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Analysis of Thermodynamic Performance of A Cascade Refrigeration System for Refrigerant Couples of R22/R404a, and R744/R404a

M-Tech Scholar Mudasir Ul Islam
Department of Mechanical Engineering
PIES, Bhopal

Prof. Sujeet Kumar Singh
Department of Mechanical Engineering
PIES, Bhopal

***Abstract* - This study presents a comparative analysis of thermodynamic performance of cascade refrigeration systems(CRSs) for refrigerant couples R22/R404a and R744/R404a to discover whether R22 and R744 is a suitable substitute for R404a. The discharge temperature, coefficient of performance(COP), exergy loss (X) and exergy efficiency (□) are chosen as the objective functions. The operating parameters considered in this paper include condensing temperature, evaporating temperature in both high-temperature cycle (HTC) and low temperature cycle (LTC). The results indicate that overall R22-R404A has a better performance than R744-R404A in cascade refrigeration system.**

***Keywords*: Cascade refrigeration systems, Thermodynamic analysis, Exergy, COP**

I. INTRODUCTION

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 favored. 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.

In view of shortage of energy and a quest to conserve it in all possible ways energy conservation is becoming a slogan of the present decade and new methods to save energy which is otherwise wasted are being explored. Energy recovery from waste heat and/or to utilize it for useful applications to improve the system efficiency is growing concern in scientific community and hence, is in use for industrial installations now-days. Ever present energy crises have forced the scientists and engineers all over the world to take into account the energy conservation measures in various industries. Reduction of electric power and thermal energy consumption are desirable but unavoidable in view of the fast and competitive industrial growth throughout the world. Refrigeration and air conditioning systems form a vital component for the industrial growth and affect both the food and energy problem of a country at large. RAC systems are also a major contributor to the energy consumption. Therefore it is desirable to provide a base for energy conservation and waste heat energy recovery from RAC & HP systems.

As energy conservation is becoming an increasingly important aspect/parameter, there is a need to optimize the thermodynamic processes for the minimum consumption of energy. Many parameters affect the performance of a refrigeration cycle. In order to optimize their design, a thorough study based on the second law of thermodynamics (exergy analysis) analysis is required.

Although, first law of thermodynamic analysis method is most commonly used, however, this is concerned only with the conservation of energy and therefore it cannot show how or where irreversibility in the system and or a process occurs. On the other hand, second law based exergy analysis is another well-known method being used to analyse these cycles. Unlike, the first law, second law analysis determine the magnitude of irreversible processes in a system and thereby, provides an indication to point out the directions in which the engineers should concentrate more to improve the performance of thermal system.

II. LITERATURE REVIEW

Continuous efforts have been made by numerous researchers on different types of cascade refrigeration system. Wonder to improve their performance and make them cost effective .Some researchers have developed thermodynamic model for the two stage and cascade refrigeration system. In Canan Cimsit (2018) study, the absorption part has been designed to improve the performance of absorption – vapor compression cascade cycle as serial flow double effect.The detailed thermodynamic analysis has been made of double effect absorption –vapour compression cascade refrigeration cycle. For the novel cycle working fluid used R-134a for vapour compression section & LiBr-H2O for absorption section. 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. R.S. Mishra (2017) deals with thermodynamic analysis of three stages cascade vapour compression refrigeration systems using eco-friendly refrigerants used for low temperature applications. The effect of thermal performance parameters on the first law thermal performances CO System and also in terms of second law efficiency of the cascade system and System exergy destruction ratio have been optimized thermodynamically using entropy generation principle. 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. 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. Umesh C. Rajmane (2016) study provides the advantages of vapor 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. Gami et.al. (2014) reported a thermodynamic energy and exergy analysis cascade refrigeration system using refrigerants pairs R134a R23and R290-R23 is presented in this paper to optimize the operating parameters of the system.

The 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 remain constant when degree of superheating increases in HT and LT system. The results show that COP and exergetic efficiency increases when degree of sub cooling increases in all three cases as discussed above. A. D. Parekh and P. R. Tailor (2014)thermodynamic analysis of cascade refrigeration system has been done using three different refrigerant pairs R13-R12, R290-R23,and R404A-R2. Thermodynamic analysis shows that out of three refrigerant pairsR12-R13, R290-R23 and R404A-R23 the COP of R290-R23refrigerant pair is highest.

