

Parametric Study of R744-R717 Cascade Refrigeration System

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ABSTRACT

In the present work thermodynamic model has been developed in Engineering Equation Solver software, for cascade refrigeration system using NH₃ in high temperature circuit (HTC) and CO₂ in low temperature circuit (LTC). Thermodynamic analysis of cascade refrigeration system has been carried out at different operating conditions to know the effect of various designs and operating parameters on the performance of the cycle. The design and operating parameters include: condenser temperature; evaporator temperature; coupling temperature; compressor isentropic efficiency; and temperature difference in cascade heat exchanger. Furthermore cascade refrigeration system, with internal heat exchanger, without internal heat exchanger and with different degree of subcooling and superheating in both circuits are compared regarding COP. Results show that use of internal heat exchanger has undesirable effect on the performance of the R744-R717 cascade system. Therefore it is advisable that, internal heat exchanger should be never used for this pair of refrigerants in cascade system. However, degree of subcooling always desirable in R744-R717 cascade system.

Keywords — Ammonia, Carbon dioxide, Cascade refrigeration system, Internal heat exchanger

1. INTRODUCTION

Many industrial applications like food storage, liquefaction of petroleum vapour and natural gases, precipitation hardening of special alloys, manufacturing of dry ice and storage of blood etc., required low temperature refrigeration in the temperature range from -30 °C to -100 °C [1]. The performance of single stage system is good as long as the temperature difference between evaporator and condenser is small. So for low temperature refrigeration, in this range, single stage systems become inefficient and impractical. A cascade system can be a suitable option if proper refrigerants are used in HTC (high temperature circuit) and LTC (low temperature circuit). A refrigeration system in which series of single stage units are thermally coupled through cascade heat exchanger is known as cascade refrigeration system. Each cycle has a different refrigerant, the lower temperature units progressively using lower boiling point refrigerants [2]. Selection of refrigerants for a cascade system mainly depends upon the temperature at

which refrigeration is required for a particular application. Apart from that heat transfer characteristics, safety, material and lubricants compatibility of refrigerant pair should be considered. In cascade system, each circuit has a different refrigerant, the lower temperature units progressively using lower boiling point refrigerants i.e. the low-temperature circuit uses low boiling refrigerants such as CO₂ whereas high-temperature circuit uses comparatively high boiling point refrigerants such as NH₃.

There have been many analytical and experimental studies done so far on the performance analysis of the cascade system with different refrigerants pairs for refrigeration and heating applications. Lee et al. (2006) analyzed a carbon dioxide–ammonia (R744– R717) cascade system thermodynamically to determine the optimum condensing temperature of R744 in the cascade condenser [3]. Bansal and Jain (2007) evaluated the optimum cascade condensing temperatures of cascade system by using different refrigerants R717, R290, R1270 and

R404A, in HTC and R744 in LTC [4]. Getu and Bansal (2008) presented theoretical analysis of R744-R717 cascade system by considering the effect of degree of superheating and subcooling as a design parameter additionally. In this analysis expressions for an optimum evaporating temperature of R717 in cascade condenser, maximum COP and optimum mass flow ratio of R717 to that of R744 in the cascade system are also presented [5]. Bingming *et al.* (2009) reported experimental data obtained from a cascade refrigeration system with CO_2 - NH_3 . They also compared the performance of the NH_3/CO_2 cascade system with single-stage NH_3 system with or without economizer and concluded that COP of the cascade system is the best among all the systems. Another experiment on CO_2 - NH_3 cascade system was conducted by Dopazo and Seara (2011). They compared their experimental results of optimal condensing temperature of CO_2 in cascade condenser with the data calculated from existing correlations that were proposed in different research works and found that there were differences between 1 and 3 percent [6]. Messineo (2012) presented thermodynamic analysis of R744-R717 cascade refrigeration system and compared results with the partial injection two-stage refrigeration system using the synthetic refrigerant R404A. In this work author concluded that for commercial applications including rapid freezing and the storage of frozen foods, the use of cascade systems using ammonia in the high-temperature part and carbon dioxide in the low-temperature one, in place of traditional two-stage systems working with synthetic fluids as R404A, is certainly a valid application for energy, security and environmental reasons [7]. Park *et al.* (2013) presented the thermodynamic analysis of R134a and R410A cascade system for water heating application and then conducted the experiment [8].

