PERFORMANCE & THERMODYNAMIC ANALYSIS OF DIFFERENT REFERIGERANTS OPERATED CASCADE REFERIGERATION 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 two different refrigerant pairs R23-R290 and R23-R600A. 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 R23-R290 and R23-R600A, the COP of R23-R600A refrigerant pair is highest.

Keywords: Thermodynamic analysis, cascade refrigeration system, COP, exergetic efficiency.

1. 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.

2. REVIEW OF PAST STUDIES

1. Gaudy Prada Botia (2018) document presents a combined refrigeration system consisting of two vapour compression refrigeration cycles linked by a heat exchanger that not only reduces the work of the compressor but also increases the amount of heat absorbed by the refrigerated space as a result of the cascade stages & improves the COP of a refrigeration system.

2.Jinkun Zhou et al (2018) find out that waste heat can be utilized in absorption refrigeration systems. In this article, the performance of an auto-cascade absorption refrigeration system using R23/R134a/DMF solutions as the working substance was analyzed. Optimization analysis results showed that to some extent, the COP could be increased when the low pressure of the system decreased. The reasonable upper limit of the high pressure was the high pressure at the turning point of COP, and the reasonable lower limit of the low pressure was the low pressure at the turning point of COP. The COP of the system monotonously increased with the increase of the mole fraction of R23 in solutions. The low R23 mole fractions were more appropriate.

3. Umesh C.Rajmane (2017) study is presented a cascade refrigeration system using as refrigerant (R23) in low temperature circuit and R404a in high temperature circuit. The operating parameters considered in this paper include superheating, condensing, evaporating and sub cooling temperatures in the refrigerant (R404a) high temperature circuit and in the refrigerant (R23) low temperature circuit.

4. Manoj Dixit et al (2016) study helps to find out the best refrigerants and appropriate operation parameters. It is found in the study that cascade condenser, compressor and refrigerant throttle valve are the major source of exergy destruction. The analysis has been realized by means of mathematical model of the refrigeration system.

5. Umesh C. Rajmane(2016) study provides the advantages of vapour compression refrigeration system & also summaries various techniques used in cascade refrigeration system. The operating parameters considered in this study include Condensing , Sub Cooling, Evaporating & Super heating temperatures in high – temperature circuit & temperature difference in Cascade heat exchanger. Evaporating, Superheating, condensing & Sub-cooling in the low temperature circuit.

6. A. D. Parekh and P. R. Tailor (2014) thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R12-R13, R290-R23, and R404A-R23. Thermodynamic analysis shows that out of three refrigerant pairs R12-R13, R290-R23 and R404A-R23, the COP of R290-R23 refrigerant pair is highest.

7. J. Alberto Dopazo (2009) did the experimental evaluation of a cascade refrigeration system prototype with CO_2 & NH_3 for freezing process application .They also compared the experimental results with two common single stage refrigeration systems using NH_3 as refrigerant.

8. **Jose Fernandez Seara (2006)** analysed the refrigeration in cascade with a compression system at the low temperature stage and an absorption system at high temperature stage to generate cooling at low powering by means of a cogeneration system.

9. Tung-weichen (2006)analyzed a Cascade refrigeration that uses carbon dioxide & ammonia as a refrigerant and determined the optimal condensing temperature of the cascade –condenser giving various design parameters, maximized the COP and minimized the energy destruction of the system.

10. A. Kilicarslan (2004) presented the experimental investigation and theoretical study of a different type two stage vapour compression cascade refrigeration system using R-134a as the refrigerant.

11.Kanoglu (2002) developed a thermodynamic model to perform the energy analysis of multistage cascade refrigeration cycle for natural gas liquefaction. He also obtained an expression related to minimum work.

12. Molenaar (2002) tested alternative refrigerant couples having low ODP's such as R-502/R-13 and R-22/R-23 in low temp. Refrigeration application and investigate their performance and operating system characteristics.

3. 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.

