A Simulation Research on NH_3/CO_2 Cascade Refrigeration System Based on Theoretical Model

Cui Yujie

School of Mechanical Engineering, Tianjin University of Commerce, Tianjin, China

Abstract: *The rapid development of the refrigeration industry has benefited production and life, and has also brought irreversible negative impacts on the current environment. Finding environment friendly, energy-saving, stable, and new-type alternative refrigerants has become a common concern and research hot spot of researchers and the refrigeration industry around the world. In this article, a NH_3/CO_2 cascade refrigeration system model is established. CO_2 is used as the refrigerant in the low temperature cycle, NH_3 is used as the refrigerant in the high temperature cycle, and the condensing evaporator is used to couple the heat exchange between the high and low temperature circuits. Based on the first law of thermodynamics and the second law of thermodynamics, the author carries out the energy analysis and exergy analysis of the cascade system. Applying MATLAB software to establish the simulation calculation of NH_3/CO_2 cascade cycle. Through simulation, the author explores the effects of low temperature cycle CO_2 evaporation temperature and high temperature cycle NH_3 condensation temperature cycle parameters on the system cycle performance and system exergy efficiency. This paper provides a certain theoretical basis for improving the design of system structure and the system performance coefficient through simulation calculation.*

Keywords: *cascade refrigeration; NH_3; CO_2; exergy efficiency*

1. Introduction

Refrigeration technology plays an important role on the present daily life and is closely related to various fields of daily production. However, the vigorous development of the refrigeration industry also brings irreversible negative effects. Bromine atoms and chlorine atoms in Freon refrigerants react with ozone in the stratosphere, resulting in a hole in the ozone layer and the greenhouse effect, which has attracted worldwide attention. Therefore, the exploration for the environment friendly, energy-saving, stable, and new-type alternative refrigerants has become a hot spot of common concern for researchers and the refrigeration industry around the world.

Since 1985, in order to protect the ozone layer, the Vienna Convention for the Protection of the Ozone Layer has been formulated after consultation with relevant international organizations. And with the formulation of the "Montreal Protocol" and its two amendments at the London Conference in 1990 and the Copenhagen Conference in 1992, people start to pay more attention to environmental protection, and the replacement process of refrigerants around the world is also accelerating and advancing. The Montreal Protocol restricts the use of refrigerants with high ozone-depleting potential (ODP), while the Kyoto Protocol restricts the use of refrigerants with high global warming potential (GWP).

In this article, the cascade refrigeration cycle selects NH_3 and CO_2 as the refrigerants, and uses the cascade refrigeration system of NH_3 and CO_2 to replace the traditional NH_3 system for refrigeration, which has the following advantages: (1) The low temperature cycle uses CO_2 as the refrigerant. While serving the disadvantage of high pressure, it avoids direct contact between NH_3 and the object to be cooled, which greatly improves safety; (2) the charging amount of NH_3 is greatly reduced, which is about one-eighth of the double-stage compression of ammonia; (3) Small viscosity of CO_2, good heat transfer, large refrigeration capacity per unit volume, and small cylinder volume of the compressor in the low temperature part of the refrigeration cycle. Therefore, the size and weight of the overall system can be reduced, and it is available to reduce system installation and maintenance costs as well.

