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Thermodynamic Analysis of a Cascade Refrigeration System with R744/R290 Mixtures

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Abstract

This investigation thermodynamically analyzes a cascade refrigeration system which uses an eco-friendly refrigerant R744/R290 mixture in the circuit with lower temperature as a working fluid. It has zero ODP. Condensing temperature, evaporating temperature, and cascade temperature difference with and without the effect of superheating and subcooling of both circuits are the operating parameters and design parameters considered in this investigation. In the present study, thermodynamic analysis of an eco-friendly alternative new refrigerant (mixture of R744 and R290) was proposed and performed with five refrigerants such as R407c, R408a, R410a, R404a, and R417a, which are in the higher temperature circuits of a cascade refrigeration system. MAT-LAB software was performed in terms of temperature in evaporator, temperature in condenser and difference in cascade temperature to develop an expression mathematically for excellent COP, most favorable evaporating temperature of R744/R290 mixture and most favorable mass flow ratio of high temperature refrigerant to that R744/R290 mixture.

Keywords: Binary Mixture, Cascade Refrigeration System, COP, Carbon dioxide, Propane, Theoretical Analysis

1. Introduction

Low-temperature refrigeration systems which are in the temperature range from -30˚C to -100˚C are required for applications in food, pharmaceutical, and other industries. For such lower temperatures, single-stage vapor compression systems do not suit due to higher pressure ratios because higher pressure ratio would result in high discharge, oil temperatures and low volumetric efficiencies and, hence finally it results in lower values of COP. A two stage cascade system comprises of two vapour–compression units which works separately and interconnected with each other in such a way that evaporator of one system works as condenser to the other system. A schematic layout and p-h plot of a two stage cascade system using two refrigerants are shown in “Figure 1.” and “Figure 2.”

From the lower stage, the refrigerant vapour is condensed in cascade condenser, which also serves as the evaporator of the next higher stage refrigerant.

B. Agnew et al.[1] have studied on a three stage a cascade refrigeration system which uses two different refrigerants. Nicola et al.[2] have performed a thermodynamic analysis of a cascade refrigeration system which uses HFC’s and their blends with carbondioxide as refrigerants in low-temperature circuits. Tung-Wei Chen et al.[3] have analyzed a cascade refrigeration system thermodynamically which uses carbon dioxide and ammonia as refrigerants, to determine the most favorable condensing temperature. Souvik Bhattacharyya et al.[4] have analyzed a natural refrigerant cascade refrigeration system, which uses nirous oxide and carbondioxide in low temperature and high temperature circuits respectively. Souvik Bhattacharyya et al.[5] have examined the performance of a cascade refrigeration–heat pump system analytically. Maoqiong Gong et al.[6] have examined the refrigeration performance parameters of two binary azeotropic mixtures and a ternary azeotropic mixture. The results showed that binary mixture has 10% higher COP than that of R508B. P.K. Bansal

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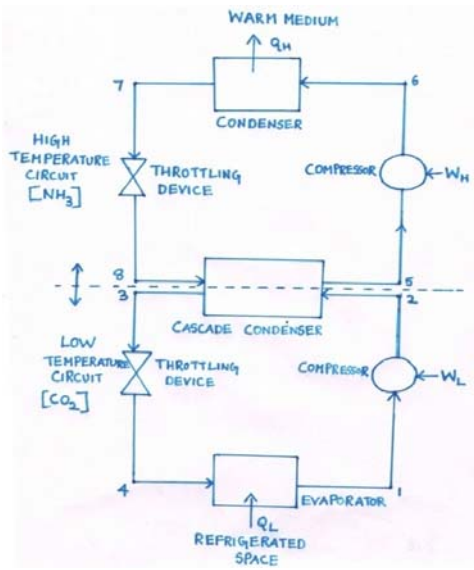


Figure 1. Schematic layout of two stage cascade refrigeration system.