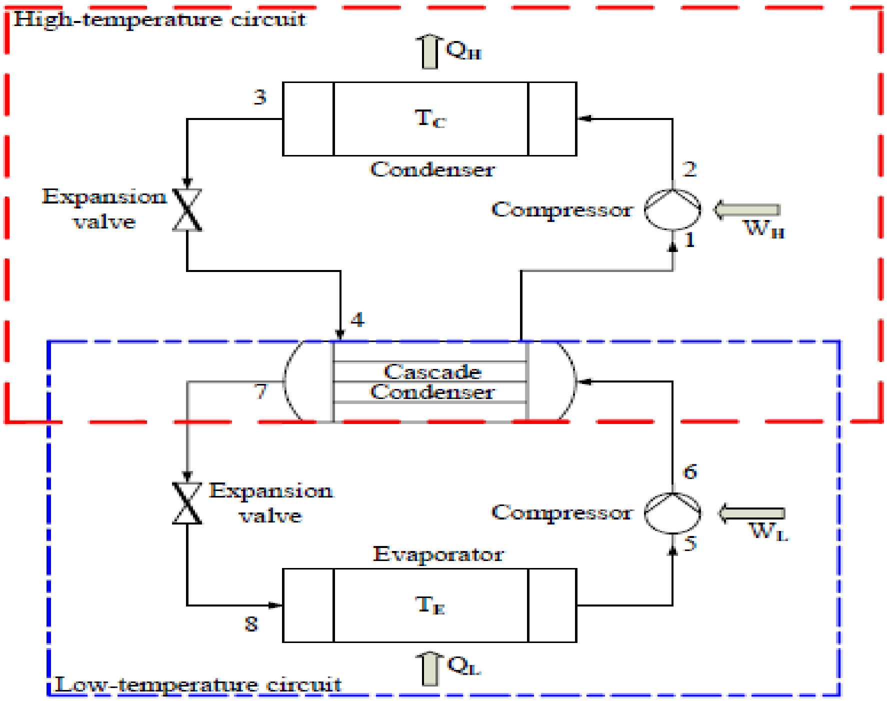

Fig. 1: Schematic diagram of the R23-R290cascade refrigeration system

Table 1: Energy and Mass Balance for R23-R290 Cascade System.

Component	Mass	Energy
R23-Compressor	$m_2=m_1$	$W_{comp}R23=m_1.(h_{2s}-h_1)$
R290-Compressor	$m_6=m_5$	$W_{comp}R90=m_5.(h_{6s}-h_5)$
R23- Exp. Device	$m_4=m_3$	$h_4=h_3$
R290- Exp. Device	$m_8=m_7$	$h_8=h_7$
Evaporator (R23)	$m_1=m_4$	$Q_{evap}R23_{=}m_1(h_1-h_4)$
Condenser (R290)	$m_7=m_6$	$Q_{cond}R290= m_5(h_7-h_6)$
Cascade heat exchanger	$m_3=m_2,m_5=m_8$	$m_1.(h_3-h_2)=m_5.(h_5-h_8)$

4. 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.

5. 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:

5.1 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 . For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases.

