



An Application for Refrigerant Selecting In the Cascade Refrigeration Systems

Reşat SELBAŞ^a

^a Süleyman Demirel University Technology Faculty Energy Systems Engineering 32260 Çünür-İSPARTA

* Sorumlu yazarın e-posta adresi: resatselbas@sdu.edu.tr

ABSTRACT:

In this study, energy and exergy analysis of a cascade refrigeration system was carried out. It is assumed that the refrigeration load is 1 kW. The temperature in condenser has been used between 50 °C to 60 °C, and the temperature in evaporator was changed between -30 °C to -40 °C. Refrigerant couples used in the cascade refrigeration system are R134a-R404A, R134a-R407C, R404A-R410A, R404A-R507, and R407C-R410A. These refrigerant couples are new generation refrigerant couples that are non-destructive to environment and to the ozone layer. The COP values and irreversibility values of the cascade refrigeration system were determined. In all cases, the refrigerant couple R134a-R407C has the highest COP and lowest irreversibility.

Keywords: Cascade refrigeration, Thermodynamic analysis, COP, exergy.

Kademeli Soğutma Sistemlerinde Soğutucu Akışkan Seçimi İçin Bir Uygulama

ÖZET:

Bu çalışmada kaskad soğutma sisteminin termodinamik analizi yapılmıştır. Soğutma kapasitesi 1 kW olarak kabul edilmiştir. Kondenser sıcaklığı 50 °C ile 60 °C arasında, evaporator sıcaklığı -30 °C ile -40 °C arasında değiştirilmiştir. Kaskad soğutma sisteminde soğutucu çifti olarak R134a-R404A, R134a-R407C, R404A-R410A, R404A-R507, R407C-R410 A kullanılmıştır. Bu soğutucu akışkan çiftlerinin ozon tabakasına ve çevreye yıkıcı etkisi yoktur. Kaskad soğutma sisteminin COP değerleri ve tersinmezlik değerleri belirlenmiştir. Bütün akışkan çiftlerin arasında en yüksek verim ve en düşük tersinmelik oranı R134a-R407C akışkan çiftinde elde edilmiştir.

Anahtar Kelimeler: Kaskad soğutma, Termodinamik analiz, COP, Ekserji

1. INTRODUCTION

Cascade refrigeration systems (Fig. 1) are suitable for industrial applications, especially in the supermarket refrigeration industry, where the evaporating temperature of frozen-food cabinets ranges from $-40\text{ }^{\circ}\text{C}$ to $-80\text{ }^{\circ}\text{C}$. It is impossible to reach these temperatures with single-stage cooling systems. In two-stage systems, evaporator and condenser are filled with the same refrigerant. In cascade cooling applications, evaporator and condenser may be filled with different refrigerant couple. The pressure–enthalpy (P–h) and the temperature entropy (T–s) diagrams of the cascade refrigeration cycle can be shown in Fig. 2

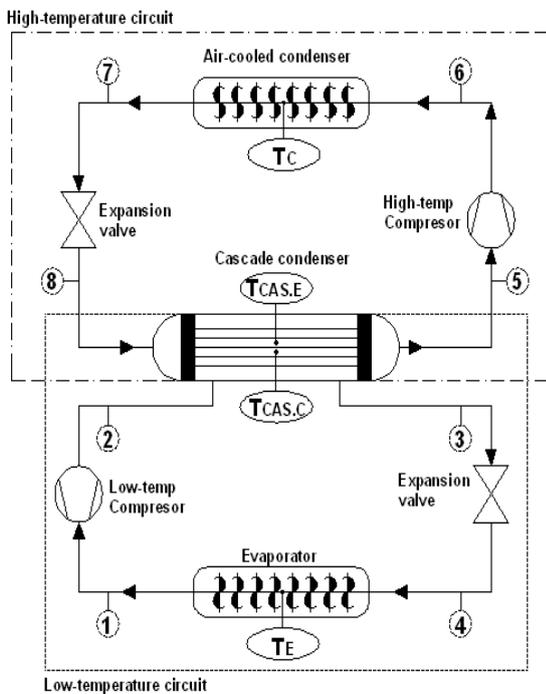


Fig.1 The two-stage vapor compression cascade refrigeration system of schematic diagram