In recent year CO_2 gaining fast attention as a refrigerant among natural refrigerants due to its some excellent characteristics such as non-toxic, odourless, non-flammable, low price and easy availability. Even carbon-dioxide is a greenhouse gas but as it is captured from environment therefore any leakage of CO_2 does not increase the overall volume of CO_2 present in environment thus does not contribute to global warming [9].

In present study, thermodynamic analysis of cascade system presented using NH_3 in HTC and CO_2 in LTC, to know effect of various operating and design parameters which include

condenser temperature; evaporator temperature; coupling temperature; compressor isentropic efficiency; and temperature difference in cascade heat exchanger on system performance. Apart from that effect of subcooling and superheating also investigated.

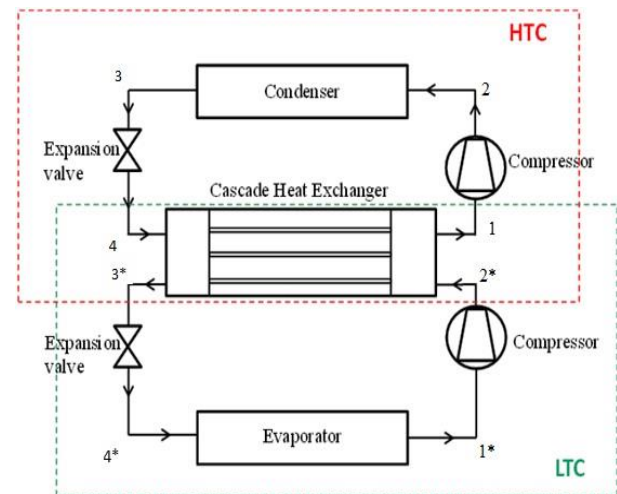


Fig. 1. Schematic diagram of the R744-R717 cascade refrigeration system

2. SYSTEM DESCRIPTION

A schematic diagram of a two-stage cascade refrigeration system is shown in Fig. 1. This system comprises two separated circuit: the high temperature circuit and low temperature circuit with R717 and R744 as refrigerants respectively. These two cycles are connected by a cascade heat exchanger; in which R717 evaporate by absorbing heat rejected in condensation of R744. The corresponding T-s and p-h diagrams for the cascade refrigeration system are shown in Fig. 2 and Fig. 3 respectively. Fig. 2 shows the temperature difference between R744 condensing and R717 evaporating temperature in cascade heat exchanger.