2. NH₃/CO₂ Cascade Refrigeration System Theoretical Analysis

2.1 NH₃/CO₂ cascade refrigeration system working principle

The schematic diagram and pressure-enthalpy diagram of the NH_3/CO_2 cascade refrigeration cycle are shown in Figure 1 and Figure 2. The refrigeration system includes two circuits, in which NH_3 is used as a high temperature circuit of the refrigerant, and CO_2 is used as a low temperature circuit of the refrigerant. The high temperature circuit and the low temperature circuit are connected as a whole using a condensing evaporator. At the same time, the heat exchanger acts as the evaporator of the high temperature loop ammonia cycle and the condenser of the low temperature loop carbon dioxide cycle in the cascade system [1].
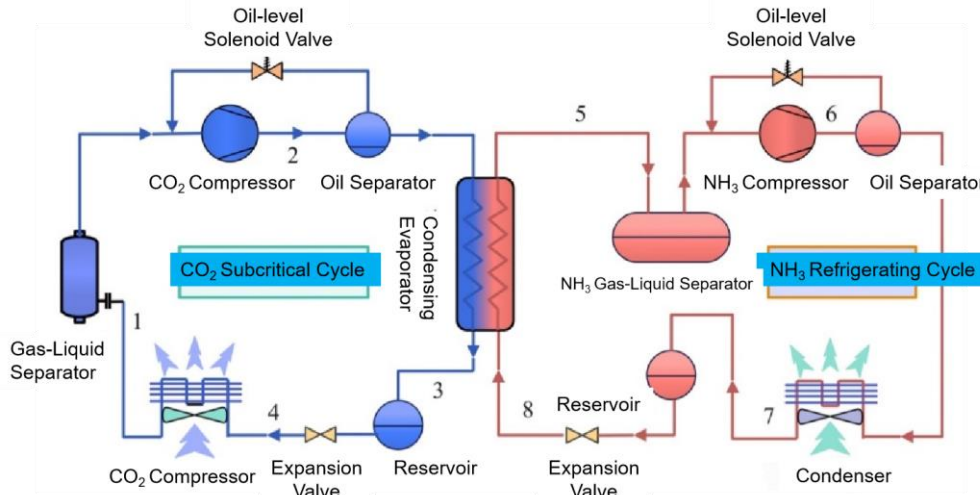

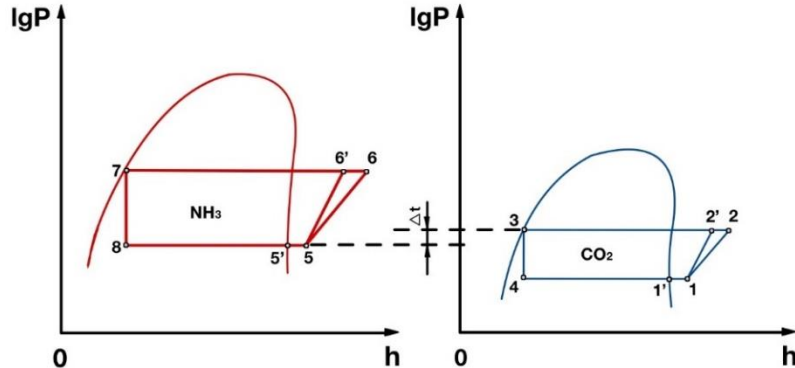*Figure 1: Schematic diagram of NH₃/CO₂ cascade refrigeration system*

Figure 2: Pressure - enthalpy diagram of NH³/CO² cascade refrigeration system

2.2 NH₃/CO₂ cascade refrigeration system thermodynamic model

Mass flow of low temperature circulating working fluid CO_2[2,3]:

$$Q_0 = m_l \left(h_1 - h_4 \right) \tag{1}$$

Where, Q_0—system circulating cooling capacity, unit W; h_4, h_1—enthalpy value of CO_2 working fluid at inlet and outlet of evaporator, unit kJ/kg; m_l—mass flow rate of low temperature circulating CO_2, unit kg/s.

Input work of low temperature circulating CO_2 compressor:

$$W_L = \frac{m_l(h_{2s} - h_1)}{\eta_{sl}\eta_m\eta_e} \tag{2}$$

Where, η_{sl}、η_m、η_e—low-temperature cycle CO_2 compressor $\eta_{sl,}$ mechanical efficiency η_m =0.95, and

motor efficiency $\eta_e = 0.9$.

Low temperature circulating CO_2 condenser (condensing evaporator) load:

$$Q_{KL} = m_l \left(h_2 - h_3 \right) \tag{3}$$

Mass flow rate of high temperature circulating working fluid NH_3:

$$Q_{KL} = m_h \left(h_5 - h_8 \right) \tag{4}$$

Where, h_8, h_5—the enthalpy of the NH_3 working fluid at the inlet and outlet of the condensing evaporator, in kJ/kg; m_h—the mass flow of NH_3 in high temperature circulation, in kg/s.

