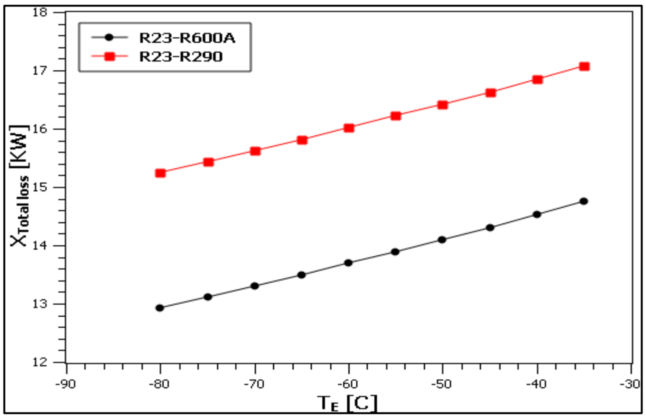

Fig. 5: Effect of evaporator temperature on total exergetic loss

Fig. 5 shows that as evaporator temperature increases the total exergetic loss decreases. Among two pair R23-R600A shows maximum change in exergetic efficiency followed by R290-R23.

B. Effect of Condenser Temperature

The condenser temperature is varied from 25°C to 45°C in the interval of 5°C and other parameters are kept constant. The effect on COP, exergetic efficiency and total exergetic loss is shown in Figs. 4 (a), (b), and (c) respectively.

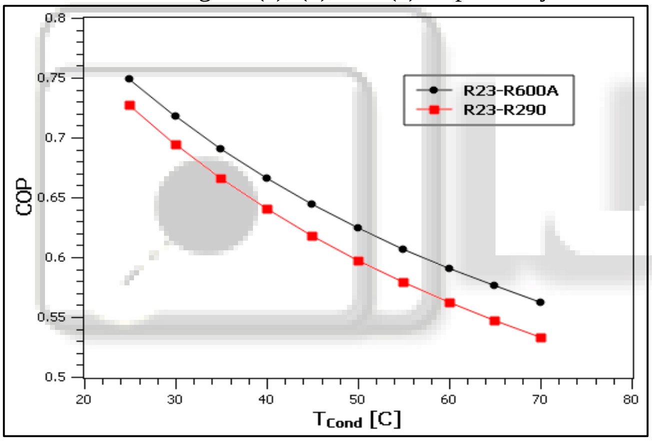

Fig. 6: Effect of condenser temperature on COP

Fig. 6 shows that as condenser temperature increases the COP decreases. Among two pair R23-R600A shows maximum change in COP followed by R290-R23.

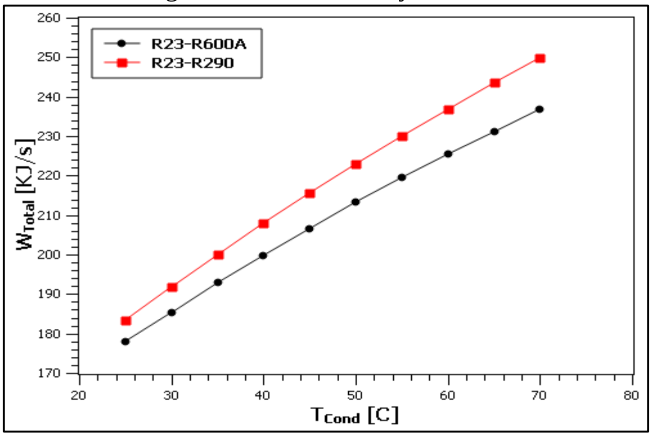

Fig. 7: Effect of condenser temperature on total compressor work

Fig. 5.19 shows that as condenser temperature increases the total compressor work increases. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.