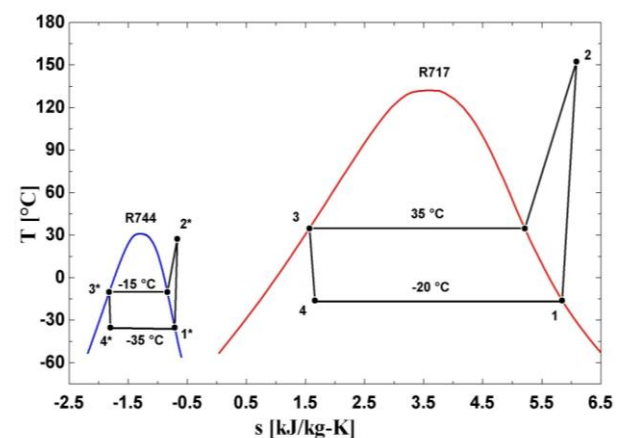


Fig. 2. T-s diagram of a R744-R717 cascade refrigeration system

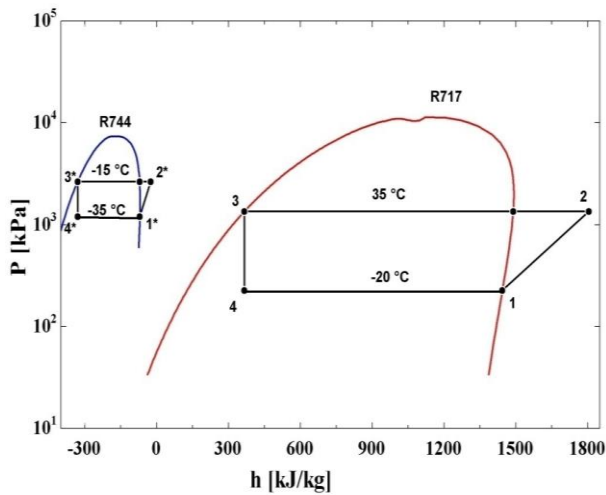


Fig. 3. p-h diagram of a R744-R717 cascade refrigeration system

3. THERMODYNAMIC ANALYSIS

The thermodynamic analysis of R744-R717 cascade refrigeration system performed based on the following assumptions:

- Compression process is adiabatic with an isentropic efficiency of 0.73 in both HTC and LTC;
- The expansion process is isenthalpic;
- Negligible heat interaction in the cascade heat exchanger with surrounding;
- Negligible changes in kinetic and potential energy;
- The system is at steady state condition. All processes are steady flow processes.
- Temperature difference in the cascade heat exchanger is 5 °C.

The thermo-physical properties of R744 and R717 specified in this work were calculating using a software package called engineering equation solver (EES) [12]. A major feature of EES is the high accuracy thermodynamic and transport property database that is provided for hundreds of substances in a manner that allows it to be used with the equation solving capability. The cycle is modelled by applying mass balance and energy balance equation for each individual process of the cycle. The equations for the different components of the cascade refrigeration system are given in the Table I.

The COP of the system can be express as:

$$COP = \frac{(COP_{LTC})(COP_{HTC})}{1 + COP_{LTC} + COP_{HTC}} \quad \dots\dots (1)$$

Where,

$$COP_{LTC} = \frac{Q_0}{\dot{W}_L} \quad \dots\dots (2)$$

$$COP_{HTC} = \frac{Q_{ex}}{\dot{W}_H} \quad \dots\dots (3)$$

Table I

Mass and energy balance for the R744-R717 cascade refrigeration system.

Component	Mass balance	Energy balance
LTC expansion valve	$\dot{m}_L = \dot{m}_{3*} = \dot{m}_{4*}$	$h_{3*} = h_{4*}$
Evaporator	$\dot{m}_L = \dot{m}_{4*} = \dot{m}_{1*}$	$\dot{Q}_0 = \dot{m}_L(h_{1*} - h_{4*})$
LTC compressor	$\dot{m}_L = \dot{m}_{1*} = \dot{m}_{2*}$	$\dot{W}_L = \dot{m}_L(h_{2*} - h_{1*})$
Cascade heat exchanger	$\dot{m}_L = \dot{m}_{2*} = \dot{m}_{3*}$ $\dot{m}_H = \dot{m}_4 = \dot{m}_1$	$\dot{Q}_{ex} = \dot{m}_L(h_{2*} - h_{3*})$ $= \dot{m}_H(h_1 - h_4)$
HTC compressor	$\dot{m}_H = \dot{m}_1 = \dot{m}_2$	$\dot{W}_H = \dot{m}_H(h_2 - h_1)$
Condenser	$\dot{m}_H = \dot{m}_2 = \dot{m}_3$	$\dot{Q}_C = \dot{m}_H(h_2 - h_3)$
HTC expansion valve	$\dot{m}_H = \dot{m}_3 = \dot{m}_4$	$h_3 = h_4$

4. 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.

4.1. Effect of Evaporator Temperature

Fig. 4 shows the effect of evaporator temperature on the COP of cascade system, refrigeration effect (Q_0) and required work (W_C) in compressors. The results are obtained at fixed 35 °C condenser temperature and 15 °C coupling temperature (condensing temperature of R744 in cascade heat exchanger).