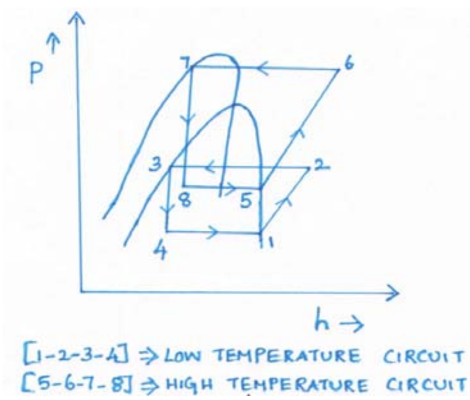


Figure 2. p-h Diagram of cascade refrigeration system.

et al.[7] have presented thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system is to optimize the design and operating parameters of the system. A multilinear regression analysis was employed in this work. Jaime Sieres et al.[8] have carried out a study by using a mathematical model to analyze a cascade refrigeration system. Kilicarslan[9] have carried out a experimental study on a cascade refrigeration system using R-134a as refrigerant in both high and temperature circuits. It was seen that with the increase in refrigeration load, COP increases. Antonio Messineo[10] have carried out a thermodynamic analysis by considering different operating parameters by using carbon dioxide as refrigerant in lower temperature circuit and ammonia in higher temperature circuit. The results showed that this system could act as a alternative to other refrigeration systems. In the present analysis, an environmental-friendly alternative new refrigerant (mixture of R744 and R290) was taken and performed with five different refrigerants such as R404a, R407c, R408a, R410a and R417a, which are in the high temperature circuits the system.

2. Thermodynamic Analysis of Cascade System

Considering "Figure 1." the below equations were used for the thermodynamic analysis,

The evaporator load is given by "Equation (1)":

$$Q_E = m_L (h_1 - h_4) \tag{1}$$

Work done by the compressor of higher-temperature circuit is given by "Equation (2)":

$$W_H = m_H (h_6 - h_5) \tag{2}$$

Where,

m_L is the flow rate of refrigerant in the low temperature cascade system and

m_H is the flow rate of refrigerant in the high temperature cascade system.

Power consumption for Compressor in low-temperature circuit, it is given by "Equation (3)":

$$W_L = m_L(h_2 - h_1) \tag{3}$$

The rate of heat transfer in the cascade heat exchanger is given by "Equation (4)":

$$Q_{CAS} = m_L(h_2 - h_3) = m_H(h_5 - h_8) \tag{4}$$

Mass flow is given by "Equation (5)":

$$\frac{m_H}{m_L} = \frac{(h_2 - h_3)}{(h_5 - h_8)} \tag{5}$$

The rate of heat rejection by the condenser is given by "Equation (6)":

$$Q_H = m_H(h_6 - h_7) \tag{6}$$

The coefficient of performance of the system is given by "Equation (7)":

$$COP = \frac{Q_E}{W_H + W_L} \tag{7}$$

The coefficient of performance can be given in terms of enthalpies by "Equation (8)"

$$COP = \frac{(h_5 - h_8)(h_1 - h_4)}{(h_6 - h_5)(h_2 - h_3) + (h_5 - h_8)(h_2 - h_1)} \quad (8)$$

3. Results and Discussion

3.1 Effect of Condensing and Evaporating Temperature

Figures 3-5 shows the variation of COP and Figures 6-8 shows the variation of flow ratio for change in cascade condensing ($T_{CAS,C}$) and evaporating (T_E) in the lower temperature circuit and evaporating ($T_{CAS,E}$) temperatures. Firstly cascade condensing temperature was varied from -30^{0}C to -40^{0}C and was performed for various evaporating temperatures between -70^{0}C to -80^{0}C, while the other temperatures such as condensation temperature (T_C

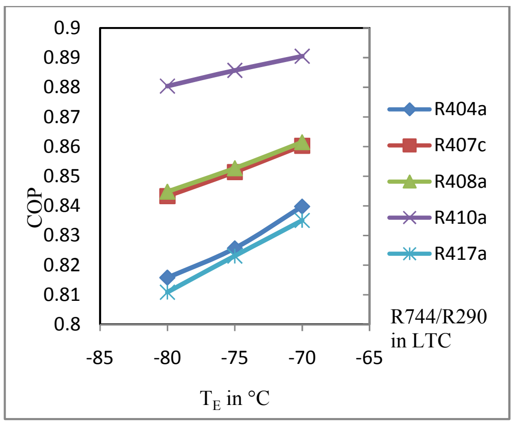


Figure 3. COP for various evaporating temperature and condensation temperature –30 °C.

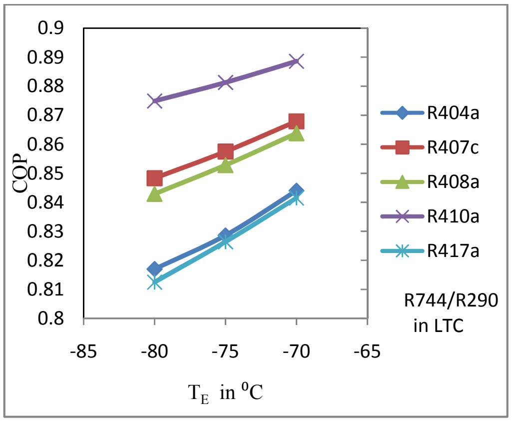


Figure 4. COP for various evaporating temperature and condensation temperature –35 °C.