III. OBJECTIVES OF STUDY

The main objective of this work is to comparetwo different cascade system using two refrigerant pairsR22-R404a and R744-R404a. The objectives of the present work can be listed as follows:

- To study the comparative analysis of thermodynamic performance of cascade refrigeration systems (CRSs) for refrigerant couples R22-R404a and R744-R404a.
- To discover whether R404a is a suitable substitute for R22.
- To study the effect of operating parameters on the performance of cascade refrigeration systems (CRSs) for refrigerant couples R22-R404a and R22-R744.

IV. SYSTEM MODELING

To aid in analysis of engineering problem it is necessary to realize the Physical model in a mathematical model. To do this, we first write state point equations of thermodynamic properties and then develop a polynomial for thermodynamic properties with the help of software or, directly taken from the reference. Therefore this chapter involves the description of physical model, mass, and energy balance, assumptions, state point equations and thermodynamic properties. To show the superiority of cascade system for low temperature application or to justify the utility of cascade system for low temperature cooling (below -40° c), it becomes necessary to analyze them separately.

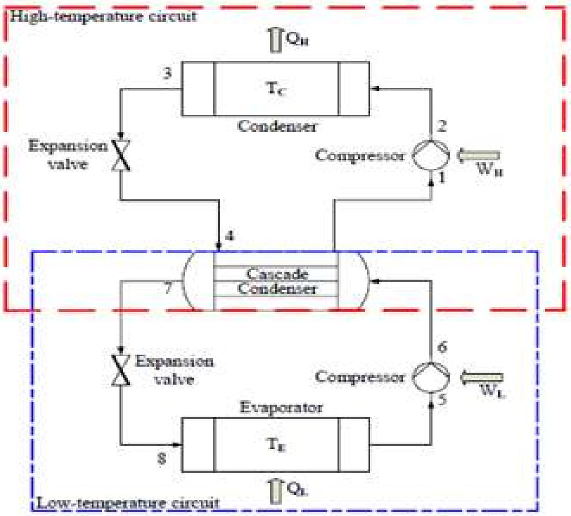

Fig. 1: Schematic diagram of the R22-R404acascade refrigeration system.

V. ASSUMPTIONS

- All components are assumed to be a steady state and steady flow processes. The changes in the potential and the kinetic energy of the components are negligible.
- The low circuit compressor is isentropic
- All throttling devices are isenthalpic.
- Refrigerants at the cascaded heat exchanger outlet, condenser outlet and evaporator outlet are saturated.
- Negligible pressure and heat losses or gains in the pipe networks or system components.
- The dead state is Ta=25°C and Pa=1 atm.

Table 2: Input parameter values assumed in the simulation models

Input parameters	**Value**
Q_{eva} (KW)	10
ΔT (°C)	5
T_{con}(°C)	50
$T_{cas,eva}$(°C)	0
T_{eva}(°C)	-30
$T_{cas,cond}$ (°C)	10
$\square_h$	0.8
$\square_l$	0.8
T_a(°C)	25

Table 2: Energy and Mass Balance for R22-R404a Cascade System

Component	**Mass**	**Energy**
R22-Compressor R404a-Compressor R22- Exp. Device R404a- Exp. Device Evaporator (R22) Condenser (R404a) Cascade heat exchanger	$m_7=m_8$ $m_6=m_5$ $m_5=m_6$ $m_4=m_1$ $m_6=m_7$ $m_4=m_3$ $m_1=m_2,m_5=m_8$	$W_{comp}R22=m_1.(h_8-h_7)/\square_1$ $W_{comp}R404a=m_2.(h_3-h_2)/\square_h$ $h_5=h_6$ $h_4=h_1$ $Q_{evap}R22=m_1(h_7-h_6)$ $Q_{cond}R404a=m_5(h_4-h_3)$ $m_1.(h_1-h_2)=m_2.(h_5-h_8)$

VI. MATHEMATICAL FORMULATION

Mass balance

$$\sum_{in} m^{\cdot} = \sum_{out} \dot{m}$$

Energy balance:

$\dot{Q}$- $\dot{w}$=$\sum_{out} \dot{m}$-$\sum_{in} \dot{m}$

Exergy balance:

$$X_{Lost}^{\cdot}=\sum_{out}\left(1-\frac{T_o}{T_i}\right)\dot{Q}_\iota - \dot{w}+\sum_{in}\dot{m}\varphi - \sum_{out}\dot{m}\,\varphi$$

$$\dot{m}_l = \frac{Q_e}{h_1 - h_5}$$

The compressor input work of LTC:

$$w_{comp,l} = \frac{\dot{m}_l(h_2 - h_1)}{\eta_l}$$

The heat load of cascade heat exchanger:

$$Q_{cas} = \dot{m}_l \times (h_2 - h_4) = \frac{Q_e(h_2 - h_4)}{h_1 - h_5}$$

The coefficient of performance in LTC:

$$COP_l = \frac{Q_e}{w_{comp,l}} = \frac{(h_1 - h_5)\eta_l}{h_2 - h_1}$$

The mass flow rate of HTC:

$$\dot{m}_h = \frac{Q_{cas}}{h_6 - h_{10}} = \frac{Q_e(h_2 - h_4)}{(h_6 - h_{10})(h_1 - h_4)}$$

$$w_{comp.h} = \frac{\dot{m}_h(h_7 - h_6)}{\eta_h}$$

The coefficient of performance in HTC:

$$COP_h = \frac{Q_{cas}}{w_{comp.h}}$$

The total input work of the both compressors:

$$w_{comp} = w_{comp.l} + w_{comp.h}$$

The heat load of the condenser:

$$Q_{cond.h} = \dot{m}_h(h_7 - h_9)$$

The overall coefficient of performance of CRS:

$$COP = Q_e / w_{comp}$$

The exergy loss in the compression process in LTC:

$$X_{comp.l} = T_a \dot{m}_l (s_2 - s_1)$$

The exergy loss in the expansion process in LTC:

$$X_{exp.l} = T_a \dot{m}_l (s_5 - s_4)$$

The exergy loss in the evaporation process in LTC:

$$X_{eva.l} = T_a \left[\dot{m}_l (s_1 - s_5) - \frac{Q_e}{T_e + \Delta T}\right]$$

The exergy loss in the compression process in HTC:

$$X_{comp.h} = T_a \dot{m}_h (s_7 - s_6)$$

The exergy loss in the condensation process in HTC:

$$X_{cond.h} = T_a \left[\dot{m}_h (s_9 - s_7) + \frac{Q_{cond}}{T_a}\right]$$

The exergy loss in the expansion process in HTC:

$$X_{exp.h} = T_a \dot{m}_h (s_{10} - s_9)$$

The exergy loss in cascade heat exchanger in the refrigeration system:

$$X_{cas} = T_a[\dot{m}_l (s_4 - s_2) + \dot{m}_h (s_6 - s_{10})]$$

The total exergy loss in the cascade refrigeration system:

$$X_{total} = X_{comp.l} + X_{comp.h} + X_{cond.h} + X_{exp.h} + X_{exp.l} + X_{eva.l} +$$

The exergy efficiency of the system

$$\eta = \frac{w_{comp.l} + w_{comp.h} - X_{total}}{w_{comp.l} + w_{comp.h}}$$

VII. 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.

- **Effect of Evaporator Temperature**
  The effect on COP, exergetic efficiency and total exergetic loss, when evaporator temperature varied from -60°C to -15°C in the interval of 5°C keeping other parameters constant is shown below respectively. For a given condensing temperature, the pressure ratio increases as the evaporator temperature decreases.

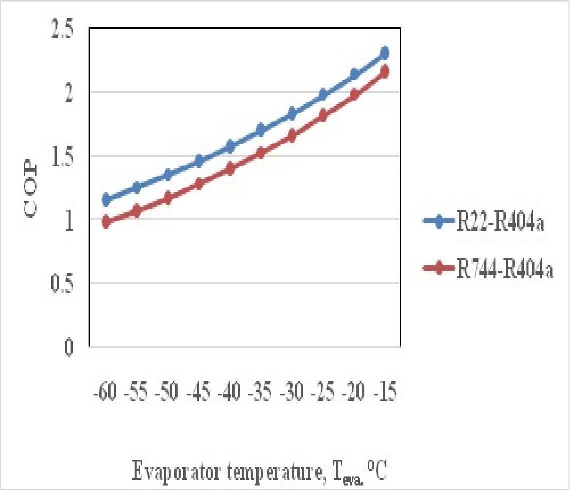

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Fig. 2: Effect of evaporator temperature on COP.

Fig. 2 shows that as evaporator temperature increases the COP increases. COP increases for R22-R404a and R744-R404arespectively. Among two pair R22-R404a shows maximum change in COP followed by R744-R404a.