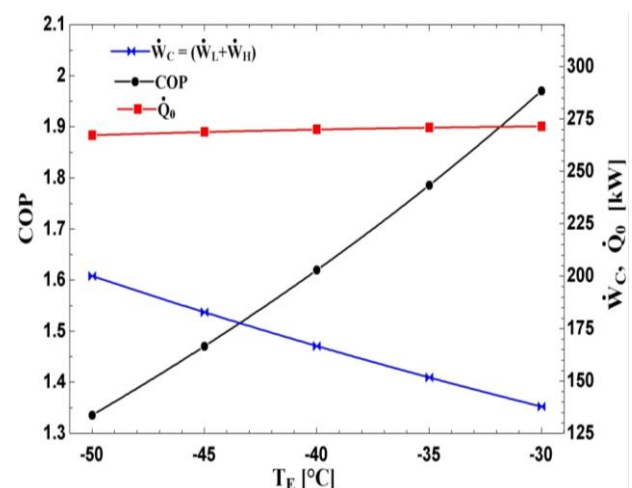


Fig. 4. Variation in COP, total compressor work and refrigeration effect of a R744-R717 cascade system with evaporator temperature

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.

4.2. Effect of Condenser Temperature

Fig. 5 shows the effect of condenser temperature on the COP of cascade system, refrigeration effect and required work in compressors. The results are obtained at fixed -35°C evaporator temperature and 15°C coupling temperature. As the evaporator and coupling temperatures are fixed, the refrigeration effect will be constant for entire range of condenser temperature. However required work in HTC increases due to increase in pressure ratio in HTC. Hence combined work required increases, therefore the COP of cascade system decreases.

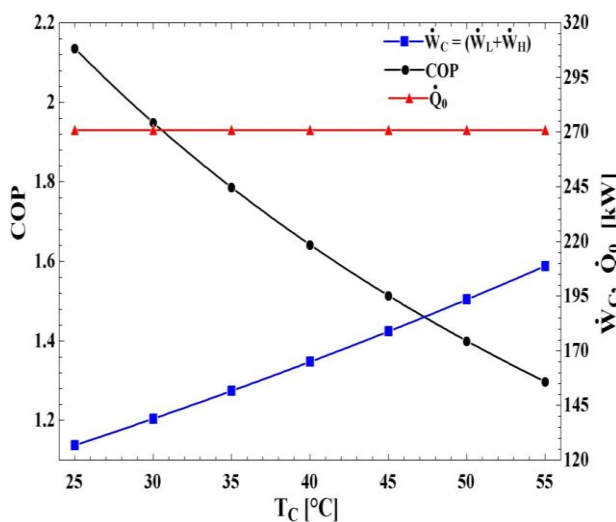


Fig. 5. Variation in COP, total compressor work and refrigeration effect of a R744-R717 cascade system with condenser temperature

4.3. Effect of coupling Temperature

The variations in COP of cascade system, COP of LTC and COP of HTC with coupling temperature (T_{CT}) are shown in Fig. 6 at fixed -45°C evaporator and 45°C condenser temperatures. From the Fig. 6 it is observed that the COP of LTC decreases with increases in coupling temperature although the COP of HTC increases and COP of cascade system first increases; attains maximum value and after that it decreases. The coupling temperature at which, the COP of

cascade system is maximum is known as optimum coupling temperature.

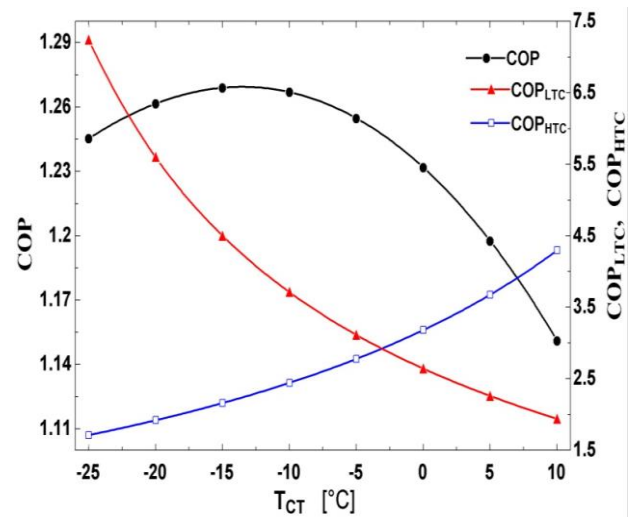


Fig. 6. Variation in COP, COP_{LTC} and COP_{HTC} of a R744-R717 cascade system with coupling temperature