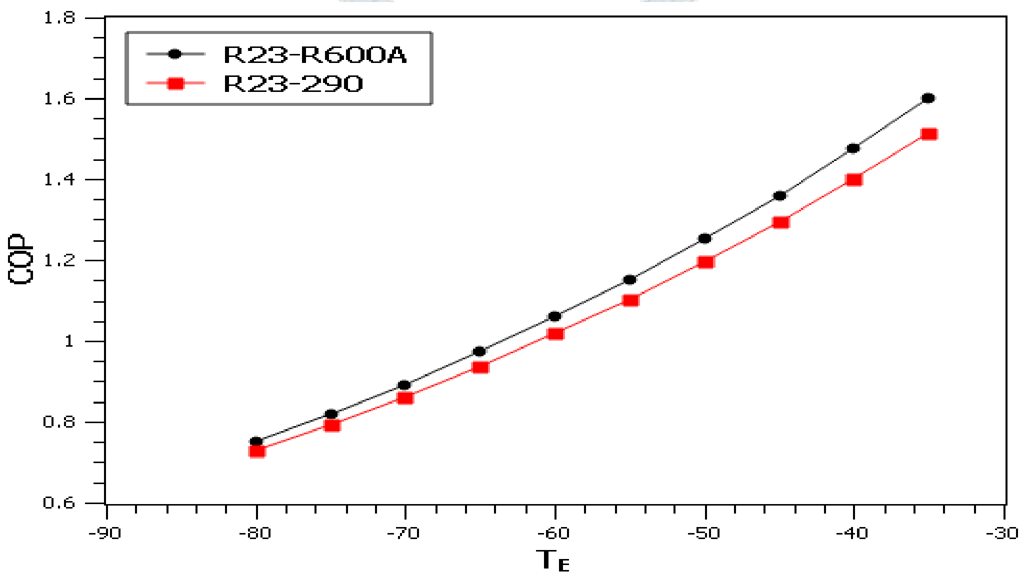

Fig. 2: Effect of evaporator temperature on COP

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

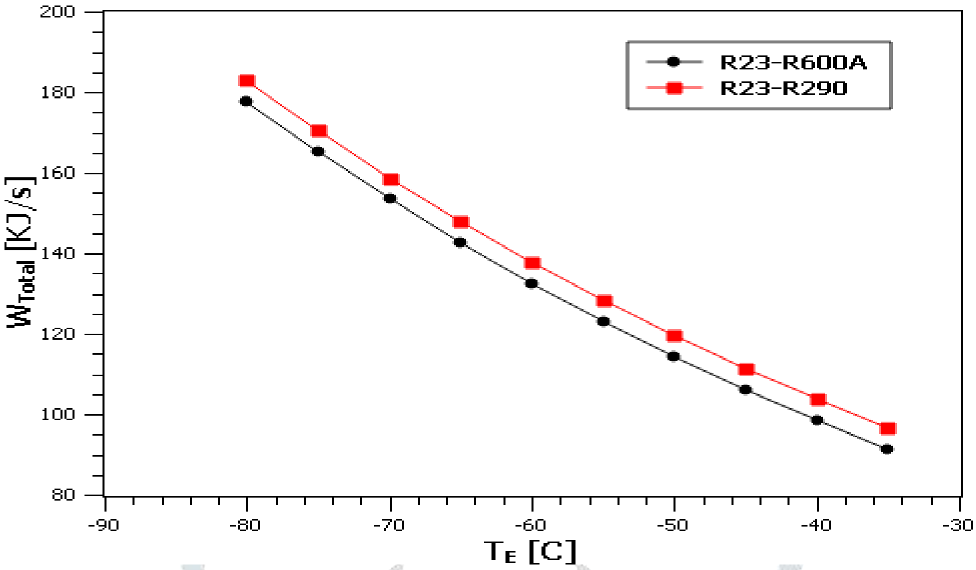

Fig. 3: Effect of evaporator temperature on total compressor work

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

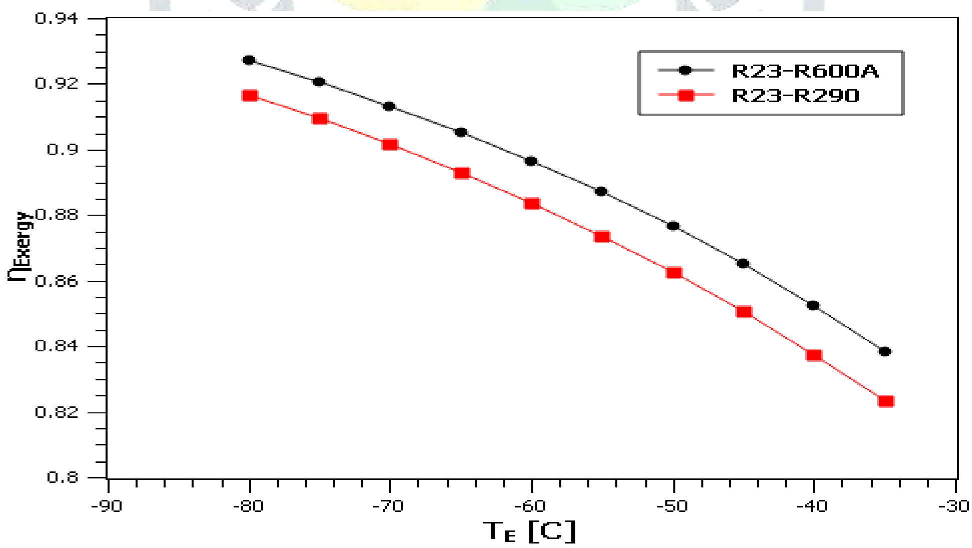

Fig. 4: Effect of evaporator temperature on exergetic efficiency

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 R23-R290.

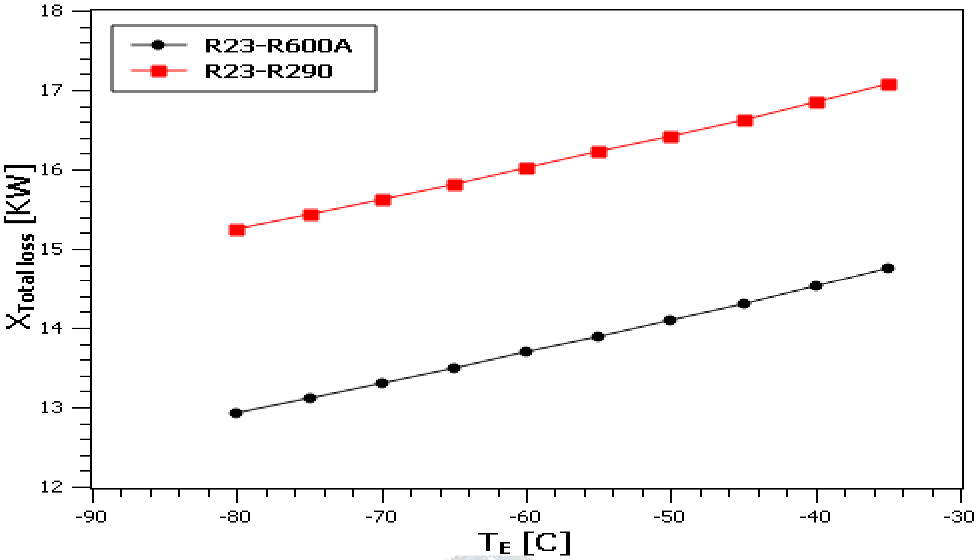

Fig. 5: Effect of evaporator temperature on total exergetic loss

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 R23-R290.

5.2.2 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.