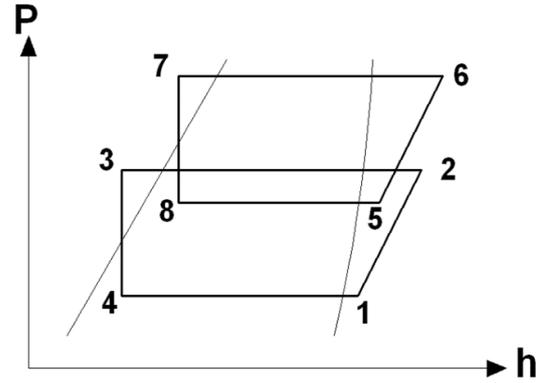


Fig.2 The two-stage vapor compression cascade refrigeration system of P-h diagram

Several researchers have evaluated the thermodynamic performance of the two-stage cascade refrigeration systems. Kilicarslan (2004) carried out experimental investigation and theoretical study of a different type of two-stage vapor compression cascade refrigeration system. It is observed that the predictions of theory and experiment results are in close agreement [1]. Silva et al. (2012) performed comparison of a R744 cascade refrigeration system with R404A and R22 conventional systems for supermarkets. Authors analyzed energy efficiency comparisons carried out between the CO_2 cascade system and the direct expansion conventional system using R404A and R22, and discuss their advantages and disadvantages, along with a comparison of a cost analysis with carbon dioxide [2]. Kilicarslan and Hosoz carried out energy and irreversibility analysis of a cascade refrigeration system employing various refrigerant couples, namely R152a–R23, R290–R23, R507–R23, R234a–R23, R717–R23 and R404A–R23. Refrigerant couple R717–R23 is the best couple for the vapour compression cascade refrigeration systems

among all considered couples. However, if there are some limitations for the use of the natural refrigerants, the couple R152a–R23 is the solution [3]. Mafi et al. presented exergy analysis for multistage cascade low temperature refrigeration systems used in olefin plants. The exergy analysis results on the refrigeration system indicate that the major irreversibilities are due to losses within the compression system, driving forces across the heat exchangers, and losses due to refrigerant let down. The overall exergetic efficiency of the cascade refrigeration system is determined to be 30.88% indicating a great potential for improvements [4].

Dopazo and Fernandez-Seara designed a prototype of a cascade refrigeration system using NH₃ and CO₂ as refrigerants. The prototype is used to supply a 9 kW refrigeration capacity horizontal plate freezer at an evaporating temperature of -50°C as design conditions. The discussions on the experimental results include the influence of the operating parameters on the cascade system's performance. In addition, the experimental results are compared with two common doublestage refrigeration systems using NH₃ as refrigerant [5]. Bingming et al. analyzed the performance of a refrigeration system in cascade with ammonia and carbon dioxide as working fluids. Performance of the cascade system with NH₃/CO₂ was compared with that of two-stage NH₃ system and single-stage NH₃ system with or without economizer. All the experimental results indicate that the NH₃/CO₂ cascade system is very competitive in low temperature applications [6].

Messineo presented a thermodynamic analysis of a cascade refrigeration system using as refrigerant carbon dioxide in low-temperature circuit and ammonia in high-temperature circuit. In addition, values for R744-R717 cascade refrigeration system are compared with the values obtained for a partial injection two-stage refrigeration system using the synthetic refrigerant R404A, a nearly azeotropic blend, specially used for commercial refrigeration. Results show that a carbon dioxide-ammonia cascade refrigeration system is an interesting alternative to R404A two-stage refrigeration system for low evaporating temperatures (-30°C/-50°C) in commercial refrigeration for energy, security and environmental reasons [7].

Dopazo et al. analyzed a cascade refrigeration system with CO₂ and NH₃ as working fluids in the low and high temperature stages. Results of COP and exergetic efficiency versus operating and design parameters have been obtained. In addition, an optimization study based on the optimum CO₂ condensing temperature has been done [8]. Bhattacharyya et al. analyzed a natural refrigerant based cascaded system, with nitrous oxide as the low temperature fluid and carbon dioxide as the high temperature fluid. Effects of significant design and operating parameters on system performance are studied. Optimization of intermediate pressure for maximum COP for various design and operating parameters are presented as well. Results show that use of internal heat exchanger has marginal influence on system performance [9].