4.4. Effect of Compressor Efficiency

The variation in COP of cascade system with coupling temperature (T_{CT}) is shown in Fig. 7 for different compressor isentropic efficiencies. The results are obtained at fixed 35°C condenser and -35°C evaporator temperatures. It is observed from the figure that COP of cascade system increases with increase in compressor efficiency, due to reduction in compressor work.

4.5. Effect of Temperature Difference in Cascade Condenser

Variation in COP with coupling temperature at different temperature difference in cascade heat exchanger is shown in Fig. 8. In cascade system condenser of LTC rejects heat to the evaporator of HTC. To transfer heat from LTC to HTC, there should be a temperature difference in cascade heat exchanger. When the temperature difference in cascade heat exchanger increases, the performance of system will fall although the cost of system will also decreases (due to small size of cascade heat exchanger) vice-versa. Therefore, the temperature difference should have an optimum value to balance the cost and performance of the system. Generally, the value of temperature difference is recommended to be greater than or equal to 5°C .

4.6. Performance Improvement of Cascade System

The state of the refrigerant entering in the expansion devices of these cycles is assumed to be saturated liquid. However,

liquid cooling below saturation can increase the refrigerating effect and potentially improve the COP. For improvement in COP by subcooling, effect of internal heat exchanger and condenser subcooling are investigated.

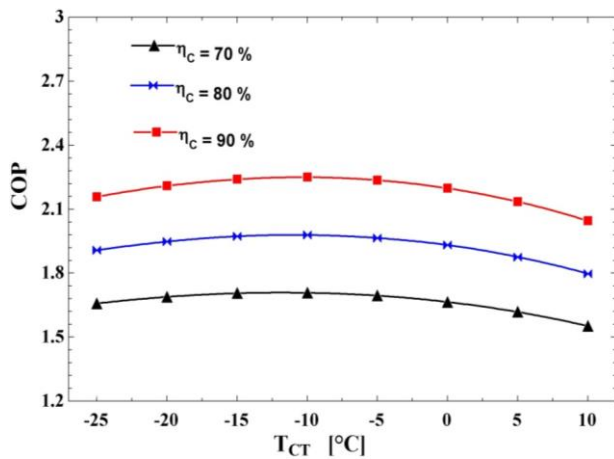


Fig. 7. Variation in COP of a R744-R717 cascade system with coupling temperature at different compressor isentropic efficiency

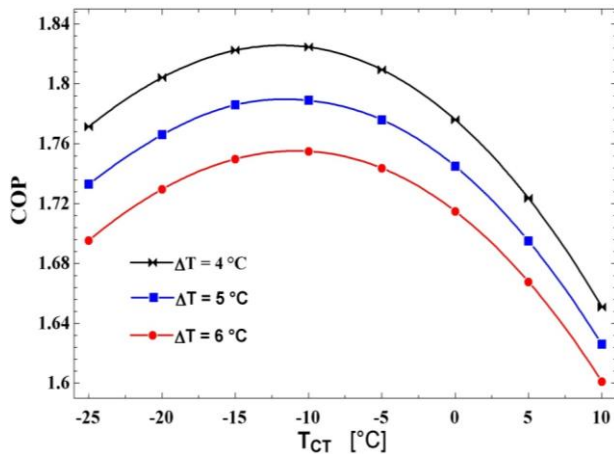


Fig. 8. Variation in COP of a R744-R717 cascade system with coupling temperature at different temperature difference in cascade heat exchanger