Input work of high temperature circulating NH_3 compressor:

$$W_H = \frac{m_h (h_{6s} - h_5)}{\eta_{sh} \eta_m \eta_e} \tag{5}$$

Where, η_{sh}、η_m、η_e—high-temperature cycle NH_3 compressor, isentropic efficiency η_{sh}, mechanical efficiency $\eta_m = 0.95$, and motor efficiency $\eta_e = 0.9$.

High temperature circulating NH_3 condenser load:

$$Q_H = m_h \left(h_6 - h_7 \right) \tag{6}$$

NH_3/CO_2 Cascade refrigeration system COP:

$$COP = Q_0 \left(W_L + W_H \right) \tag{7}$$

Low temperature cycle CO_2 compressor exergy loss:

$$E_{lcomp} = m_l \left(e_{x1} - e_{x2} \right) + W_L = T_0 m_l \left(s_2 - s_1 \right) - m_l \left(h_2 - h_1 \right) + W_L \tag{8}$$

Low temperature cycle CO_2 expansion valve exergy loss:

$$E_{l\exp} = T_0 m_l \left(s_4 - s_3 \right) \tag{9}$$

CO_2 evaporator exergy loss in low temperature circulating:

According to the law of conservation of energy, the exergy loss of the evaporator is the difference between the exergy of CO_2 and air flowing into the evaporator and the exergy of CO_2 and air flowing out of the evaporator.

$$E_{evap} = m_l (h_4 - h_1) - T_0 m_l (s_4 - s_1) - m_{al} (h_{4l} - h_{1l}) + T_0 m_{al} (s_{4l} - s_{1l}) \tag{10}$$

$$m_l \left(h_1 - h_4 \right) = m_{al} \left(h_{4l} - h_{1l} \right) \tag{11}$$

NH_3 compressor exergy loss in high temperature cycle:

$$E_{hcomp} = m_h \left(e_{x5} - e_{x6} \right) + W_H = T_0 m_h \left(s_6 - s_5 \right) - m_h \left(h_6 - h_5 \right) + W_H \tag{12}$$

Exergy loss of NH_3 expansion valve in high temperature cycle:

$$E_{h\exp} = T_0 m_h \left(s_8 - s_7 \right) \tag{13}$$

NH_3 condenser exergy loss in high temperature circulating:

According to the law of conservation of energy, the exergy loss of the condenser is the difference between the exergy of NH_3 and air flowing into the condenser and the exergy of NH_3 and air flowing out of the condenser.

$$E_{cond} = m_h (h_6 - h_7) - T_0 m_h (s_6 - s_7) - m_{ah} (h_{6h} - h_{7h}) + T_0 m_h (s_{6h} - s_{7h}) \tag{14}$$

$$m_h \left(h_7 - h_6 \right) = m_{ah} \left(h_{6h} - h_{7h} \right) \tag{15}$$

Exergy loss of condensing evaporator:

$$E_{cascond} = m_h \left(h_8 - h_5 \right) - T_0 m_h \left(s_8 - s_5 \right) + m_l \left(h_2 - h_3 \right) - T_0 m_l \left(s_2 - s_3 \right) \qquad (16)$$

System input exergy:

$$E_{x\,i\,n} = W_{\underset{L}{+}} W \qquad (17)$$

Total system exergy loss:

$$I_{\text{int}} = E_{cond} + E_{cascond} + E_{evap} + E_{h\exp} + E_{l\exp} + E_{hcomp} + E_{lcomp} \qquad (18)$$

System exergy:

$$\eta_{ex} = 1 - \frac{I_{\text{int}}}{E_{xin}} \qquad (19)$$

3. Thermodynamic Analysis of NH₃/CO₂ Cascade Refrigeration System

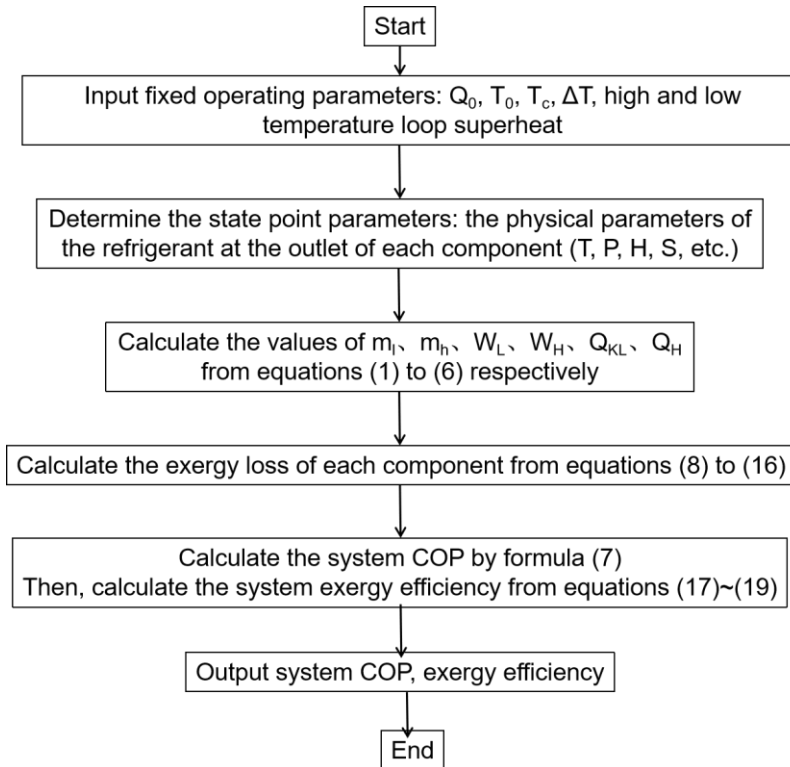### 3.1 System algorithm flow

Figure 3: Simulation flow chart of NH₃/CO₂ cascade refrigeration cycle system

Taking the effect of evaporation temperature on system COP and exergy efficiency as an example, input parameters: system refrigerating capacity, high temperature circuit condensing temperature, ambient temperature, and heat exchange temperature difference inside the condensing evaporator, and output parameters: system COP value, system exergy efficiency. Draw the simulation flow chart of the NH₃/CO₂ cascade refrigeration cycle system. The program flow chart is shown in Figure 3.

The specific algorithm flow is as follows: input known parameters; assume low temperature evaporation temperature; calculate the intermediate temperature (NH₃ evaporation temperature in high temperature circulation) and CO₂ condensation temperature in low temperature circulation according to the empirical formula of Mailer Prasat. Based on the system cycle schematic diagram and the system cycle pressure-enthalpy diagram, call the refpropm statement in MATLAB to obtain physical parameters (pressure, temperature, enthalpy valule, entropy value) of the high and low temperature points on the pressure-enthalpy diagram (evaporator outlet, condenser outlet, condensation evaporator outlet, and compressor outlets). Then use energy conservation to obtain the refrigerant mass flow rate

of high and low temperature, compressor power consumption and condenser load, and substitute the data into formula (7) to obtain the system COP value.

Call the refpropm statement in MATLAB to obtain the air physical parameters (pressure, temperature, enthalpy, entropy) at the outlet of the high-temperature condenser and the outlet of the low-temperature evaporator. The mass flow of air at the outlet of the high-temperature stage condenser and the outlet of the low-temperature stage evaporator is obtained by using the law of conservation of energy. The optimal mass flow rate is selected as the calculation parameter, the exergy loss of each component is obtained by using the energy conservation and exergy balance equation, and the data is substituted into equations (17) to (19) to obtain the system exergy efficiency. Output system COP and exergy efficiency.