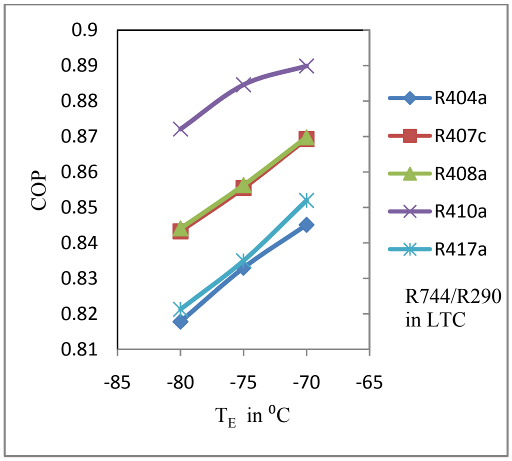


Figure 5. COP for various evaporating temperature and condensation temperature –40 °C.

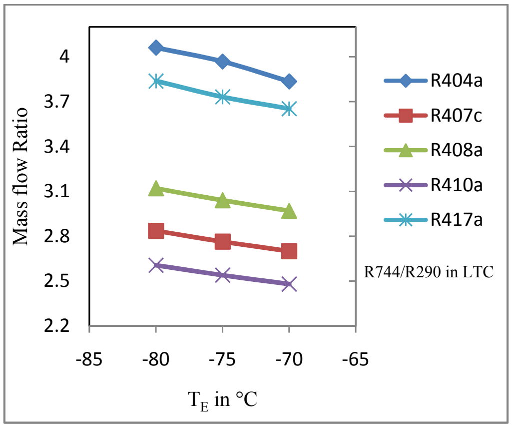
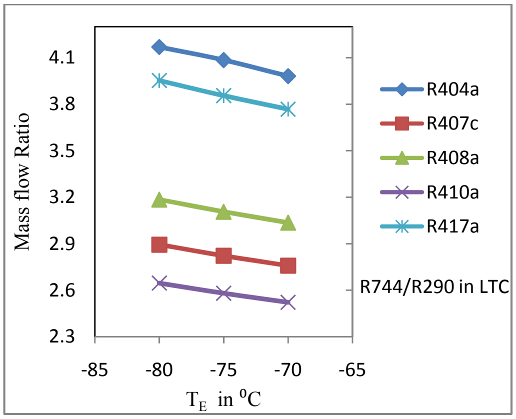


Figure 6. Mass flow Ratio for various evaporating temperature and condensation temperature –30 °C.



= 30^{0}C), subcooling (T_{sub} = 0^{0}C) and superheat (T_{sup} = 0^{0}C) were held constant.

From the graph, it is observed that the COP of the whole system increased with the decrease in cascade condensing temperature. With the increase in evaporating temperature, the COP of the system increases. Mass flow ratio decreases with increase in cascade condensing and evaporating temperatures. From these results showed, R410a performed well because it has much higher value of COP than other refrigerants and also it has lowest value of mass flow ratio than others. R404a has larger mass flow ratio than others combinations for the above prescribed cases.

3.2 Effect of Degree of Subcooling

Figures 9-11 shows the variation of COP and Figures 12-14. shows the Mass flow ratio variation for change in subcooling temperature. Subcooling temperature was

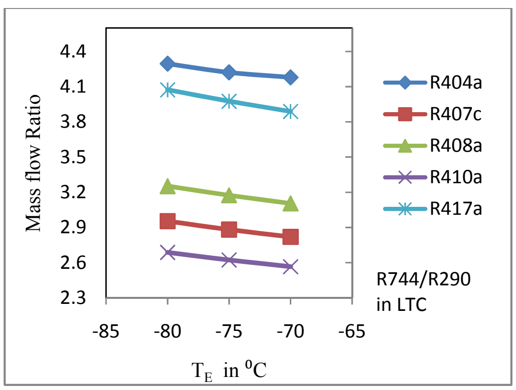


Figure 8. Mass flow Ratio for various evaporating temperature and condensation temperature –40°C.