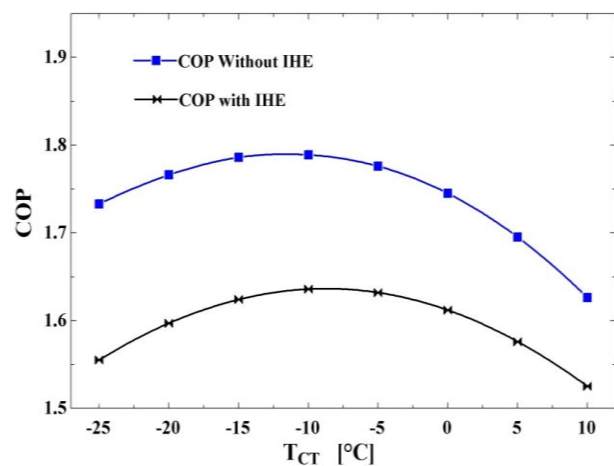


Fig. 9. Effect of IHE on the COP of a R744-R717 cascade system with coupling temperature

Cascade refrigeration system with internal heat exchanger in both circuits and without internal heat exchanger are compared in Fig. 9 at fixed -35°C evaporator and 35°C condenser temperatures. It is observed from Fig. 9 that, R744-R717 cascade system has negative impact of internal heat exchanger on the performance of the system. Therefore it is concluded from the figure that internal heat exchanger is not advantageous with ammonia and carbon dioxide refrigerants pair in cascade system.

Regarding improvement in system performance, effect of degree of subcooling and superheating on the R744-R717 cascade system also investigated. Fig. 10 shows the variation in COP with coupling temperature at various degrees of subcooling and superheating in both the circuits. It can be observed from the Fig. 10 that, degree of subcooling increases the system performance and superheating always has undesirable consequence on the performance.

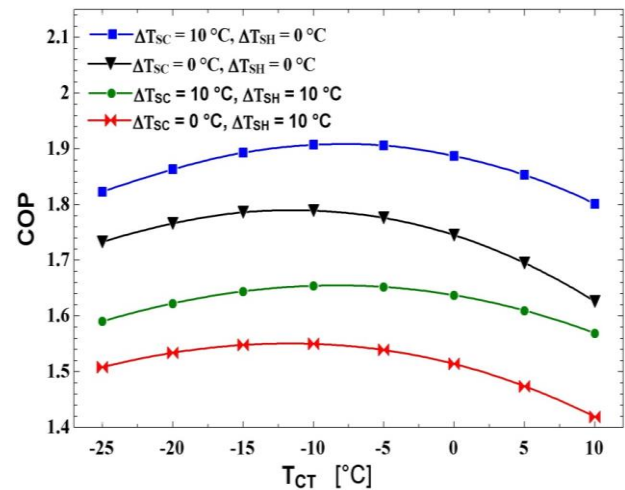


Fig. 10. Effect of degree of subcooling and superheating on the COP of a R744-R717 cascade system with coupling temperature

5. CONCLUSIONS

In this study thermodynamic analysis of cascade refrigeration system is presented using carbon dioxide in low temperature circuit (LTC) and ammonia in high temperature circuit (HTC) as refrigerants. This analysis leads to following conclusions:

1. COP of the cascade system, increases with increase in evaporator temperature and decreases with increase in condenser temperature.
2. For particular condenser and evaporator temperatures, COP of the cascade system is maximum at a optimum value of coupling temperature (condensing temperature of R744)

3. With the improvement in compressor isentropic efficiency, performance of cascade system increases. However 70 % is an average value for the most modern compressors.
4. Use of internal heat exchanger in cascade system is not beneficial. However degree of subcooling in both the circuits advantageous.

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NOMENCLATURE

h	specific enthalpy	(kJ/ kg)
IHE	internal heat exchanger	
m	mass flow rate	(kg/ s)
Q	heat transfer	(kJ)
s	specific entropy	(kJ/kg- K)
T	temperature	(°C)
w	specific work	(kJ/s)
Greek		
η	efficiency	
Δ	change	
Subscripts		
1–4	refrigerant state points in HTC	
1*–4*	refrigerant state points in LTC	
C	condenser	
CT	coupling temperature	
E	evaporator	
ex	cascade heat exchanger	
H	higher	