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THERMODYNAMIC ANALYSIS OF CO2/NH3 CASCADE REFRIGERATION SYSTEM

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ABSTRACT

This article presents an energy and exergy analysis of CO2/NH3 cascade refrigeration system. CO2 refrigerant is used in low temperature cycle and NH3 refrigerant is used in high temperature cycle. In present work, condensing and evaporating temperatures of NH3 in high temperature cycle is selected as 35°C and -10°C, while that of CO2 in low temperature cycle are 5°C and -40° respectively. Effect of temperature difference in cascade heat exchanger (CHE) on COP, second law efficiency, and exergy destruction rate is studied. A complete mathematical model is prepared for the present work. Calculated results show that maximum energy is found in condenser of high temperature cycle and minimum energy in the compressor of high temperature cycle while maximum exergy destruction rate is found in compressor of low temperature cycle and minimum exergy destruction rate in the expansion device of high temperature cycle.

Keywords: *cascade refrigeration system, COP, exergy destruction rate, second law efficiency*

INTRODUCTION

Low temperature applications like storage of frozen food, biomedical preservations requires temperature lower than -40°C. Conventional vapour compression refrigeration system can produce effective cooling of approximately -40°C. Cascade refrigeration system is the best solution to produce temperature lower that -40°C. A cascade system is operated by two or three separate common cycles. This is worked in joint of one another on various temperature levels. This inner stage heat exchanger is the condenser for first stage & evaporator for second stage. This first stage is called low stage while second stage is high stage.

Synthetic refrigerants causes environmental problems like global warming and ozone depletion, hence use of natural refrigerants is the present requirement. The use of CO2 refrigerant in low temperature cycle of cascade refrigeration is preferable due to its environment-friendly nature and low ozone depletion index.

There are several theoretical and experimental study carried out by the different researchers on cascade refrigeration system. Cascade refrigeration system are more suitable for the evaporating temperature in the range of -30°C to -50°C [1]. The CO2/NH3 cascade refrigeration system provides better COP and lower charge amount of ammonia compared to ammonia two-stage refrigeration system [2-4]. Messineo [5] studied on R744-R717 cascade refrigeration system to predict the performance of the system for the different operating parameters. Their results showed that R744-R717 cascade refrigeration system is suitable alternative to R404A two-stage refrigeration system for energy and environmental aspects at lower evaporating temperatures. Thermodynamic analysis of cascade refrigeration system using carbon dioxide and ammonia as refrigerants to find the optimal condensing temperature was carried out by Lee et al. [6]. It was concluded that maximum COP at optimal condensing temperature depends on condensing temperature, evaporating temperature and the temperature in cascade condenser. Researchers carried out thermodynamic analysis of CO2/NH3 cascade refrigeration system to predict the performance of the system [7-8]. Dopazo and Seara [9] developed a prototype of CO2/NH3 cascade refrigeration system to supply 9 kW refrigeration at evaporating temperature of -50°C. Thermodynamic analysis of CO2/NH3 cascade refrigeration system was carried out by Tripathy et al. [10] to obtain maximum COP at optimum condensing temperature at different operating parameters. It was concluded that maximum COP of the system increases with increase of evaporating temperature and decrease of condensing as well as temperature

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difference in cascade condenser. Sun et al. [11] analyzed cascade refrigeration system assisted with expander and mechanical sub cooling using CO2 and NH3 as refrigerants. It was observed that COP of the system improved when it combines mechanical sub cooling system and expander. Alhamid et al. [12] optimize cascade refrigeration system using carbon dioxide and ethane-propane as refrigerants for the bio medical cold storage application. In their work, energy and exergy analysis both were performed. Regression equations were developed for the maximum COP, the optimum mass flow ratio, and optimum evaporating temperature of high temperature circuit. Thermodynamic analysis of cascade refrigeration system using three different refrigerant pairs were carried out by Parekh and Tailor [13]. Selected refrigerant pairs are R12-R13, R290-R23, and R404A-R23. Their results showed that R290-R23 provides highest COP compared to remaining two refrigerant pairs. Yilmaz et al. [14] analyzed cascade refrigeration system using CO2/ R404A refrigerants pair to optimize condensing temperature. Energy and exergy analysis were performed to obtain maximum COP and second law efficiency. Rupesh et al. [15] carried out thermodynamic analysis of cascade refrigeration system using R134a-R23 as refrigerant pairs to estimate maximum COP for the different operating parameters. In their work along with energy analysis, exergy analysis were also performed to find irresersibilities in the system and system components. Comparative thermodynamic analysis using different pairs of cascade system for heating and cooling applications were presented by Yilmaz and Selbas [16]. In their analysis work, CO2 refrigerant used in low temperature cycle and the HFE 7000, R134a, R152a, R32, R1234yf, and R365mfc refrigerant were used in high temperature cycle. It was concluded that CO2/ 365mfc provides COP of 1.835 which is highest compared to all other refrigerant pairs. Kumar et al. [17] carried out energy and exergy analysis of cascade refrigeration system using different refrigerant pairs. In their work, R13 was used in low temperature cycle and R134a, R290, and R717 were used in high temperature cycle. It was conclude that among all refrigerant pairs, R13-R717 provides best performance compared to two other refrigerant pairs.