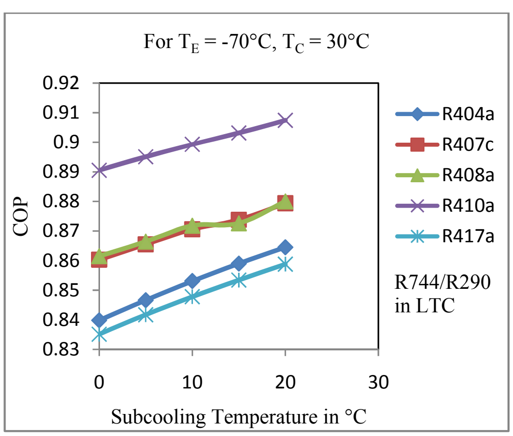


Figure 9. COP for various subcooling temperature and condensation temperature –30 °C.

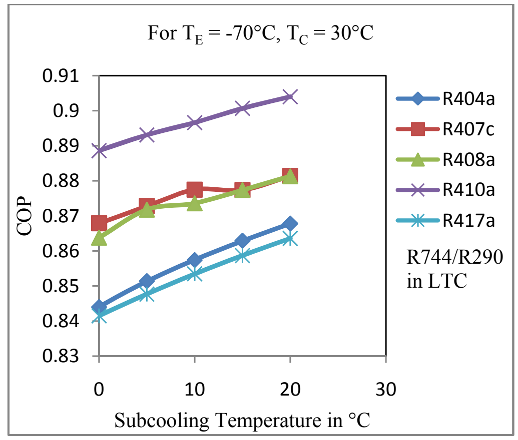


Figure 10. COP for various subcooling temperature and condensation temperature -35°C.

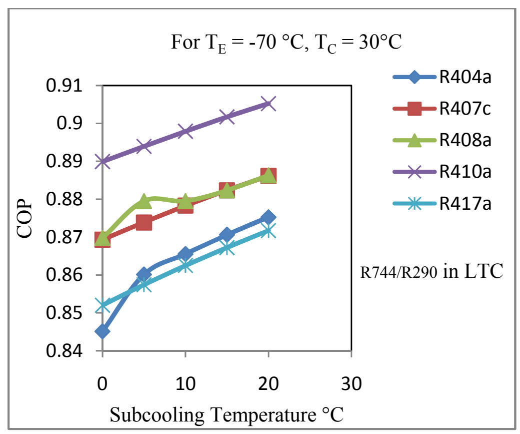


Figure 11. COP for various subcooling temperature and condensation temperature –40°C.

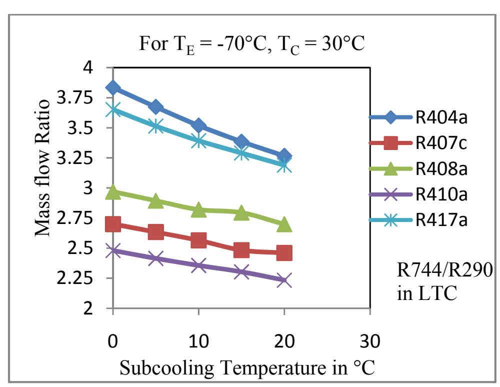


Figure 12. Mass flow Ratio for various subcooling temperature and condensation temperature –30°C.

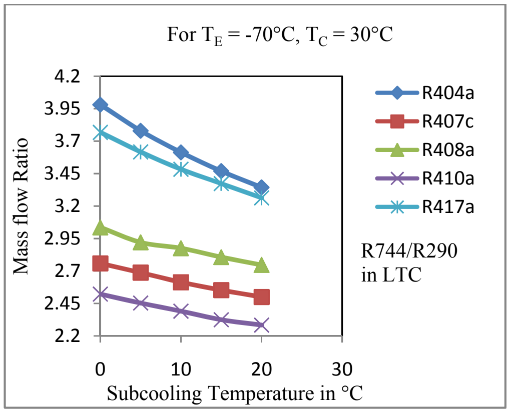


Figure 13. Mass flow Ratio for various subcooling temperature and condensation temperature –35°C.

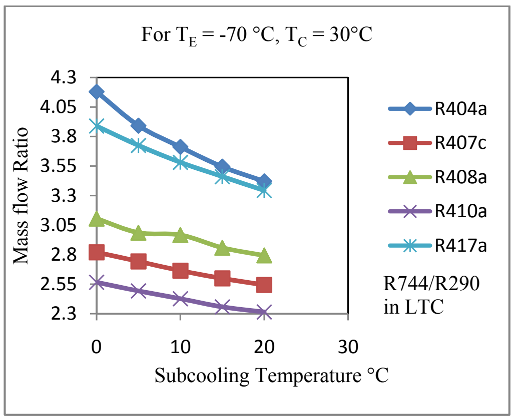


Figure 14. Mass flow Ratio for various subcooling temperature and condensation temperature –40°C.

varied from 0°C to 20°C for both higher temperature and lower temperature circuits. In this case, the evaporating (T_E = -70°C) and condensation temperatures (T_C = 30°C) were held constant.