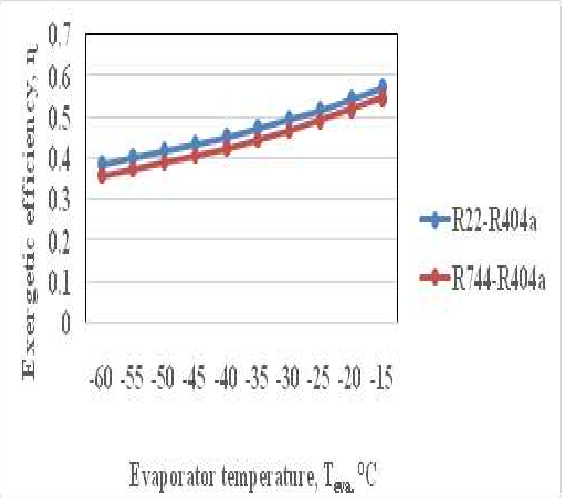

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Fig. 3: Effect of evaporator temperature on exergetic efficiency.

Fig. 3 shows that as evaporator temperature increases the exergetic efficiency increases. Among two pair R22-R404ashows maximum change in exergetic efficiency followed by R744-R404a.

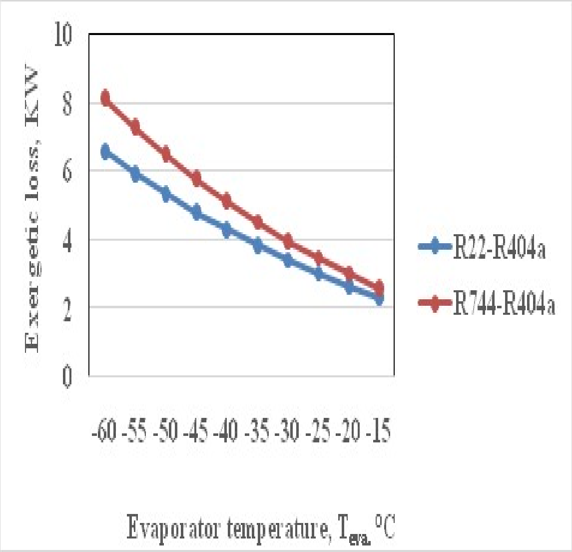

Fig. 4: Effect of evaporator temperature on exergetic loss.

Fig. 4 shows that as evaporator temperature increases the exergetic efficiency decreases. Among two pair R744-R404ashows maximum change in exergetic efficiencyfollowed by R22-R404a.

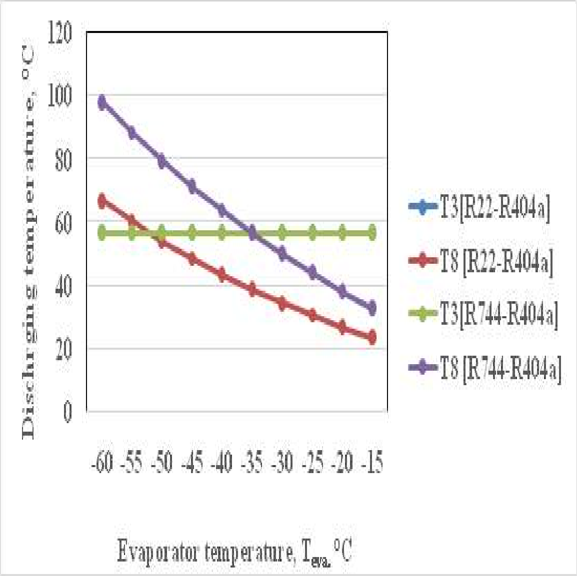

Fig. 5: Effect of evaporator temperature on discharging temperature.

The increment of T_d in LTC using R744/R404a is far more than that using R22/ R404a and the difference of T_d become larger as T_{eva} decreases.

- **Effect of Condenser Temperature**

The condenser temperature is varied from 25°C to 70°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. respectively.

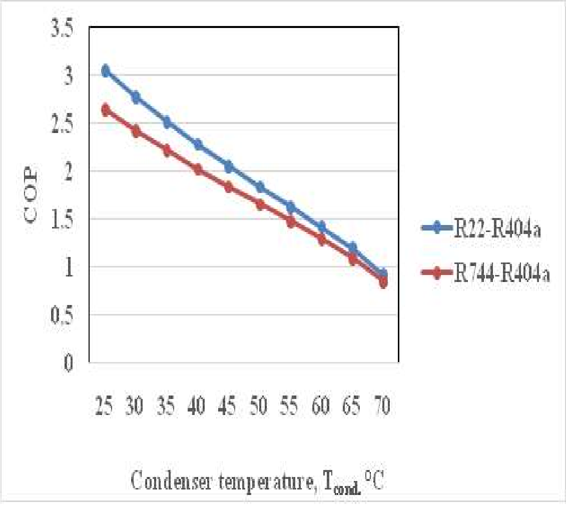

Fig. 6: Effect of condenser temperature on COP.