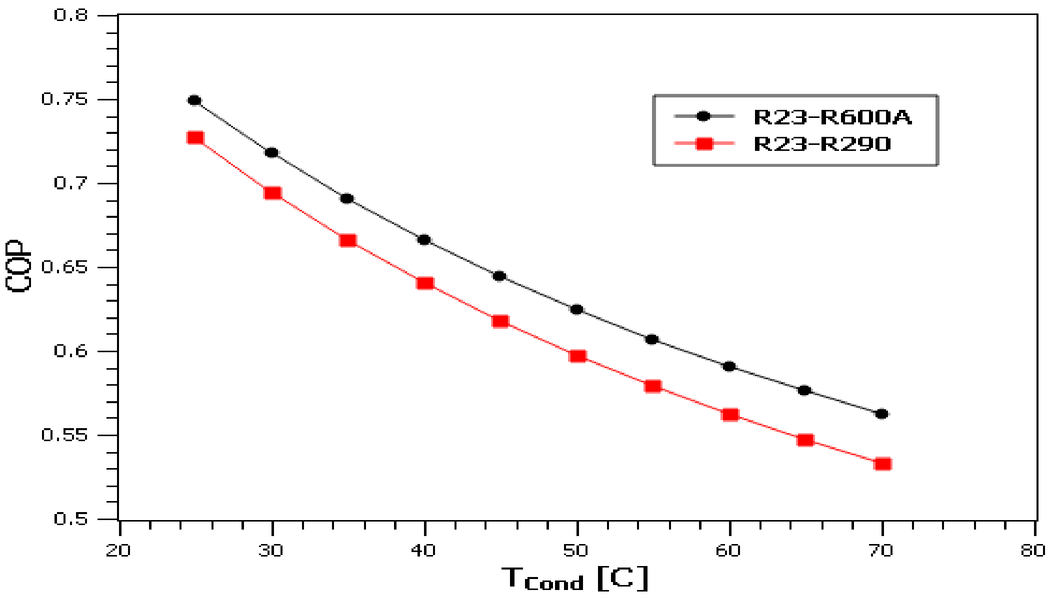

Fig. 6: Effect of condenser temperature on COP

Fig. 6 shows that as condenser temperature increases the COP decreases. Among two pair R23-R600Ashows maximum change in COP followed by R23-R290.

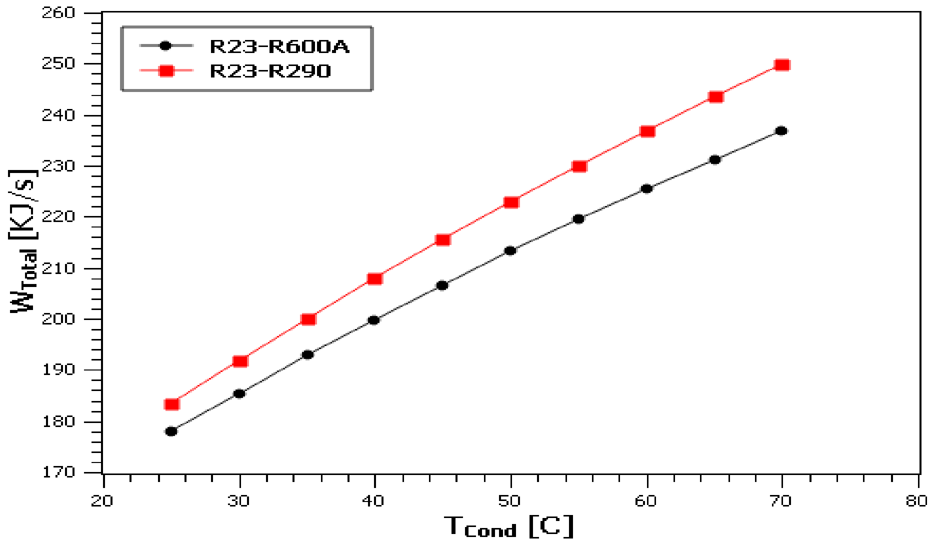

Fig. 7: Effect of condenser temperature on total compressor work

Fig. 7 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 R23-R290.