Getu and Bansal presented thermodynamic analysis of carbon dioxide–ammonia (R744–R717) cascade refrigeration system. A multi linear regression analysis was employed in terms of sub cooling, superheating, evaporating, condensing, and cascade heat exchanger temperature difference in order to develop mathematical expressions for maximum COP, an optimum evaporating temperature of R717 and an optimum mass flow ratio of R717 to that of R744 in the cascade system [10]. Rezayan and Behbahaninia carried out thermo economic optimization and exergy analysis of CO₂/NH₃ cascade refrigeration systems. The objective function is the total annual cost of the system which includes costs of input exergy to the system and annualized capital cost of the system. Results show that, optimum values of decision variables may be found by trade-off between the input exergy cost and capital cost.

Results of the exergy analysis for each of the system components in the optimum state are also given [11].

As can be seen from the literature review presented above, studies on cascade refrigeration system are available. However, study on energy and exergy analysis of cascade refrigeration system operating with R134a-R404A, R134a-R407C, R404A-R410A, R404A-R507, R407C-R410A refrigerant couples are not available in the literature. These refrigerants were developed as safe, effective alternatives to existing chlorofluorocarbon (CFC) and hydro chlorofluorocarbon (HCFC) refrigerants. In Table 1, some properties of these refrigerants were given. In this study, energy and exergy analysis of a cascade refrigeration system operating with these refrigerant couples was carried out.

Table 1. Some properties of refrigerants

Refrigerants	Boiling Point at 1.013 bar (°C)	Critical temperature (°C)	Critical pressure (MPa)	ODP	GWP
R134a	- 26.1	101.1	4.06	0	1300
R404A	- 46.6	72.1	3.74	0	3260
R407C	- 43.8	86.0	4.63	0	1530
R410A	- 51.6	70.2	4.77	0	1730
R507	- 47.1	70.7	3.71	0	3300

2. THERMODYNAMIC ANALYSIS

Thermodynamic analysis is based on the energy and irreversibility analyses of the

components of the two stage vapour compression cascade refrigeration system. Each cascade system component is considered

as a control volume at stationary flow. The following assumptions are made in the analysis:

- Refrigerants at the cascade heat exchanger outlets, condenser outlet and evaporator outlet, are saturated.
- Pressure losses in connecting pipes and heat exchangers have been neglected.
- Cascade heat exchanger and pipes are perfectly isolated.
- The dead state (ambient) is $T_0 = 25^\circ\text{C}$ and $P_0 = 1 \text{ atm}$.

The mass, energy and exergy balances are given by equation (1) – (3), respectively [12].

$$\sum_i \dot{m}_i = \sum_0 \dot{m}_0 \dots \dots \dots (1)$$

$$\dot{Q} - \dot{W} + \sum_i \dot{m} h - \sum_0 \dot{m} h = 0 \dots \dots \dots (2)$$

$$\dot{X}_{loss} = \sum_0 \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \dot{W} + \sum_i \dot{m} x - \sum_0 \dot{m} x \dots \dots \dots (3)$$

In Table 2, specific equations for each system's components are summarized.

Table 2. Balance equations for each system component

Component	Mass	Energy	Exergy
Evaporator	$\dot{m}_1 = \dot{m}_4$	$\dot{Q}_E = \dot{m}_1 x (h_1 - h_4)$	$\dot{X}_{lossE} = \left(1 - \frac{T_0}{T_E}\right) Q_E + \dot{m}_1 (\psi_4 - \psi_1)$
Compressor I	$\dot{m}_2 = \dot{m}_1$	$W_{CI} = \frac{\dot{m}_1 (h_{2s} - h_1)}{\eta_{LTC}}$	$X_{lossCI} = W_1 - (\psi_2 - \psi_1)$
Compressor II	$\dot{m}_6 = \dot{m}_5$	$W_{CII} = \frac{\dot{m}_5 (h_{6s} - h_5)}{\eta_{HTC}}$	$X_{lossCII} = W_{II} - \dot{m}_5 (\psi_6 - \psi_5)$
Expansion Device I	$\dot{m}_4 = \dot{m}_3$	$h_4 = h_3$	$X_{lossTCVI} = \dot{m}_1 (\psi_3 - \psi_4)$
Expansion Device II	$\dot{m}_1 = \dot{m}_4$	$h_8 = h_7$	$X_{lossTEVII} = \dot{m}_5 (\psi_7 - \psi_3)$
Condenser	$\dot{m}_7 = \dot{m}_6$	$\dot{Q}_K = \dot{m}_5 (h_7 - h_6)$	$X_{lossK} = \dot{m}_5 (\psi_6 - \psi_7)$
Cascade heat exchanger	$\dot{m}_3 = \dot{m}_2$ $\dot{m}_5 = \dot{m}_8$	$\dot{m}_1 (h_3 - h_2)$ $= \dot{m}_5 (h_5 - h_8)$	$X_{lossHE} = \dot{m}_5 (\psi_8 - \psi_5) - \dot{m}_1 (\psi_3 - \psi_2)$