Fig. 6 shows that as condenser temperature increases the COP decreases. Among two pair R22-R404ashows maximum change in COP followed by R744-R404a.

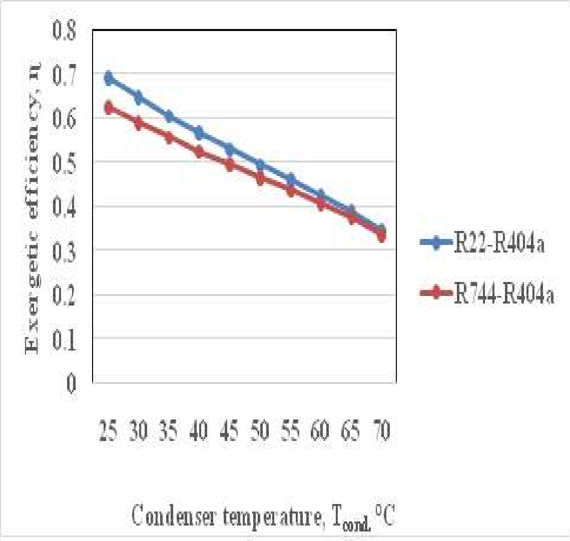

Fig. 7: Effect of condenser temperature on exergetic efficiency.

Fig. 7 shows that as condenser temperature increases the exergetic efficiency decreases. Among two pair R22-R404ashows maximum change in COP followed by R744-R404a

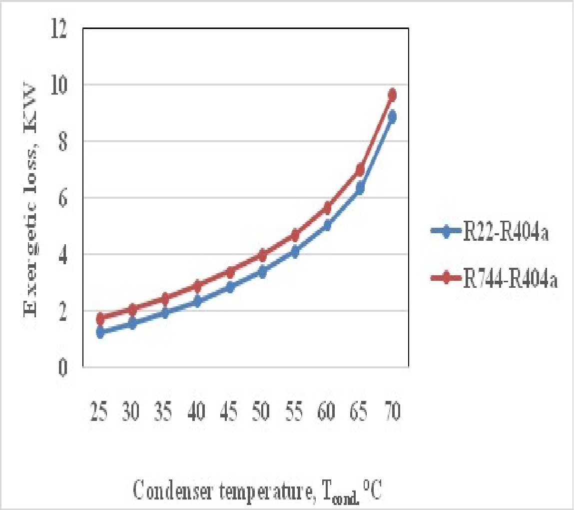

Fig. 8: Effect of condenser temperature on exergetic loss.

Fig. 8 shows that as condenser temperature increases the exergetic loss increases. Among two pair R744-R404ashows maximum change in COP followed by R22-R404a.

- **Effect of L.T Cycle Condenser Temperature (T_{casl})**

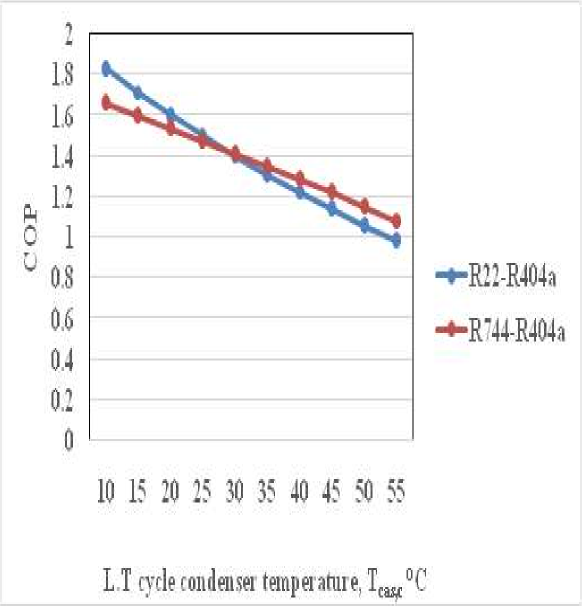

Fig. 9: Effect of L.T cycle condenser temperature on COP.

Fig. 9 shows that as LT cycle condenser temperature increases the COP decreases. Among two pair R22-R404ashows minimum change in COP lossfollowed by R744-R22.