Literature shows enormous amount of work is done on thermodynamic analysis by using different refrigerant pairs in cascade refrigeration system. Present work deals with energy and exegy calculations of different components of cascade refrigeration system.

WORKING OF CASCADE REFRIGERATION SYSTEM

The cascade refrigeration system consists of two or more vapour compression refrigeration systems in series which use refrigerants with progressively lower boiling temperatures. A two stage cascade system using CO_2/NH_3 as two refrigerants is shown in Figure 1. The compressed refrigerant vapour from the lower stage is condensed in a heat exchanger, usually called cascade condenser, which is also the evaporator of the next higher stage refrigerant. The only useful refrigerating effect is produced in the evaporator of low temperature cascade system. The high temperature cascade system uses a refrigerant with high boiling temperature. The low temperature cascade system uses a refrigerant with low boiling temperature.

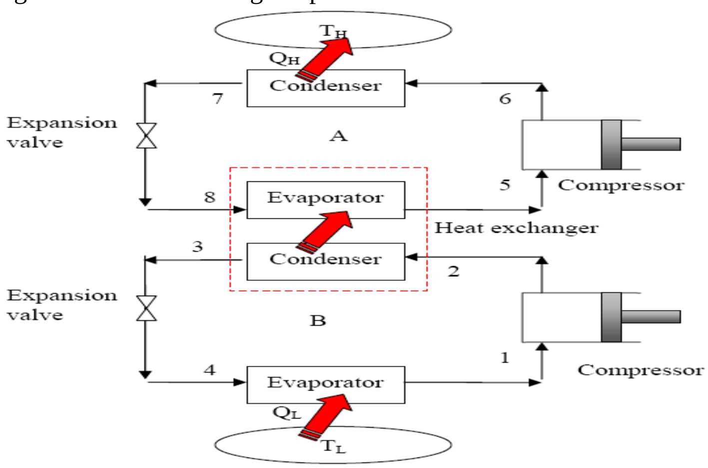

Figure 1 Schematic diagram of CO_2/NH_3 cascade refrigeration system

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In present study, NH_3 and CO_2 refrigerants are used in the upper and lower cycle respectively. These low boiling temperature refrigerants have extremely high pressure which ensures a smaller compressor displacement in the low temperature cascade system and a higher COP.

MATHEMATICAL MODELING

To calculate compressors power, heat transfer rate and exergetic efficiency, each cascade system component is considered as a control volume at stationary flow.
Following assumptions are made in the study:

- Refrigerant at the cascade heat exchanger outlets, condenser outlet and evaporator outlet is saturated.
- In both circuits, the compression is isentropic.
- Pressure losses in connecting pipes and heat exchangers are neglected.
- Cascade heat exchanger and pipes are perfectly insulated.
- The dead state is T_o = 25°C and P_o = 1 atm.
- The difference between refrigerated space temperature (T_F) and evaporation temperature ($T_{eva\ CO2}$) is constant and equal to 5°C.
- Isentropic efficiency of CO_2 and NH_3 compressor is assumed as 21% and 76% respectively.
- Mechanical and electrical efficiencies of CO_2 and NH_3 compressors are assumed same and it is 93% and 80% respectively.