The system's COP has been calculated by the following equation:

$$COP = \frac{\dot{Q}_E}{\dot{W}_{CI} + \dot{W}_{CII}} \dots \dots \dots (4)$$

The system's exergetic efficiency is given by the equation:

$$\eta_{ex} = \frac{\dot{E}_{QE}}{\dot{W}_{CI} + \dot{W}_{CII}} \dots \dots \dots (5)$$

3. RESULTS AND DISCUSSION

In this study, energy and exergy analysis of a cascade refrigeration system was carried out. The COP and irreversibility values of the refrigerant couples in the cascade refrigeration system are

determined as functions of the evaporator temperature and condenser temperature.

Fig. 3 shows the change in the COPs of the refrigerant couples with respect to the evaporator temperature. In this figure, the condenser temperature, temperature difference (ΔT) and polytropic efficiency are kept constant at 50°C , 10°C and 0.72 , respectively. The refrigeration effect of

the cascade system increases and the specific work of compression decreases on increasing the evaporator temperature. Consequently, the COP of the cascade refrigeration system increases as shown in Fig. 3. In the considered evaporator temperature range, R134a–R407C has the highest COP values, while R404A–R507 has the lowest ones.

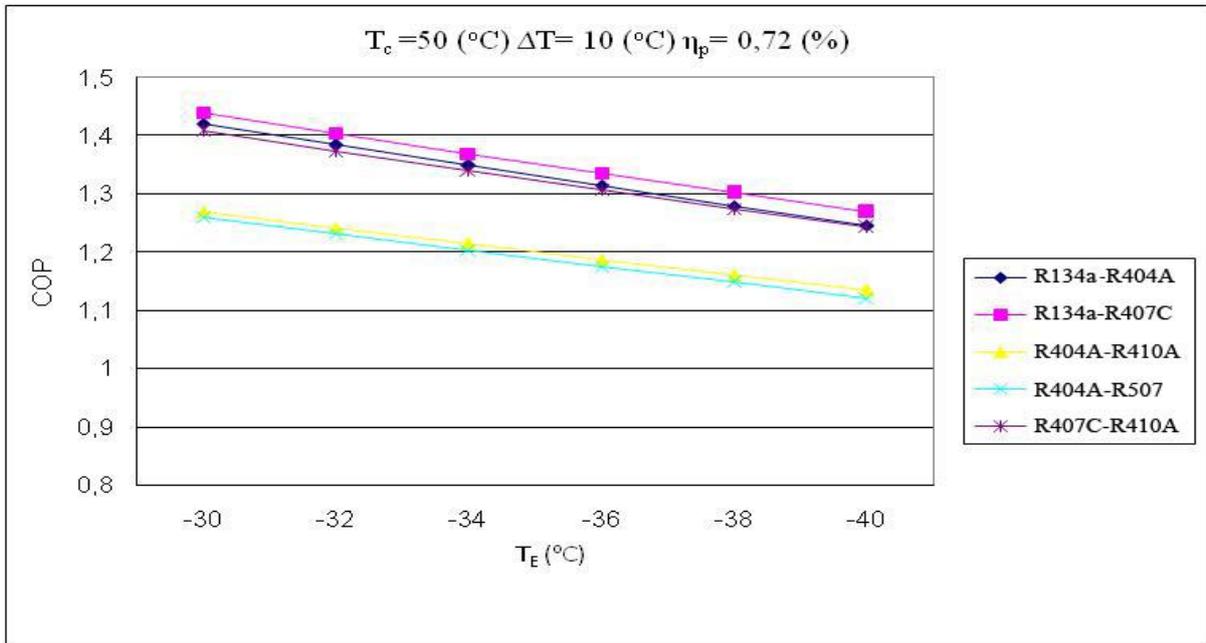


Fig.3. Variation of COP as a function of evaporator temperature

Fig. 4 shows the change in the COPs of the refrigerant couples with respect to the condenser temperature. In this figure, the evaporator temperature, ΔT and polytropic efficiency are kept constant at -30°C , 10°C and 0.72 , respectively. The COP of the cascade system for all considered refrigerant couples decrease

when the condenser temperature of the cascade system increases. In the considered condenser temperature range, R134a–R407C has the highest COP values, while R404A–R507 has the lowest ones.