From the graph, it can be seen that with the decrease in cascade condensing temperature, the COP of the whole system rises. The COP of the whole system increases, as subcooling temperature rises. Mass flow ratio decreased with increasing the cascade condensing and subcooling temperatures. From these results showed, R410a was performed well because it has much higher value of COP than other refrigerants and also it has lowest value of mass flow ratio than others.

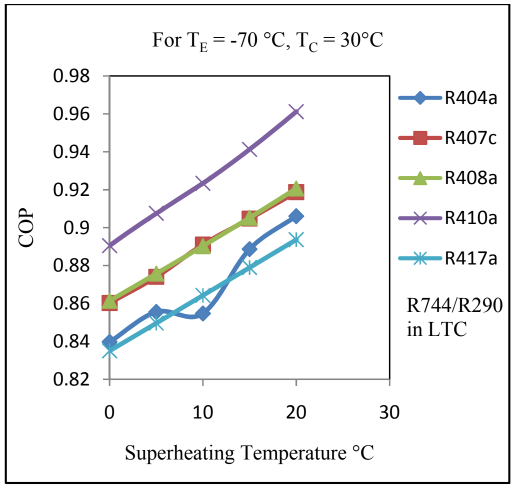


Figure 15. COP for various superheating temperature and condensation temperature –30°C.

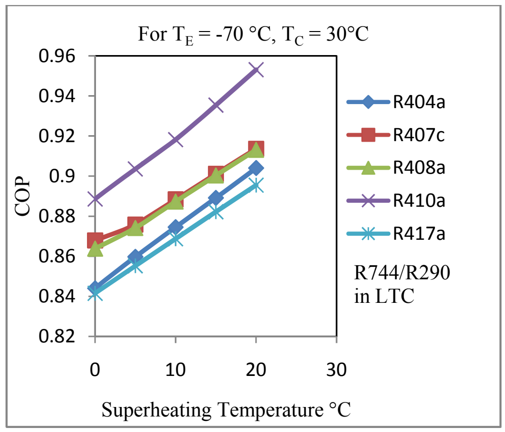
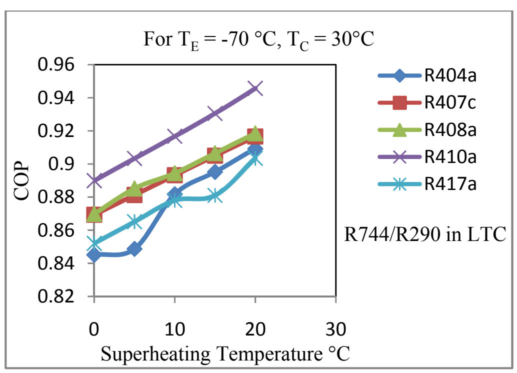


Figure 16. COP for various superheating temperature and condensation temperature –35°C.



3.3 Effect of Degree of Superheat

Figures 15-17 shows the variation of COP and Figures 18-20 shows the change of Mass flow ratio for change in

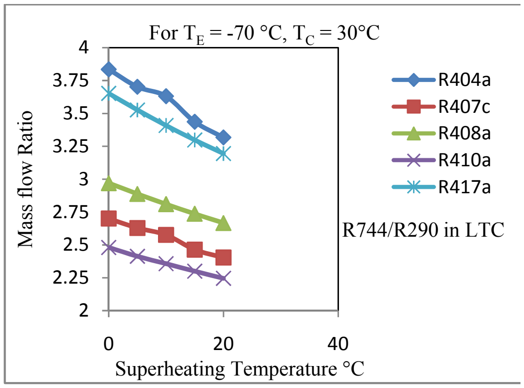


Figure 18. Mass flow Ratio for various superheating temperature and condensation temperature –30°C.