Energy and exergy calculations are done using following equations. As per Figure 1, enthalpy and entropy at different state points are obtained from the property table of CO_2 and NH_3.
Mass flow rate of CO_2 unit can be calculated by using following equation

$$\dot{m}_1 = \frac{3.5 \times Q}{h_1 - h_4}$$

(1)
Mass flow rate of NH_3 unit can be calculated by following energy balance equation

$$\dot{m}_2 \left(h_5 - h_8\right) = \dot{m}_1 \left(h_2 - h_3\right)$$

(2)
Work done of CO_2 compressor can be calculated by following equation

$$W_{comp.CO_2} = \frac{\dot{m}_1 \left(h_2 - h_1\right)}{\eta_{comp.CO_2}}$$

(3)
Work done of NH_3 compressor can be calculated by following equation

$$W_{comp.NH_3} = \frac{\dot{m}_2 \left(h_6 - h_5\right)}{\eta_{comp.NH_3}}$$

(4)
Efficiencies of CO_2 and NH_3 compressor in equations (3) and (4) are calculated using equation (5)

$$\eta_{comp} = \eta_{is} \times \eta_m \times \eta_e$$

(5)
Energy calculation of expansion device of CO_2 unit can be obtained by following equation

$$h_4 = h_3$$

(6)
Energy calculation of expansion device of NH_3 unit can be obtained by following equation

$$h_8 = h_7$$

(7)
Heat absorbed by the evaporator of CO_2 unit can be calculated sing following equation

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$$q_e = \dot{m}_1 \left(h_1 - h_4 \right)$$
(8)
Heat rejected by the condenser of NH_3 unit can be calculated by following equation
$$q_c = \dot{m}_2 \left(h_6 - h_7 \right)$$
(9)
Energy balance in cascade heat exchanger can be obtained by following equation
$$\dot{m}_1 \left(h_2 - h_3 \right) = \dot{m}_2 \left(h_5 - h_8 \right)$$
(10)
Exergy lost rate of CO_2 compressor can be calculated by following equation
$$X_{comp.CO_2} = W_{comp.CO_2} - \dot{m}_1 \left(\psi_2 - \psi_1 \right)$$
(11)
Exergy lost rate of NH_3 compressor can be calculated by following equation
$$X_{comp.NH_3} = W_{comp.NH_3} - \dot{m}_2 \left(\psi_6 - \psi_5 \right)$$
(12)
Exergy lost rate in expansion device of CO_2 unit can be obtained by following equation
$$X_{\exp.CO_2} = \dot{m}_1 \left(\psi_3 - \psi_4 \right)$$
(13)
Exergy lost rate in expansion device of NH_3 unit can be obtained by following equation
$$X_{\exp.NH_3} = \dot{m}_2 \left(\psi_7 - \psi_8 \right)$$
(14)
Exergy lost rate in CO_2 evaporator can be calculated by following equation
$$X_{e.CO_2} = \left(\left(1 - \frac{T_o}{T_F} \right) \times q_e \right) + \dot{m}_1 \left(\psi_4 - \psi_1 \right)$$
(15)
Exergy lost rate in condenser of NH_3 unit can be calculated by following equation
$$X_c = \dot{m}_2 \left(\psi_6 - \psi_7 \right)$$
(16)
Exergy lost rate in cascade heat exchanger can be calculated by following equation
$$X_{CHE} = \dot{m}_2 \left(\psi_8 - \psi_5 \right) - \dot{m}_1 \left(\psi_3 - \psi_2 \right)$$
(17)
COP of cascade refrigeration system can be calculated by following equation
$$COP = \frac{q_e}{\dot{m}_1 \left(h_2 - h_1 \right) + \dot{m}_2 \left(h_6 - h_5 \right)}$$
(18)
Second law efficiency can be calculated by following equation
$$\eta_{II} = \frac{W_{rev}}{W_{act}}$$
(19)
Reversible work can be calculated by following equation

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$$W_{rev} = q_e \left(\frac{T_o}{T_{e.CO_2}} - 1 \right)$$

(20)

Actual work can be calculated by following equation

$$W_{act} = \dot{m}_1 \left(h_2 - h_1 \right) + \dot{m}_2 \left(h_6 - h_5 \right)$$

(21)

RESULTS AND DISCUSSION

Present study carried out with the evaporating and condensing temperatures of CO_2 unit are -40°C and 5°C respectively and that of NH_3 unit are -10°C and 35°C respectively.