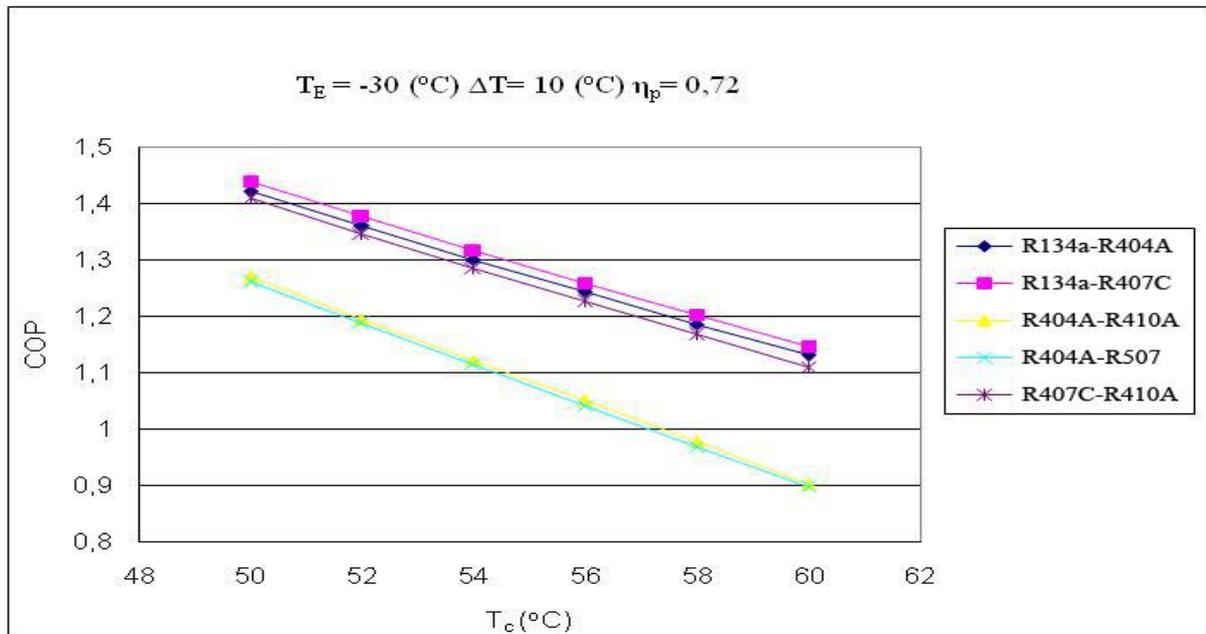


Fig.4. Variation of COP as a function of condenser temperature.

In Fig. 5, the variation in the irreversibility of the cascade system with the evaporator temperature for a condenser temperature of 50°C, ΔT of 10°C and polytropic efficiency of 0.72 is shown. As the evaporator temperature of

the cascade system increases, the irreversibility of the system decreases. It is seen that R134a–R407c has the lowest irreversibility, while R407C–R410A has the highest one.