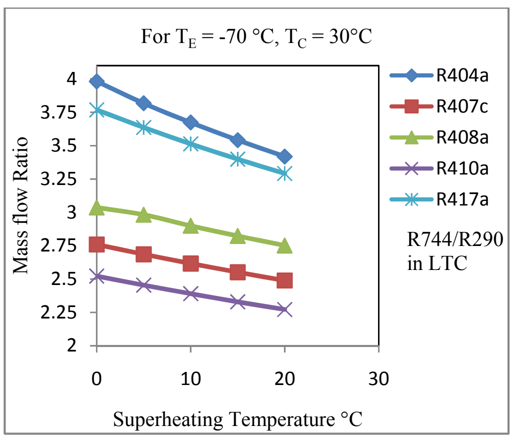


Figure 19. Mass flow Ratio for various superheating temperature and condensation temperature –35°C.

superheating temperature. Superheating temperature was varied from 0^0C to 20^0C for both higher temperature and lower temperature circuits. In this case, the evaporating (T_E = -70°C) and condensation temperatures (T_C = 30°C) were held constant.

From the graph, it can be seen that with the increase in cascade condensing temperature, the COP of the whole system increases. The COP of whole system increases and with the increase in superheating temperature. Mass flow ratio decreased with the increase in cascade condensing and superheating temperatures. From these results showed, R410a was performed well because it has much higher value of COP than other refrigerants and also it has lowest value of mass flow ratio than others. In R404a, has larger mass flow ratio than others combinations for the above prescribed cases.

3.4. Effect of Degree of Subcooling and Superheat

"Figures 21-26." shows the variation of COP and "Figures 27-32." shows the variation of Mass flow ratio for change in subcooling and superheating temperature. Subcooling and Superheating temperature was varied from 5^0C to 20^0C for both higher temperature and lower temperature circuits. Thermodynamic analysis was done wit with condensing temperature ($T_{CAS,C}$ = -30^0C), evaporating (T_E = -70°C) and condensation temperatures (T_C = 30°C) were held constant.

From the graph, it can be seen that with the increase in cascade condensing temperature for R410a, the COP of the whole system rises. It is also found that with the decrease in cascade condensing temperature, the COP of

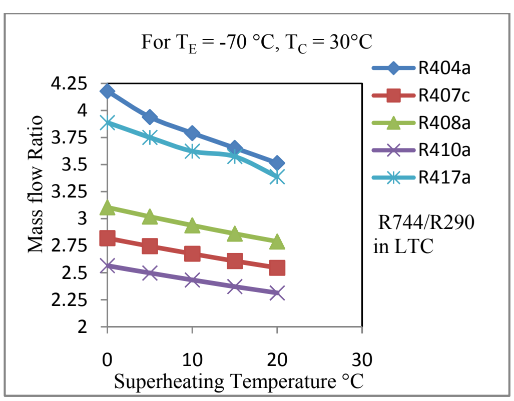


Figure 20. Mass flow Ratio for various superheating temperature and condensation temperature –40°C.

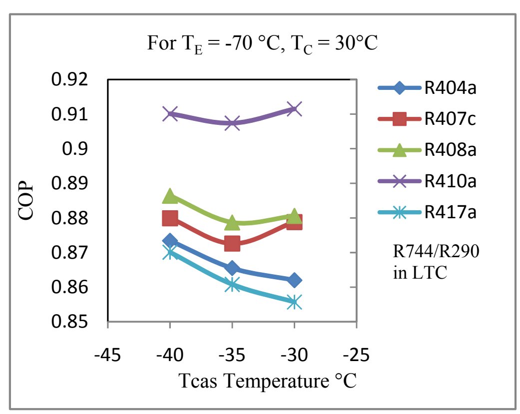
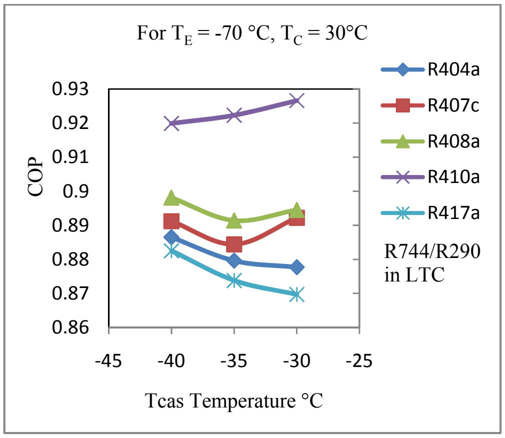


Figure 21. COP for subcooling at 5 °C and superheating at 5°C.



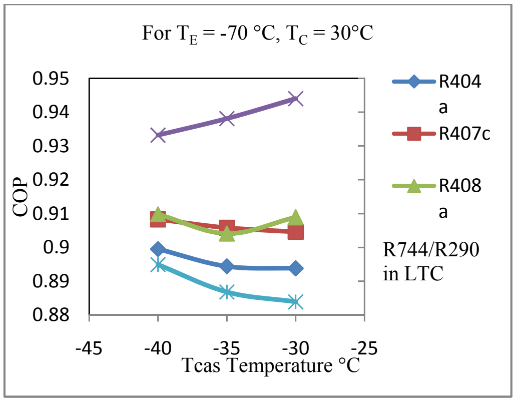


Figure 23. COP for subcooling at 5 °C and superheating at 15 °C.