Table 1 Calculated values of energy and exergy destruction rate of different components

Component	Energy (kW)	Exergy Destruction Rate (kW)
CO_2 compressor	12.45	3.19
NH_3 compressor	11.87	3.04
CO_2 expansion device	15.54	2.24
NH_3 expansion device	14.19	0.84
CO_2 evaporator	35.00	0.93
NH_3 condenser	53.15	2.11
Cascade heat exchanger	44.33	3.16

Calculation shows that value of COP and second law efficiency found as 1.9344 and 53.96% respectively for the selected evaporating and condensing temperatures. Energy and exergy calculations are done for the 10 TR capacity of the cascade refrigeration system. Calculated results show that maximum energy is found in condenser of NH_3 unit and maximum exergy destruction rate is found in compressor of CO_2 unit. Calculations are done first by varying T_3 from -3°C to 5°C at the fixed value of T_5 as -10°C and then by varying T_5 from -10°C to -2°C at the fixed value of T_3 as 5°C.

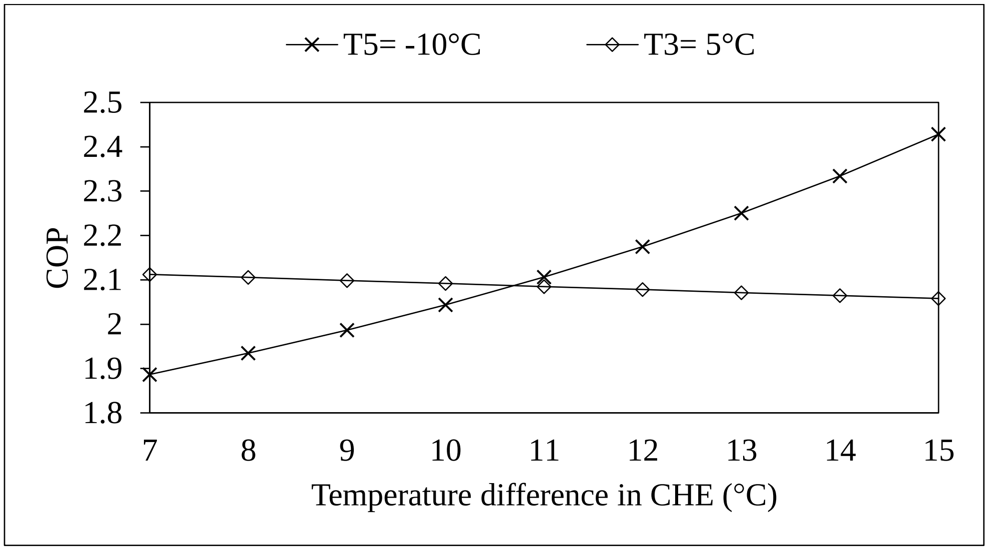

Figure 2 Variation of COP with temperature difference in CHE

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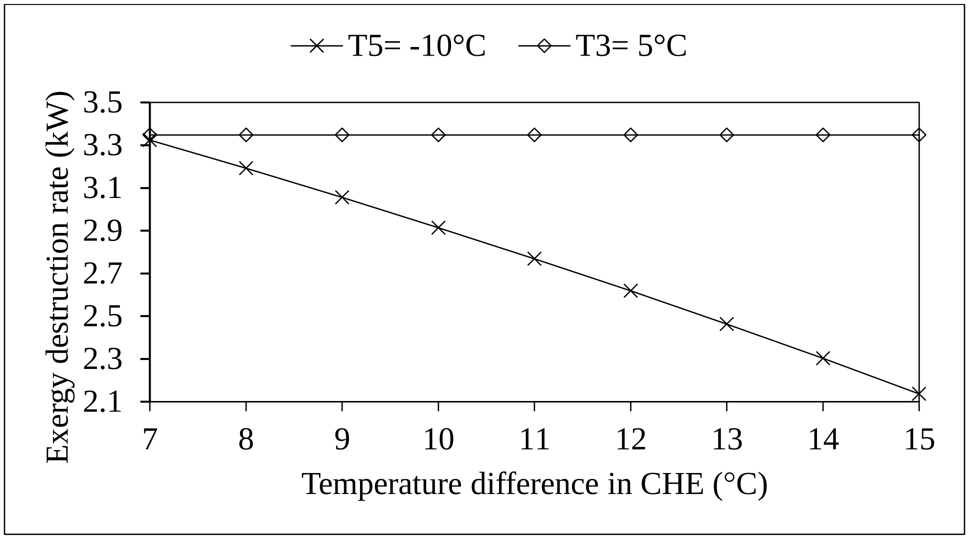