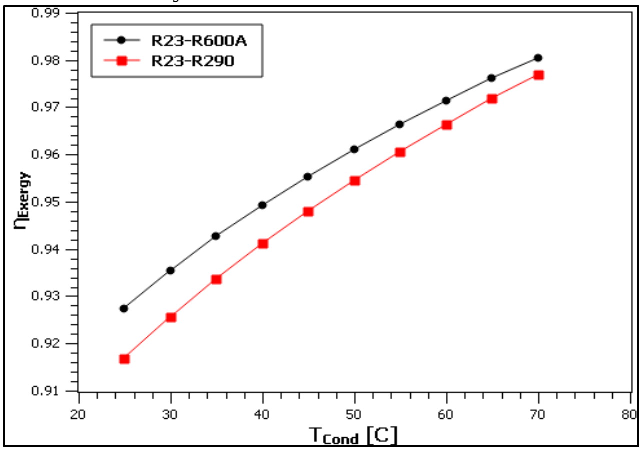

Fig. 8: Effect of condenser temperature on exergetic efficiency

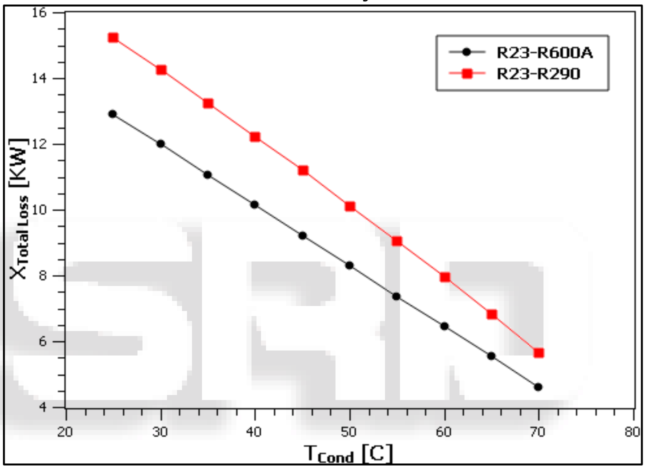

Fig. 9: Effect of condenser temperature on total exergetic loss

Fig. 9 shows that as condenser temperature increases the total exergetic loss decreases. Among two pair R23-R600A shows minimum change in total exergetic loss followed by R290-R23.

C. Effect of L.T Cycle Condenser Temperature (T_{CASL})

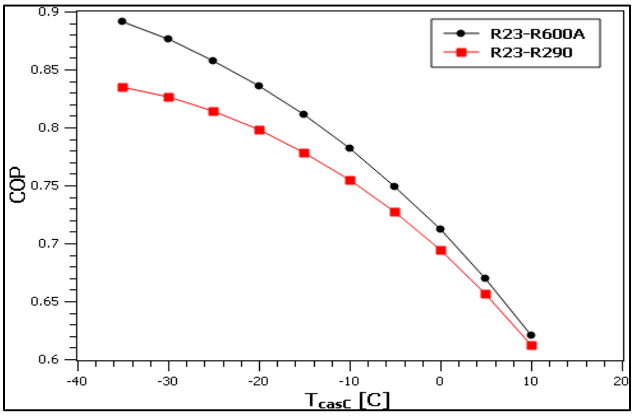

Fig. 10: Effect of L.T cycle condenser temperature on COP

Fig. 10 shows that as LT cycle condenser temperature increases the COP decreases. Among two pair R23-R600A shows minimum change in COP loss followed by R290-R23.

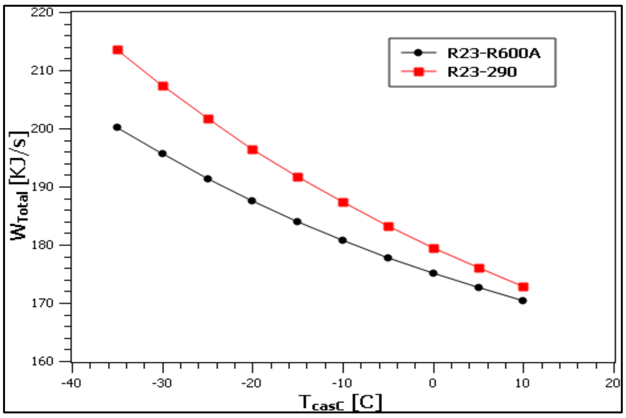

Fig. 11: Effect of L.T cycle condenser temperature on total compressor work

Fig. 11 shows that as LT cycle condenser temperature increases the total compressor work decreases. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.

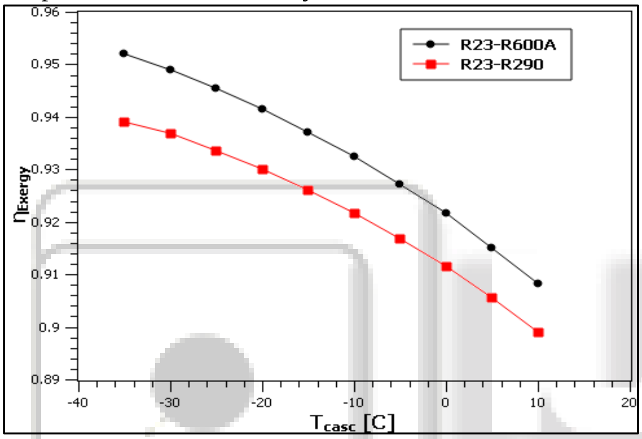

Fig. 12: Effect of L.T cycle condenser temperature on exergetic efficiency

Fig. 12 shows that as LT cycle condenser temperature increases the exergetic efficiency decreases. Among two pair R23-R600A shows minimum change in exergetic efficiency followed by R290-R23.