3.2 Effect of evaporation temperature on the performance of NH_3/CO_2 cascade refrigeration system

Figure 4 is a graph showing the effect of CO_2 evaporation temperature change on the COP of the cascade system. Figure 5 is the changing curve of the effect of CO_2 evaporation temperature on the exergy efficiency of the system.
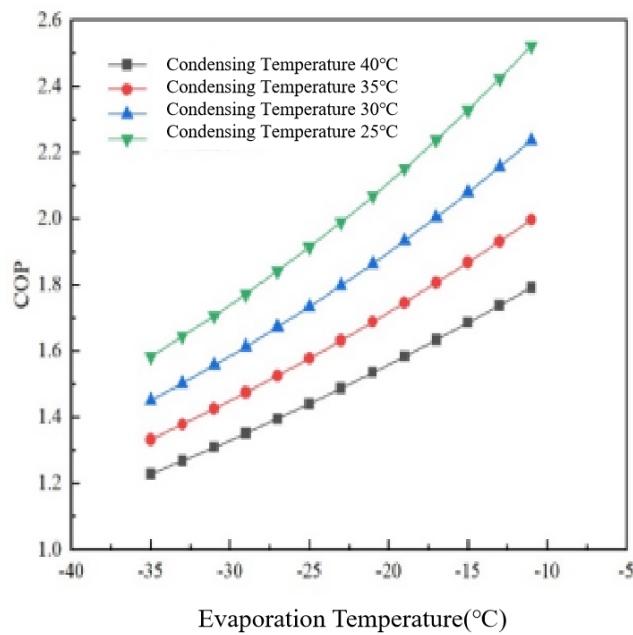

Figure 4: Effect of evaporation temperature on cascade system COP

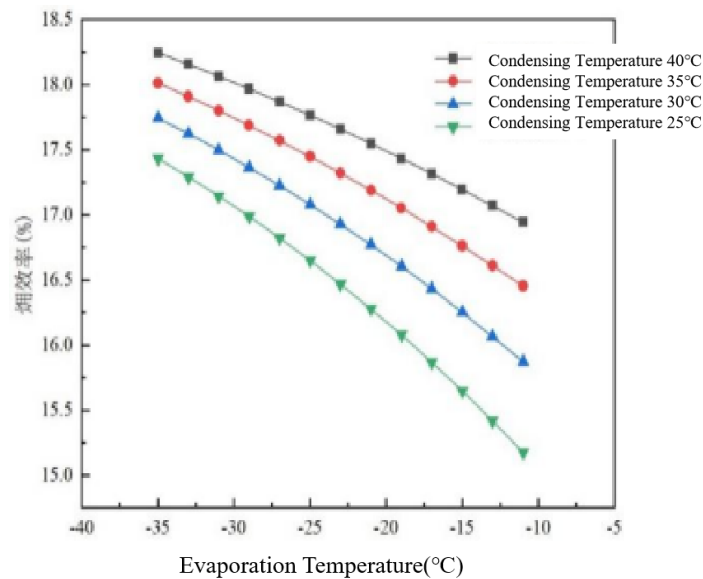*Figure 5: Effect of evaporation temperature on the exergy efficiency of cascade system*

As shown in Figure 4 and Figure 5, with the increase of CO_2 evaporation temperature, under different condensation temperatures, the performance coefficient of the system increases with the increase of evaporation temperature, and the reduction of system input exergy is greater than the system exergy loss. Therefore, the exergy efficiency of the system shows a downward trend. As the evaporation temperature of the low temperature stage increases, the pressure ratio of the low temperature stage compressor gradually decreases, the power consumption of the system decreases, the cooling capacity per unit volume of the low temperature stage increases, and the COP of the cascade system increases. Therefore, the evaporation temperature of the system should be appropriately increased to achieve a higher COP value when the process requirements of each component of the system are met.

3.3 Effect of condensation temperature on the performance of NH_3/CO_2 cascade refrigeration system

Figure 6 is a graph showing the effect of NH_3 condensation temperature changes on the COP of the cascade system. Figure 7 is the changing curve of the influence of NH_3 condensation temperature on the exergy efficiency of the system.
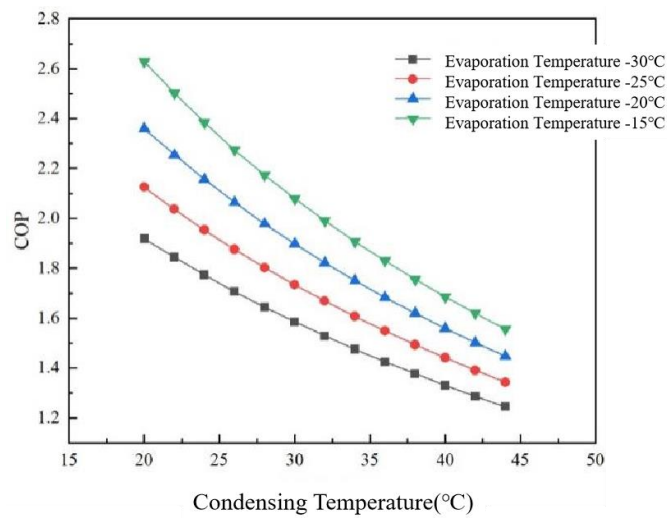