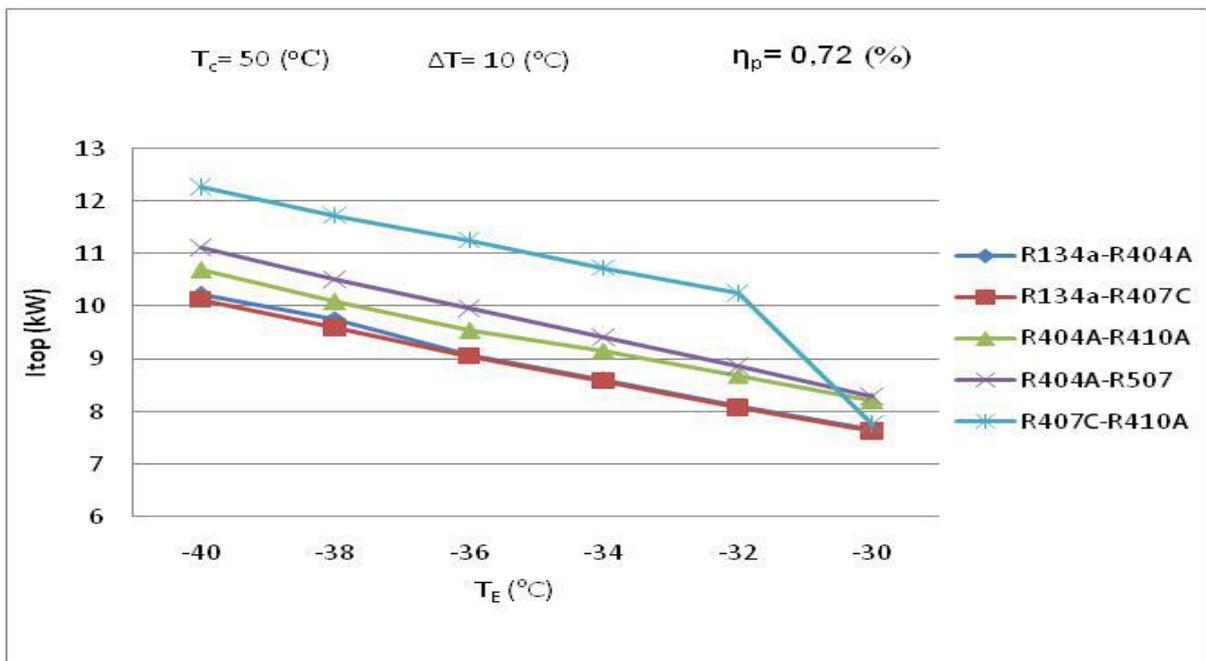


Fig.5. Variation of I as a function of evaporator temperature.

In Fig. 6, the variation in the irreversibility of the cascade system with the condenser temperature for a evaporator temperature of $-30\text{ }^{\circ}\text{C}$, ΔT of $10\text{ }^{\circ}\text{C}$ and polytropic efficiency of 0.72 is shown. As the condenser temperature of

the cascade system increases, the irreversibility of the system increases. It is seen that R134a–R407C has the lowest irreversibility, while R404A–R507 has the highest one.

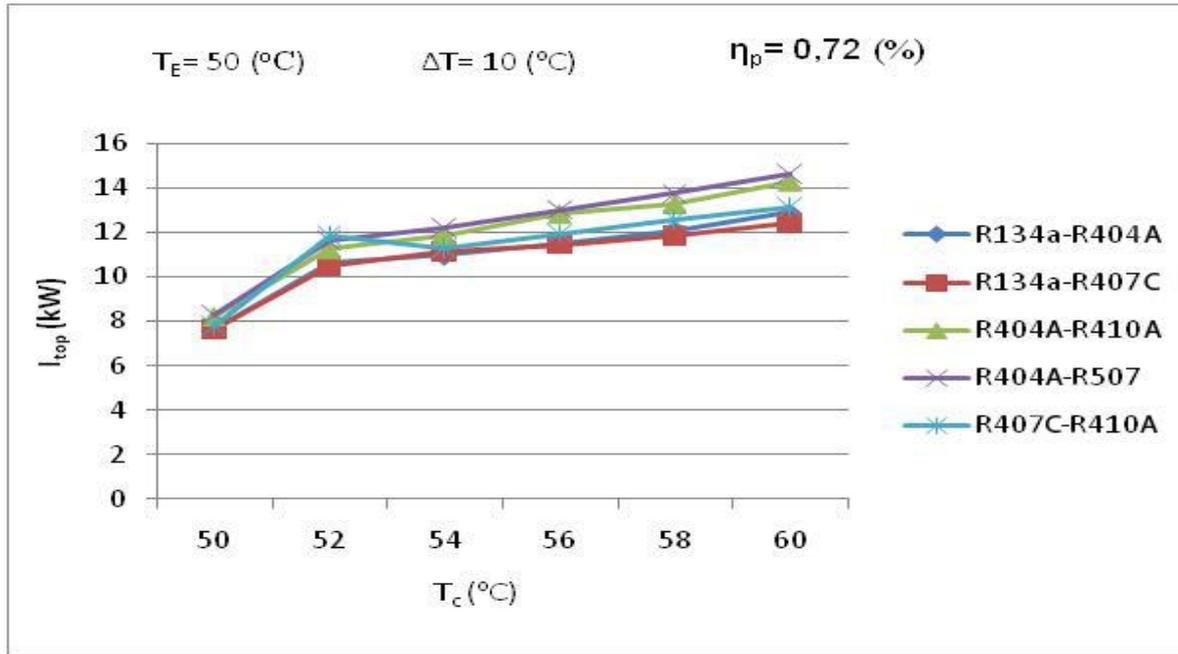


Fig.6. Variation of I as a function of condenser temperature.