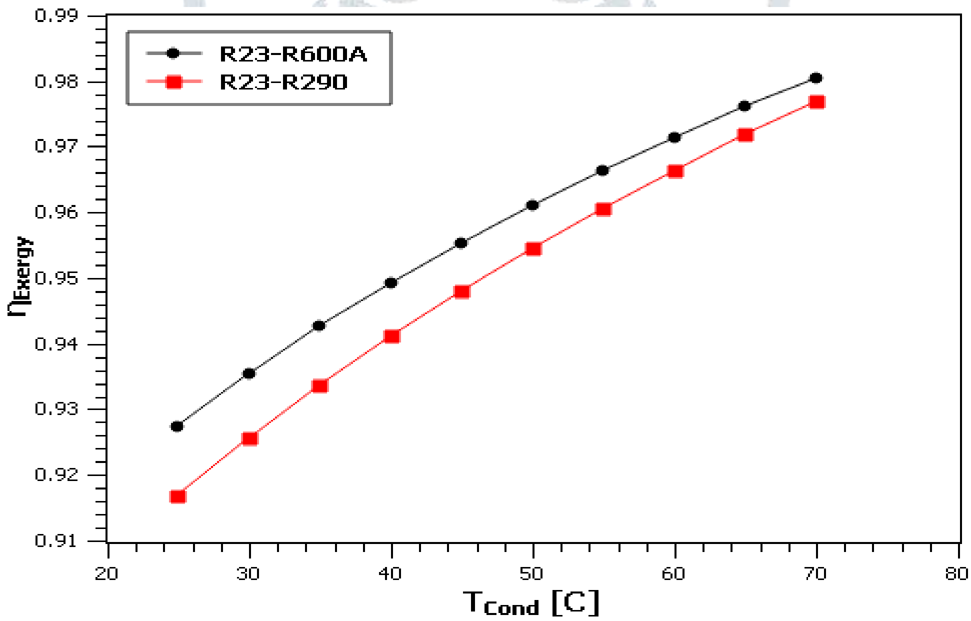

Fig. 8:Effect of condenser temperature on exergetic efficiency

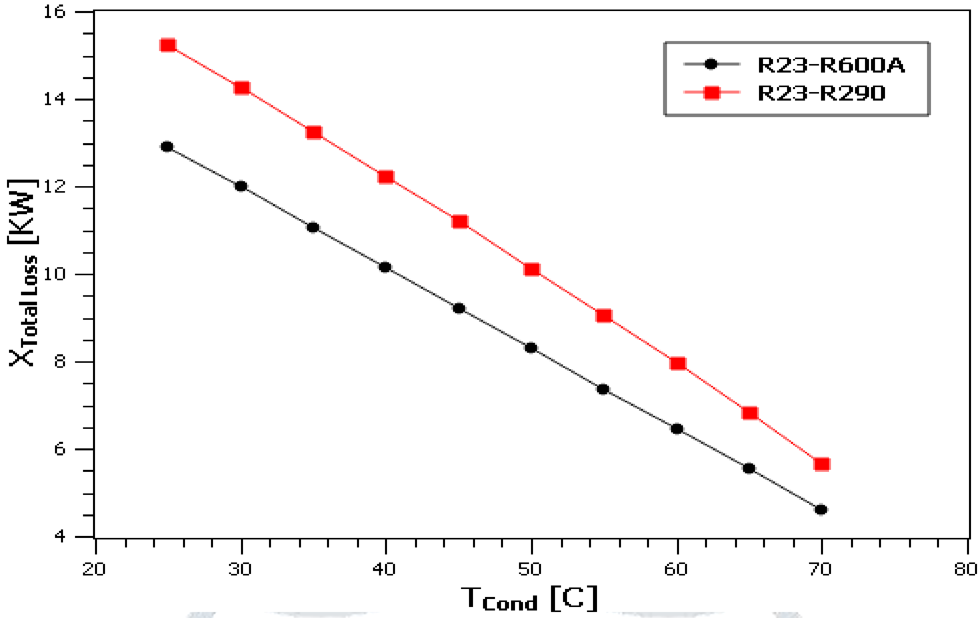

Fig. 9: Effect of condenser temperature on total exergetic loss

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 R23-R290.

10. EFFECT OF L.T CYCLE CONDENSER TEMPERATURE (T_{CASL})

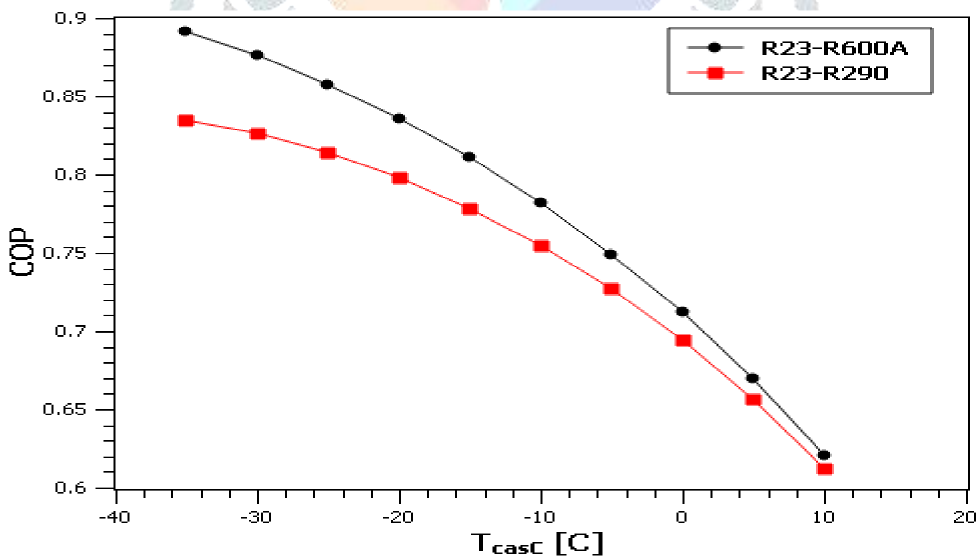

Fig. 10: Effect of L.T cycle condenser temperature on COP

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 R23-R290.