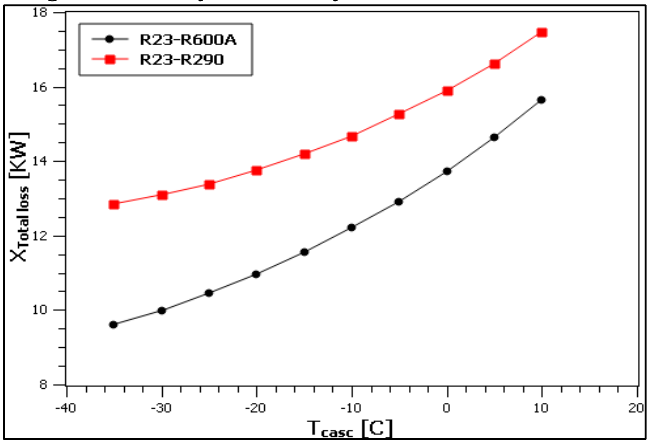

Fig. 13: Effect of L.T cycle condenser temperature on total exergetic loss

Fig. 13 shows that as LT cycle condenser temperature increases the total exergetic loss increases. Among two pair R23-R600A shows minimum change in exergetic efficiency followed by R290-R23.

D. Effect of Temperature Difference (ΔT_{CC})

The temperature difference in cascade heat exchanger is varied from 2°C to 6°C in the interval of 1°C and other parameters are kept constant. The effect of temperature difference in cascade condenser on COP, exergetic efficiency, total compressor work and total exergetic loss is shown respectively.

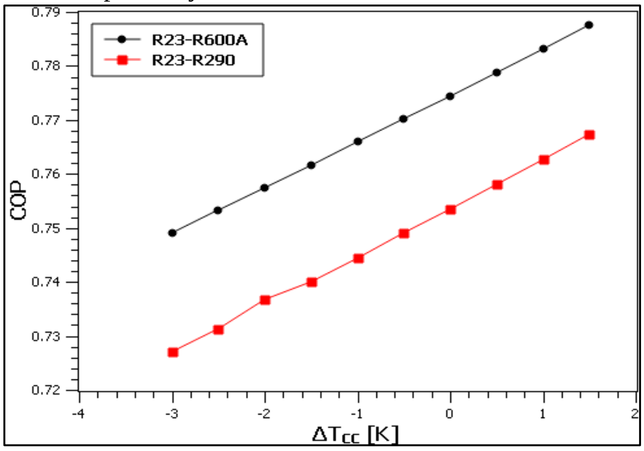

Fig. 14: Effect of temperature difference (ΔT_{CC}) on COP

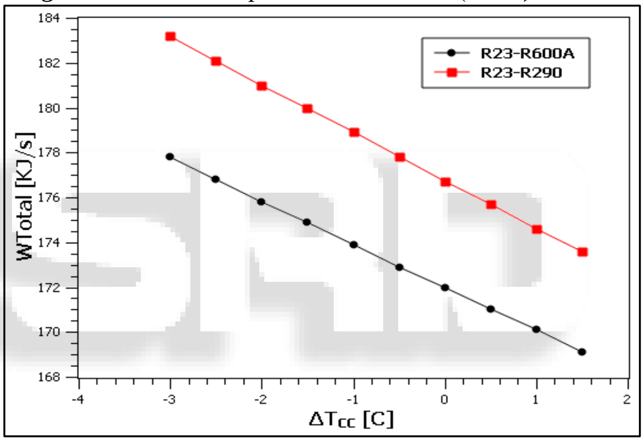

Fig. 15: Effect of temperature difference (ΔT_{CC}) on total compressor work

The effect of temperature difference in cascade condenser on COP is shown in Fig. 15, when the temperature difference in cascade condenser increases the COP of system decreases. Out of two refrigerant pairs R290-R23 responds maximum for change in temperature difference in cascade condenser.

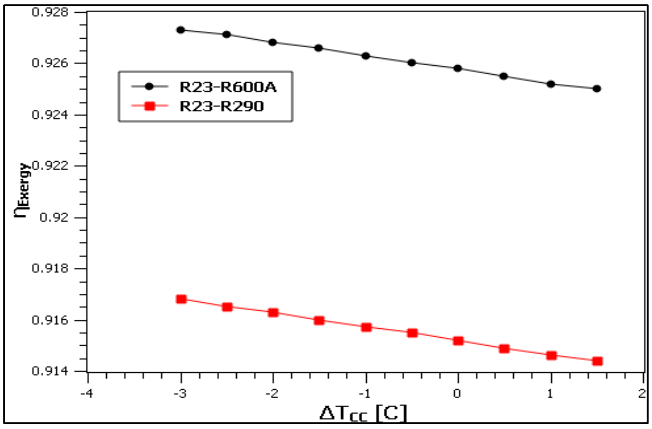

Fig. 16: Effect of temperature difference (ΔT_{CC}) on exergetic efficiency

The effect of temperature difference in cascade condenser on COP is shown in Fig. 16, when the temperature difference in cascade condenser increases the exergetic efficiency decreases. Out of two refrigerant pairs R600A-R23 responds maximum for change in temperature difference in cascade condenser.