4. CONCLUSIONS

In this study, the COP and irreversibility values of the cascade refrigeration system for the refrigerant couples R134a-R404A, R134a-R407C, R404A-R410A, R404A-R507, and R407C-R410A have been determined. Variation of COP and irreversibility values as a function of evaporator and condenser temperature has been investigated. The COP of the cascade refrigeration system increases when the evaporator temperature increases for all refrigerant couples. But, the

irreversibility of the system decreases. The COP of the cascade refrigeration system decreases when the condenser temperature increases for all refrigerant couples. But the irreversibility of the system increases. In all cases, the refrigerant couple R134a-R407C has the highest COP and lowest irreversibility.

SYMBOLS

\dot{Q} : Heat (J)
 X : Exergy (J)
 E : Evaporator

C : Compressor
 K : Condenser
 HE : Heat exchanger
 W : Work (J)
 \dot{m} : Mass flow (kg/s)
 V : Volt
 ψ : Exergy unit
 h : Enthalpy (kJ/kg)
 η : Isentropic efficiency
 LT : Low temperature (°C)
 HT : High temperature (°C)
 COP : Coefficient of Energetic
Performance

REFERENCES

[1] Kilicarlan, A., 2004. An experimental investigation of a different type vapor compression cascade refrigeration system, *Applied Thermal Engineering*, 24, 2611–2626.

[2] Silva, A., Filho, E. P. B., Antunes, A.H.P., 2012. Comparison of a R744 cascade refrigeration system with R404A and R22 conventional systems for supermarkets, *Applied Thermal Engineering*, 41, 30-35.

[3] Kilicarlan, A., Hosoz, M., 2010. Energy and irreversibility analysis of a cascade refrigeration system for various refrigerant couples, *Energy Conversion and Management*, 51, 2947–2954.

[4] Mafi, M., Naeynian, S.M.M., Amidpour, M., 2009. Exergy analysis of

multistage cascade low temperature refrigeration systems used in olefin plants, *Int. J. Refrigeration*, 32, 279 – 294.

[5] Dopazo, A.J., Fernandez-Seara, J., 2011. Experimental evaluation of a cascade refrigeration system prototype with CO₂ and NH₃ for freezing process applications, *Int. J. Refrigeration*, 34, 257-267.

[6] Bingming, W., Huagen, W., Jianfeng, L., Ziwen, X., 2009. Experimental investigation on the performance of NH₃/CO₂ cascade refrigeration system with twin-screw compressor, *Int. J. Refrigeration*, 32, 1358 – 1365.

[7] Messineo, A., 2012. R744-R717 Cascade Refrigeration System: Performance Evaluation compared with a HFC Two-Stage System, *Energy Procedia* 14, 56 – 65.

[8] Dopazo, A.J., Fernandez-Seara, J., Sieres, J., Uhia, F.J., 2009. Theoretical analysis of a CO₂-NH₃ cascade refrigeration system for cooling applications at low temperatures, *Applied Thermal Engineering* 29, 1577–1583.

[9] Bhattacharyya, S., Garaia, A., Sarkar, J., 2009. Thermodynamic analysis and optimization of a novel N₂O-CO₂ cascade system for refrigeration and heating, *Int. J. Refrigeration*, 32, 1077 – 1084.

[10] Getu H.M., Bansal, P.K., 2008. Thermodynamic analysis of an R744–

R717 cascade refrigeration system, Int. J. Refrigeration, 31, 45 – 54.

[11] Rezayan, O., Behbahaninia, A., 2011. Thermoeconomic optimization and exergy analysis of CO₂/NH₃ cascade

refrigeration systems, Energy 36, 888-895.

[12] Çengel YA, Boles MA. 1994. Thermodynamics: an engineering approach. 2nd ed. McGraw-Hill.