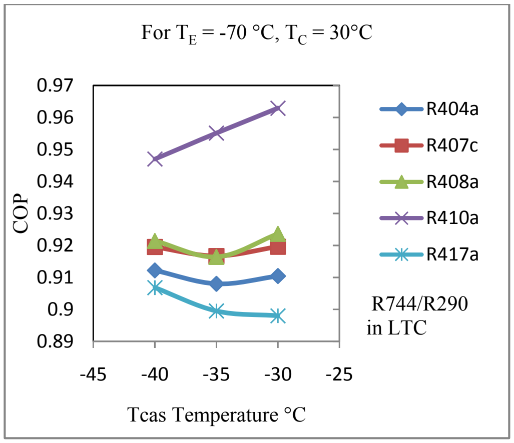


Figure 24. COP for subcooling at 5 °C and superheating at 20 °C.

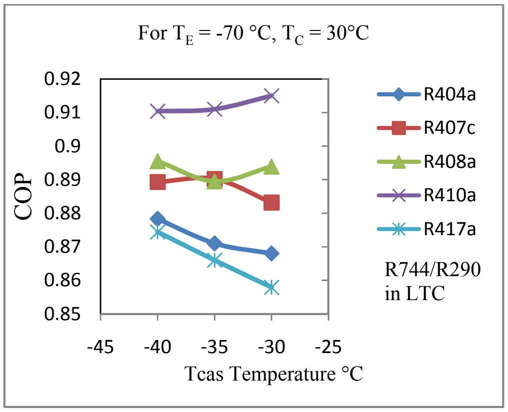


Figure 25. COP for subcooling at 10°C and superheating at 5°C.

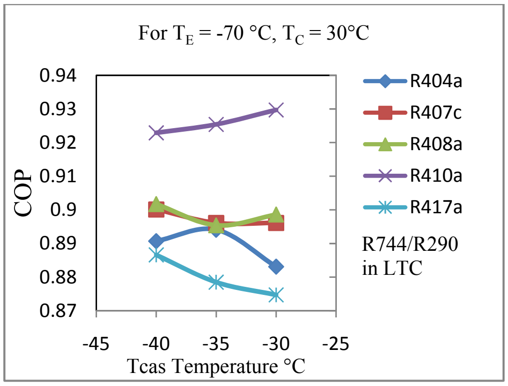


Figure 26. COP for subcooling at 10°C and superheating at 10°C.

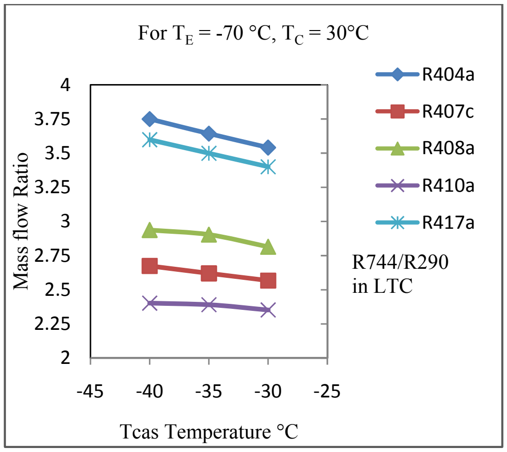


Figure 27. Mass flow Ratio for subcooling at 5 °C and superheating at 5 °C.

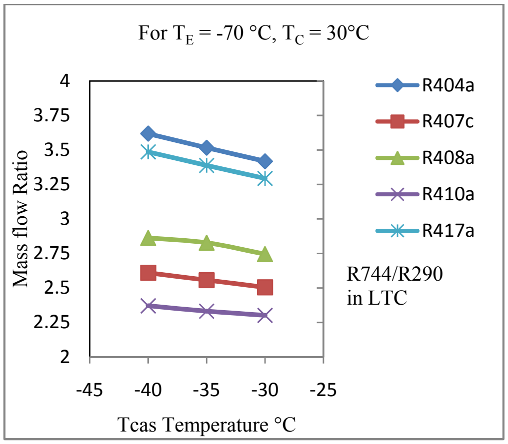


Figure 28. Mass flow Ratio for subcooling at 5 °C and superheating at 10 °C.