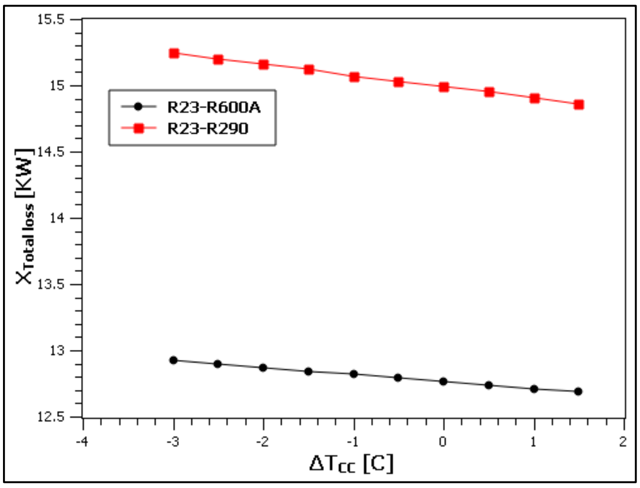

Fig. 17: Effect of temperature difference (ΔT_{CC}) on total exergetic loss

The effect of temperature difference in cascade condenser on COP is shown in Fig. 17, when the temperature difference in cascade condenser increases the exergetic loss decreases. Out of two refrigerant pairs R290-R23 responds maximum for change in temperature difference in cascade condenser.

V. Conclusion

In present work thermodynamic analysis of cascade refrigeration system has been carried out by developing computational model in EES to find the effect of various operating parameters on the performance parameters. The following conclusions are drawn from present study.

1) For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases. As the evaporator temperature increases, the refrigeration effect increases marginally and the required compressors work decrease significantly, therefore the performance of the cascade system increases considerably. Compression Work required in LTC decreases with increase in evaporator temperature since pressure ratio is decreases. Hence combined work required also reduces.
2) It is observed that as evaporator temperature increases the COP increases. COP increases for R23-R600A and R290-R23 respectively. Among two pair R23-R600A shows maximum change in COP followed by R290-R23.
3) It is observed that as evaporator temperature increases the total compressor work decreases. The total compressor work decreases for R23-R600A followed by R290-R23 respectively. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.
4) It is observed that as evaporator temperature increases the exergetic efficiency decreases. Among two pair R23-R600A shows maximum change in exergetic efficiency followed by R290-R23.
5) It is observed that as evaporator temperature increases the total exergetic loss decreases. Among two pair R23-R600A shows maximum change in exergetic efficiency followed by R290-R23.
6) It is observed that as condenser temperature increases the COP decreases. Among two pair R23-R600A shows maximum change in COP followed by R290-R23.
7) It is observed that as condenser temperature increases the total compressor work increases. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.
8) It is observed that as condenser temperature increases the total exergetic loss decreases. Among two pair R23-R600A shows minimum change in total exergetic loss followed by R290-R23.
9) It is observed that as LT cycle condenser temperature increases the COP decreases. Among two pair R23-R600A shows minimum change in COP loss followed by R290-R23.
10) It is observed that as LT cycle condenser temperature increases the total compressor work decreases. Among two pair R23-R600A shows minimum change in total compressor work followed by R290-R23.
11) It is observed that as LT cycle condenser temperature increases the exergetic efficiency decreases. Among two pair R23-R600A shows minimum change in exergetic efficiency followed by R290-R23.
12) It is observed that as LT cycle condenser temperature increases the total exergetic loss increases. Among two pair R23-R600A shows minimum change in exergetic efficiency followed by R290-R23.
13) The effect of temperature difference in cascade condenser on COP is shown in Fig. 5.26, when the temperature difference in cascade condenser increases the COP of system decreases. Out of two refrigerant pairs R290-R23 responds maximum for change in temperature difference in cascade condenser.
14) When the temperature difference in cascade condenser increases the exergetic efficiency decreases. Out of two refrigerant pairs R600A-R23 responds maximum for change in temperature difference in cascade condenser.
15) When the temperature difference in cascade condenser increases the exergetic loss decreases. Out of two refrigerant pairs R290-R23 responds maximum for change in temperature difference in cascade condenser.

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