Figure 3 Variation of exergy destruction rate with temperature difference in CHE

Figure 2 shows the variation of COP with the temperature difference in cascade heat exchanger (CHE). It is observed that with the fixed value of temperature T_5 in cascade heat exchanger if temperature T_3 is varied then as temperature difference increases, COP of the system also increases. And if temperature T_3 is fixed and temperature T_5 varied then as temperature difference in cascade heat exchanger increases COP of the system decreases. So, as shown in figure intersecting point provides optimum value of COP for the particular temperature difference. Figure 3 shows the variation of exergy destruction rate with the temperature difference in CHE. It is observed that if in cascade heat exchanger temperature T_5 is fixed and if temperature T_3 varied then as temperature difference increases exergy destruction rate of the system decreases. And if temperature T_3 is fixed and temperature T_5 varied then as temperature difference in cascade heat exchanger increases exergy destruction of the system remains constant.

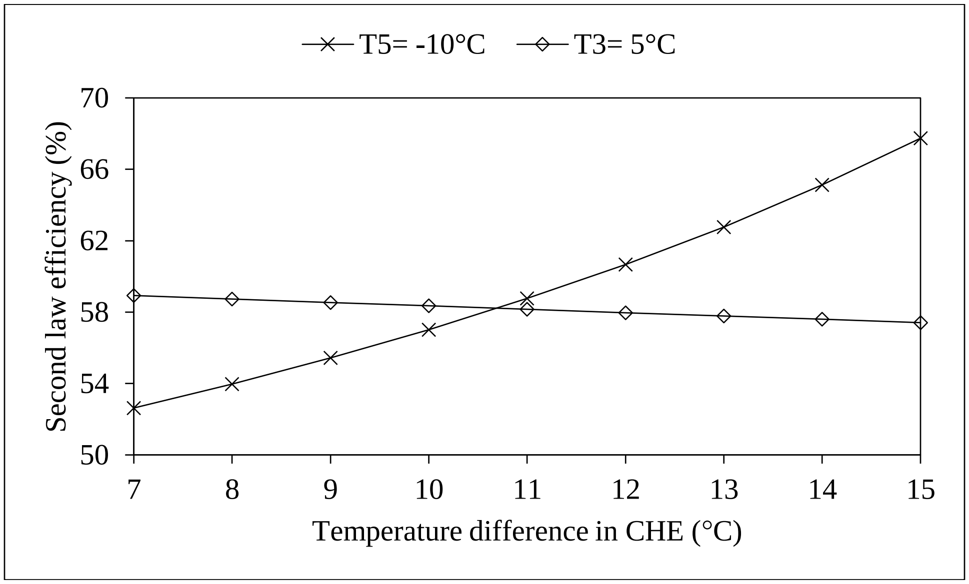

Figure 4 Variation of second law efficiency with temperature difference in CHE

Figure 4 shows the variation of second law efficiency with the temperature difference in CHE. It is observed that with the fixed value of temperature T_5 in cascade heat exchanger temperature if temperature T_3 varied then with the increase of temperature difference second law efficiency of the system increases. And if temperature T_3 is fixed and temperature T_5 varied then as temperature difference in cascade heat exchanger increases second law efficiency of the system decreases. Which shows that at the intersecting point indicates the optimum value of second law efficiency for that particular temperature difference.

CONCLUSION

Present work deals with the energy and exergy analysis of 10 TR capacity of CO2/NH3 cascade refrigeration system. It is observed from the calculated results that maximum value of energy is found in NH3 condenser as 53.15 kW, while that is minimum in NH3 compressor as 11.87 kW. It is also observed that maximum exergy destruction rate is found in CO2 compressor as 3.19 kW and that is minimum in NH3 expansion device as 0.84 kW. Present work also deals with the study of effect of temperature difference in CHE on COP, exergy destruction rate, and second law efficiency.

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