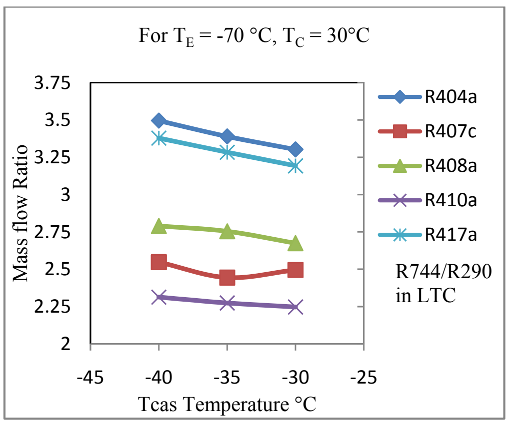


Figure 29. Mass flow Ratio for subcooling at 5 °C and superheating at 15 °C.

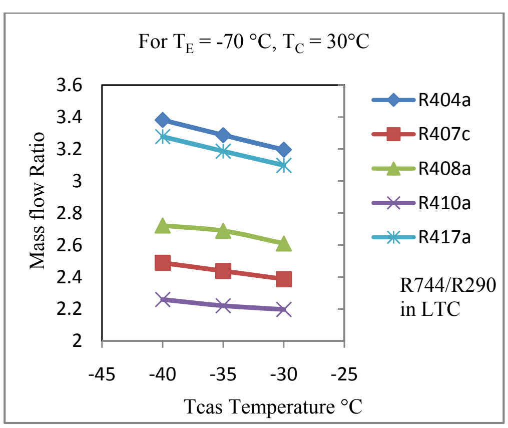


Figure 30. Mass flow Ratio for subcooling at 5 °C and superheating at 20 °C.

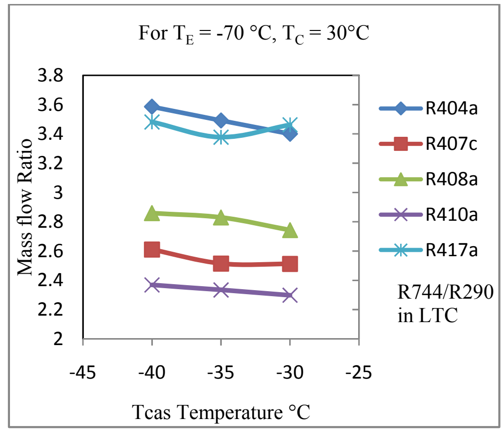


Figure 31. Mass flow Ratio for subcooling at 10°C and superheating at 5 °C.

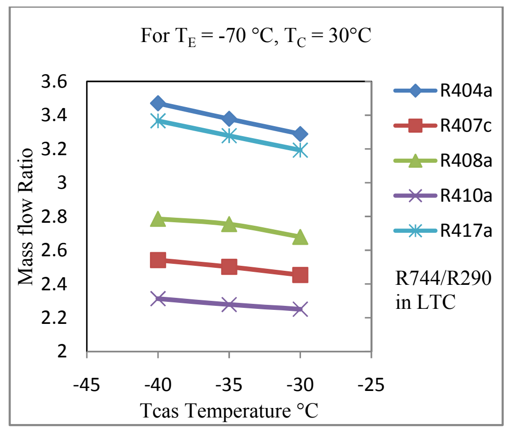


Figure 32. Mass flow Ratio for subcooling at 10°C and superheating at 10°C7.

the whole system decreases for other all four refrigerants. Mass flow ratio decreased with increase in cascade condensing temperatures. From these results showed, R410a was performed well because it has much higher value of COP than other refrigerants and also it has lowest value of mass flow ratio than others. In R404a, has larger mass flow ratio and R417a has lowest value of COP than others combinations for the above described cases.

4. Conclusion

A thermodynamic analysis for a cascade refrigeration system shows that for operating conditions of -70°C evaporating temperature and 30°C condensing temperature R410A has the highest coefficient of performance and R404A has the minimum coefficient of performance. R404A requires maximum mass flow ratio and R410a requires the lowest mass flow. A rise in subcooling rises the COP of the system but reduces mass flow ratio of the system. From the thermodynamic analysis it can be concluded that,

- The coefficient of performance and mass flow ratio of the cascade refrigeration system increases with the increase in superheating temperature.
- The coefficient of performance of the cascade refrigeration system decreases with the increase in cascade condensing temperature.
- The coefficient of performance increases and the mass flow ratio decreases with the increase in evaporating temperature where as both the coefficient of performance and mass flow ratio decreases with the decrease in condensing temperature.

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