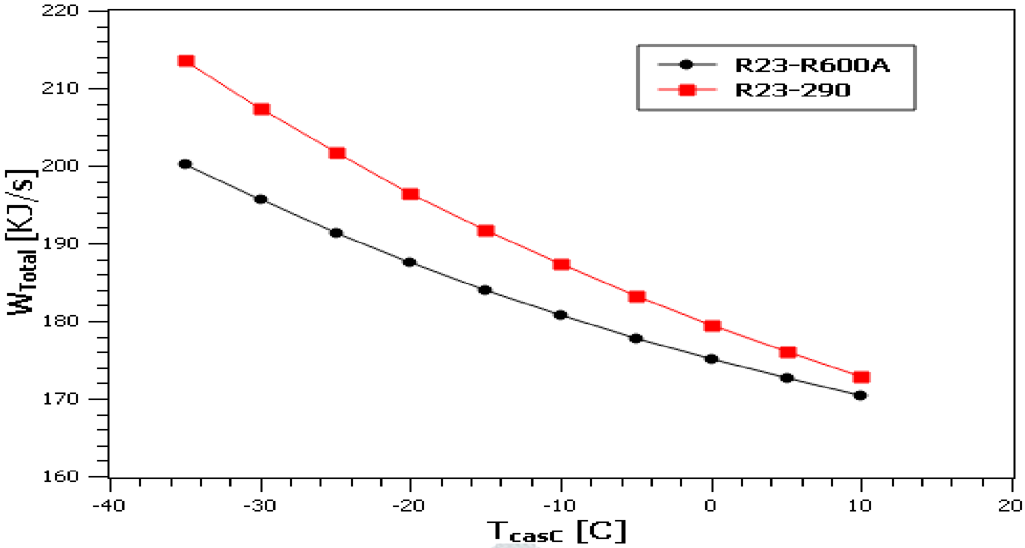

Fig. 11: Effect of L.T cycle condenser temperature on total compressor work

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 R23-R290.

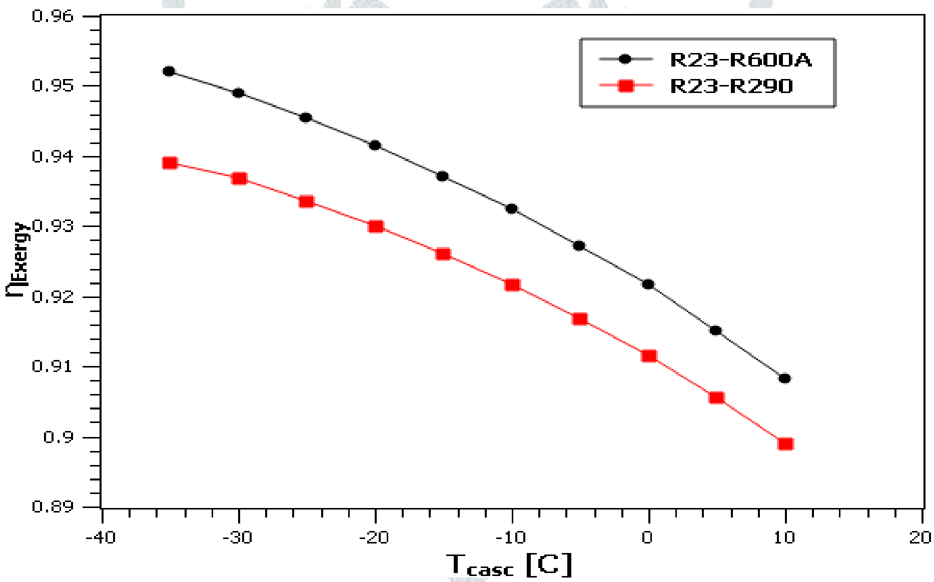

Fig. 12: Effect of L.T cycle condenser temperature on exergetic efficiency

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 R23-R290.

