Thermodynamic Analysis of Different CO_2 Cascade Refrigeration Cycles

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Abstract: Five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycles are analyzed. It shows that at given condition, the NH_3/CO_2 cycle has the maximum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle is almost the same, the COP of five different cascade refrigeration cycles increased with the evaporating temperatures t_1 rise, while it decreased with the heat-transfer temperature difference of condenser-evaporator Δt and condensing temperature of LTC t_3 rise, and different cascade refrigeration cycles except $R404a/CO_2$ cycle have a best COP with the condensing temperature t_7 rise, the $R404a/CO_2$ cycle has the minimum COP when the condensing temperature t_7 is less than -10°C, but it almost have the same COP as NH_3/CO_2 cycle when condensing temperature t_7 is 0°C.

Introduction

In refrigeration applications for temperatures between -40 and -80°C the cascade system is often a convenient option, usually using Freon. Natural refrigerants are increasingly becoming the refrigerant of choice to replace the environmentally harmful CFCs and HCFCs. CO_2 has its unique advantages [1] as a refrigerant such as environmental safety, favorable thermodynamic properties, and non-flammability.
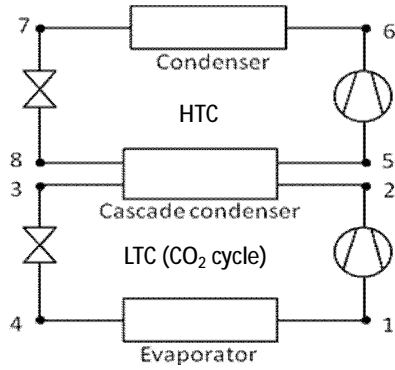
The results indicated that the low-temperature cycle (LTC) of the refrigeration system may use CO_2, whereas the high-temperature cycle (HTC) of a cascade refrigeration system can normally be charged with NH_3, R32, N_2O, R134a, R1270[2-6], But they have disadvantages which limit their application.

In the paper, thermodynamic analysis is carried out with five different refrigeration(NH_3, R22, R32, R290, R404a) as the high temperature (HTC)fluid and carbon dioxide as the low temperature (LTC) fluid in cascaded system. Effects of evaporation temperature, Condensing temperature, heat-transfer temperature difference of condenser-evaporator and Condensing temperature of LTC are investigated, which could provide a basis for the optimization of CO_2 cascade refrigeration cycle.
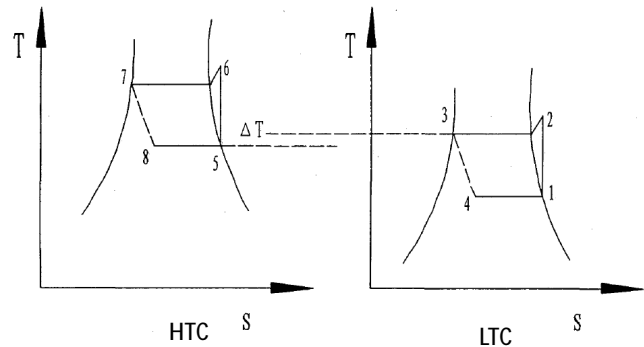
The investigated cycles

Fig.1(a) schematically depicts different CO_2 cascade refrigeration cycles, it comprises two separate refrigeration cycle, the high-temperature cycle(HTC) with five different refrigeration(NH_3, R22, R32, R290, R404a) as the fluid and the low-temperature circuit(LTC) with carbon dioxide as the fluid. The cycles are thermally connected to each other through a condenser-evaporator, which acts as an evaporator for the HTC and a condenser for the LTC. Fig.1(b) presents the corresponding

temperature-entropy diagrams.

(a) Flow description	(b) Temperature-Entropy diagram

Fig.1 CO_2 cascade refrigeration cycle

Thermodynamic Analysis

The following assumptions have been made for the analysis: (1) The outlet of the condenser and the cascade-condenser are at saturated liquid states and that of the evaporator is at saturated vapor state. (2) Compression process is adiabatic but non-isentropic. (3) All throttling devices are isenthalpic. (4) Pressure drop in the heat exchanger and piping is negligible.

In view of the schematic and state points of Fig.1, the following sequence of equations was applied for the analysis.