Figure 6: Effect of condensing temperature on cascade system COP
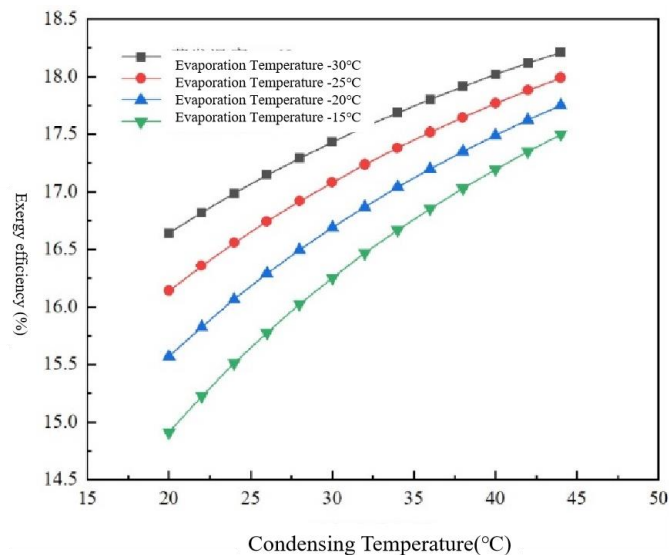

Figure 7: Effect of condensing temperature on the exergy efficiency of cascade system

As shown in Figure 6 and Figure 7, with the increase of the condensation temperature, the performance coefficient of the system decreases under different evaporation temperatures. When the evaporation temperature, condensation temperature and heat exchange temperature difference of low

temperature stage CO_2 are constant, with the increase of high temperature stage condensation temperature, the pressure ratio of high temperature stage compressor gradually decreases, the system power consumption increases, and the COP of the cascade system decreases. The increase of the system input exergy is greater than the increase of the system exergy loss, so the exergy efficiency of the system shows an upward trend. Increasing the condensing temperature of the cycle will increase the exergy efficiency of the system slightly, but with the increase of the condensing temperature, the COP of the cascade refrigeration cycle will continue to decrease.

4. Conclusion

Based on the energy conservation and the system exergy equilibrium equation, this paper carries out the thermodynamic analysis of the system, and draws the following conclusions.

Under certain conditions of other cycle parameters, the power consumption of the system decreases, and the performance coefficient of the system increases with the increase of the evaporation temperature; the exergy loss of the system decreases, and the exergy efficiency of the system decreases with the increases of the evaporation temperature. Therefore, the evaporation temperature of the system should be appropriately increased to achieve a higher COP value when the process requirements of each component of the system are met.

Under certain conditions of other cycle parameters, with the increase of the condensation temperature, the performance coefficient of the system decreases with the increase of the evaporation temperature; the exergy loss of the system increases, and the exergy efficiency of the system increases with the increase of the condensation temperature. Therefore, in order to meet the technological requirements of each component of the system, the condensation temperature of the system should be appropriately reduced to achieve a higher COP value.

References

[1] Omid Rezayan, Ali Behbahaninia, Thermoeconomic optimization and exergy analysis of CO$_2$/NH$_3$ cascade refrigeration systems, [J]. Energy, 2011,36(2): 888-895
[2] Mehdi Aminyavari, Behzad Najafi, Ali Shirazi, Fabio Rinaldi, Exergetic economic and environmental analyses, and multi-objective optimization of CO$_2$/NH$_3$ cascade refrigeration system. [J]. Applied Thermal Engineering, (2014)42-50
[3] Lee, T.S, Liu, C.H, Chen, Termodynamic analysis of optimal condensing temperature of cascade-condenser in NH$_3$/CO$_2$ cascade refrigeration systems [J]. Refrigeration 29, 1100-1108