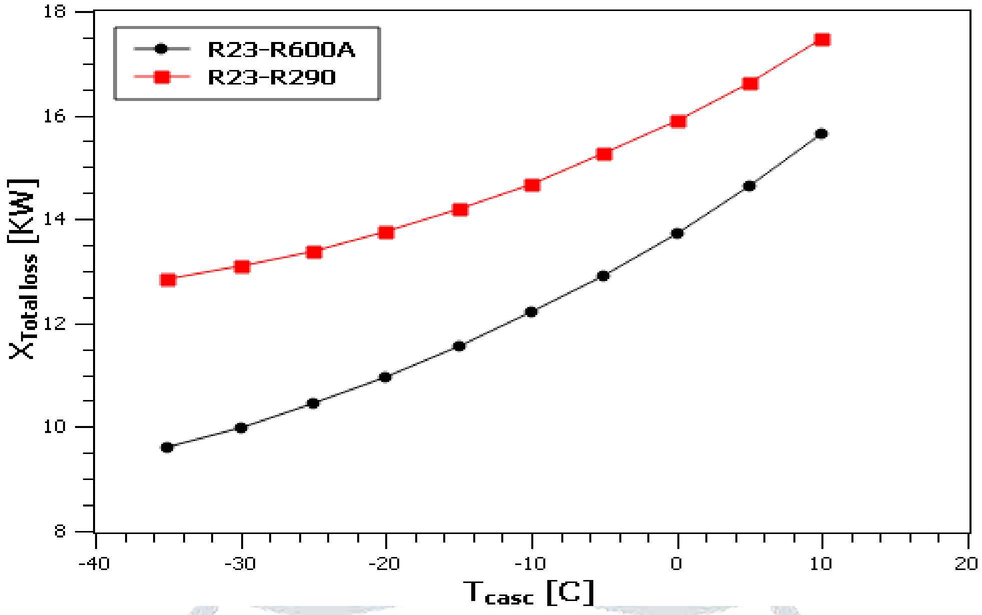

Fig. 13: Effect of L.T cycle condenser temperature on total exergetic loss

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 R23-R290.

14. 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.

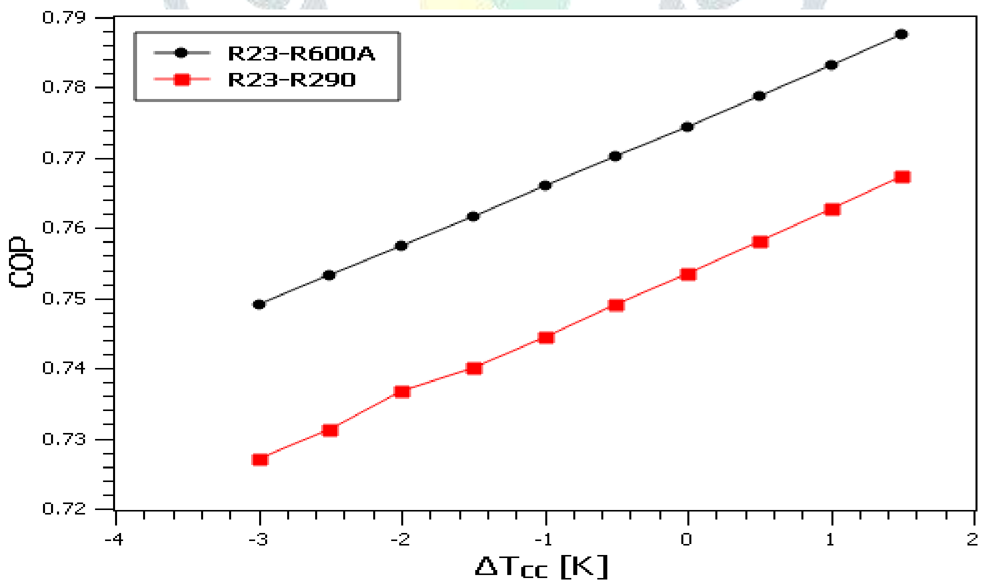

Fig. 14: Effect of temperature difference (ΔT_{CC}) on COP

The effect of temperature difference in cascade condenser on COP is shown in Fig. 14, when the temperature difference in cascade condenser increases the COP of system decreases. Out of two refrigerant pairs R23-R290 responds maximum for change in temperature difference in cascade condenser.

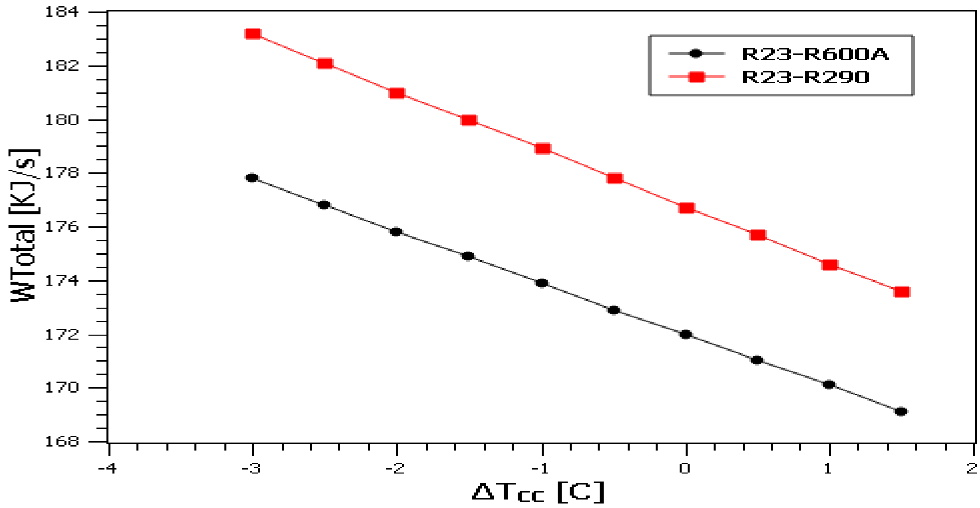

Fig. 15: Effect of temperature difference (ΔT_{CC}) on total compressor work

The effect of temperature difference on total compressor work is shown in fig.15, when the temperature difference in cascade condenser increases the total compressor work decreases.