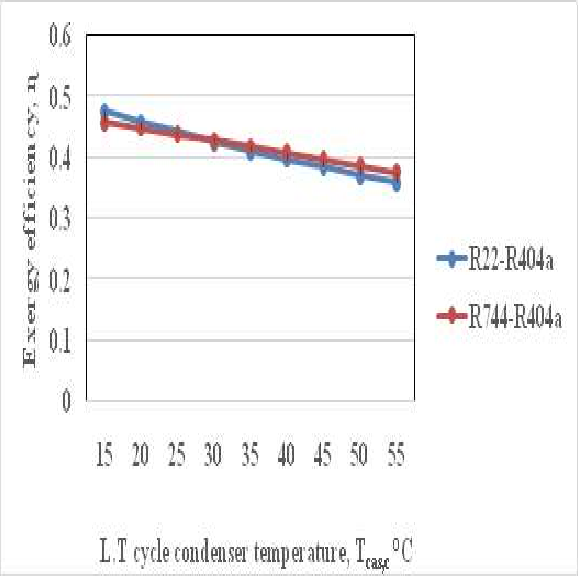

Fig. 10: Effect of L.T cycle condenser temperature on exergetic efficiency.

Fig. 10 shows that as LT cycle condenser temperature increases the exergetic efficiency decreases. Among two pair R744-R404ashows minimum change in exergetic efficiency followed by R22-R404a.

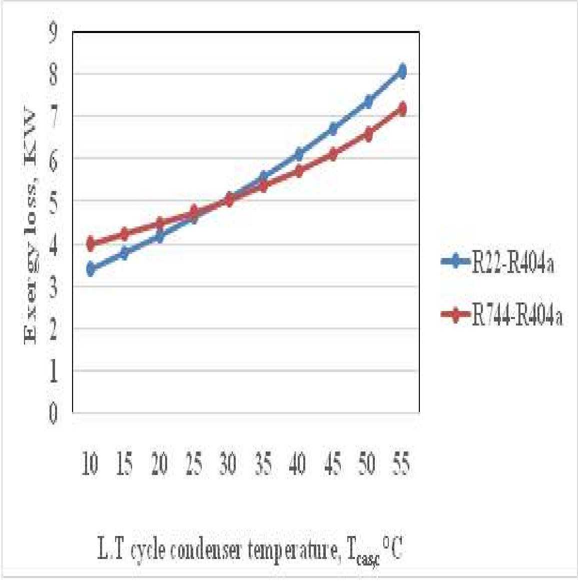

Fig. 11: Effect of L.T cycle condenser temperature on exergetic loss.

Fig. 11 shows that as LT cycle condenser temperature increases the exergetic loss increases. Among two pair

R22-R404ashows minimum change in exergetic lossfollowed by R744-R404a.

VIII. 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. The following conclusions are drawn from present study.

- It is observed that evaporator temperature increases the COP increases. COP increases for R22-R404a and R744-R404a respectively. Among two pair R22-R404a shows maximum change in COP followed by R744-R404a.
- Same trend is observed that as evaporator temperature increases the exergetic efficiency increases. Among two pair R22-R404a shows maximum change in exergetic efficiency followed by R744-R404a.
- However, when evaporator temperature increases the exergetic loss decreases. Among two pair R744-R404a shows maximum change in exergetic efficiency followed by R22-R404a.
- The increment of Td in LTC using R744/R404A is far more than that using R22/ R404A and the difference of Td become larger as Te decreases.
- It is observed that condenser temperature increases the COP decreases. Among two pair R22-R404a shows maximum change in COP followed by R744-R404a.
- Similar trend is observed that condenser temperature increases the exergetic efficiency decreases. Among two pair R22-R404a shows maximum change in COP followed by R744-R404a.
- However, when condenser temperature increases the exergetic loss increases. Among two pair R744-R404a shows maximum change in COP followed by R22-R404a.
- When LT cycle condenser temperature increases the COP decreases. Among two pair R22-R404a shows minimum change in COP loss followed by R744-R22.
- When LT cycle condenser temperature increases the exergetic efficiency decreases. Among two pair R744-R404a shows minimum change in exergetic efficiency followed by R22-R404a.
- When LT cycle condenser temperature increases the exergetic efficiency increases. Among two pair R22-R404a shows minimum change in exergetic efficiency followed by R744-R404a.
- Overall R22-R404A has a better performance than R744-R404A in cascade refrigeration system

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