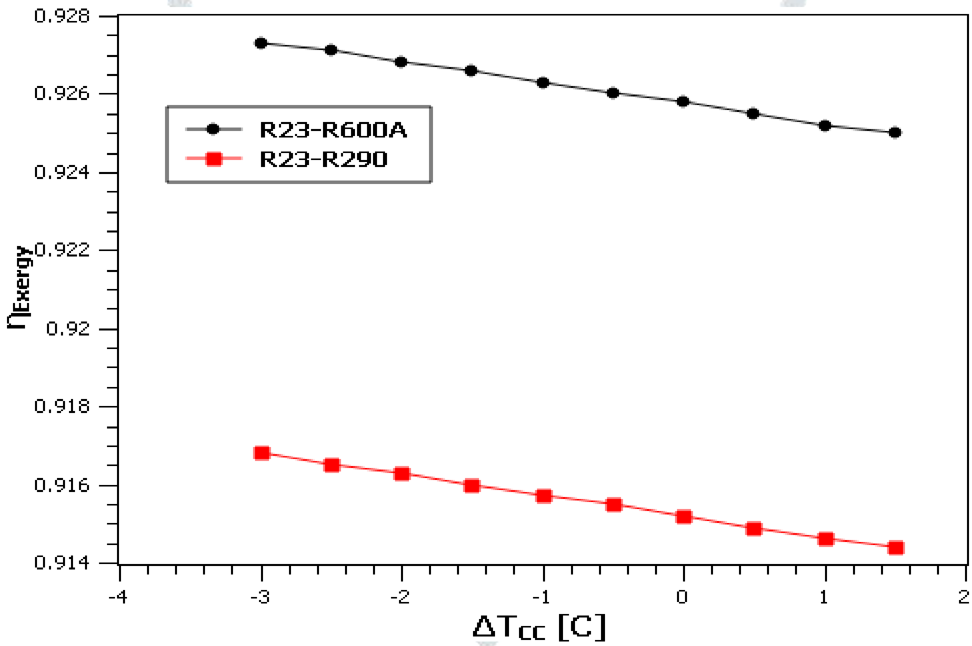

Fig. 16: Effect of temperature difference (ΔT_{CC}) on exergetic efficiency

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

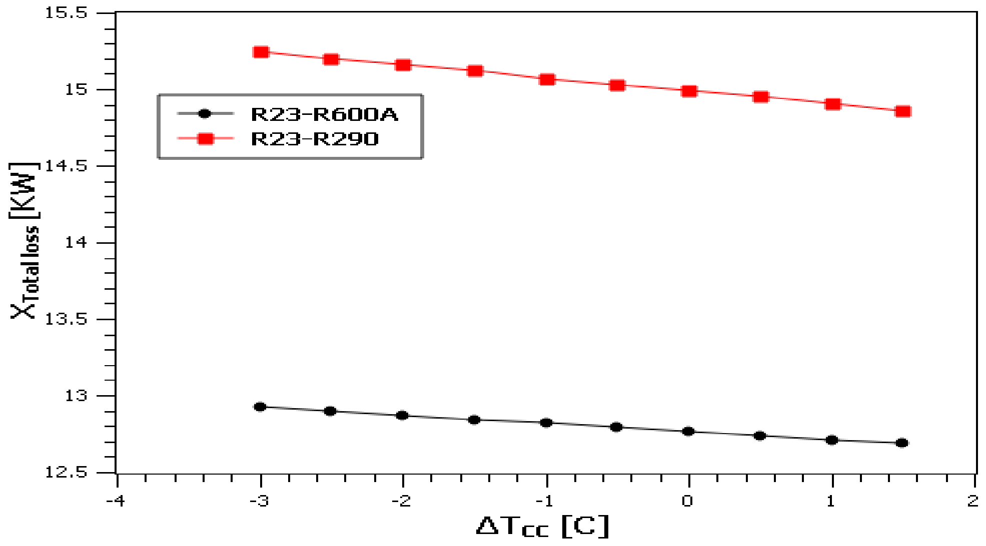

Fig. 17: Effect of temperature difference (ΔT_{CC}) on total exergetic loss

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

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

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 R23-R290.
6. It is observed that as condenser temperature increases the COP decreases. Among two pair R23-R600A shows maximum change in COP followed by R23-R290.
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 R23-R290.
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 R23-R290.
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 R23-R290.
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 R23-R290.
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 R23-R290.
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 R23-R290.
13. The effect of temperature difference in cascade condenser on COP is shown in Fig. 14, when the temperature difference in cascade condenser increases the COP of system decreases. Out of two refrigerant pairs R23-R290 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 R23-R290 responds maximum for change in temperature difference in cascade condenser.

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