Mass flow rate of LTC is expressed as:

$$m_L = \frac{Q_e}{h_1 - h_5}$$

(1)

Power input for the LTC compressor is expressed as:

$$W_L = \frac{m_L(h_{2s} - h_1)}{h_L} = \frac{m_L(h_{2s} - h_1)}{h_m h_{is,L} h_{el}} = \frac{m_L(h_2 - h_1)}{h_m h_{el}}$$

(2)

The coefficient of performance of LTC can be formulated as:

$$COP_L = \frac{Q_e}{W_L}$$

(3)

The rate of heat transfer in the cascade-condenser is determined from:

$$Q_{cas} = \frac{Q_e(h_2 - h_4)}{h_1 - h_4}$$

(4)

Mass flow rate of HTC is expressed as:

$$m_H = \frac{Q_{cas}}{h_6 - h_{10}} = \frac{Q_e}{h_6 - h_{10}} \cdot \frac{h_2 - h_4}{h_1 - h_4}$$

(5)

The work input for the HTC compressor is represented by:

$$W_H = \frac{m_H(h_{7s} - h_6)}{h_H} = \frac{m_H(h_{7s} - h_6)}{h_m h_{is,H} h_{el}} = \frac{m_H(h_7 - h_6)}{h_m h_{el}}$$

(6)

Heat transfer from the HTC condenser is estimated from:

$$Q_H = m_H(h_7 - h_9)$$

(7)

The coefficient of performance of HTC can be formulated as:

$$COP_H = \frac{Q_{cas}}{W_H}$$

(8)

The COP of the system is determined by:

$$COP = \frac{Q_e}{W} = \frac{COP_L \cdot COP_H}{1 + COP_L + COP_H}$$

(9)

Analysis of the results

The thermodynamic analysis evaluation covers evaporating temperatures t_1 is from-55°C to -45°C, condensing temperature t_7 is from 30°C to 40°C, heat-transfer temperature difference of condenser-evaporator Δt is from 5°C to 9°C and condensing temperature of LTC t_3 is from -30°C to 0°C.

Fig.2 shows the variation of COP with evaporating temperatures t_1 of five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycles at t_3=-10°C, Δt=5°C, t_7=40°C. It shows that at given condition, the COP of five different cascade refrigeration cycles increased with the evaporating temperatures t_1 rise. The NH_3/CO_2 cycle has the maximum COP, while the $R404a/CO_2$ cycle has the minimum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle are almost identical.

Fig.3 shows the variation of COP with condensing temperature t_7 of five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycle at t_3=-10°C, Δt=5°C, t_1 =-50°C. It shows that at given condition, different cascade refrigeration cycles except $R404a/CO_2$ cycle have a best COP with the condensing temperature t_7 rise. The NH_3/CO_2 cycle has the maximum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle are almost identical. The COP of $R404a/CO_2$ cycle growing very fast with the condensing temperature t_7 rise, it has the minimum COP when the condensing temperature t_7 is less than -10°C, but it almost have the same COP as NH_3/CO_2 cycle when condensing temperature t_7 is 0°C.
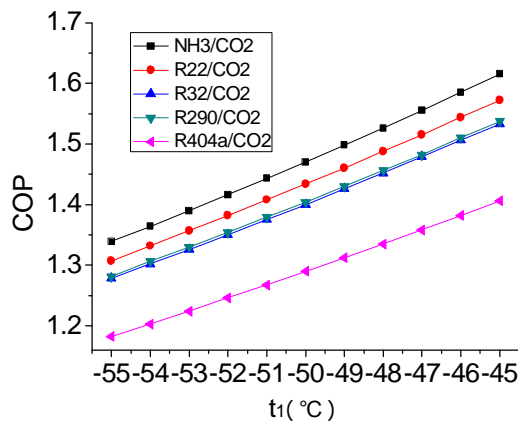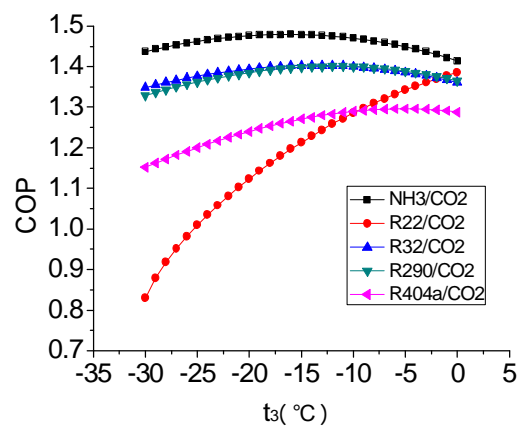

Fig.2 Variation of *COP* with t_3

Fig.3 Variation of *COP* with t_7

Fig.4 shows the variation of COP with heat-transfer temperature difference of condenser-evaporator Δt of five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycle at t_3=-10°C, t_1=-50°C, t_7=40°C. It shows that at given condition, the COP of five different cascade refrigeration cycles decreased with the heat-transfer temperature difference

of condenser-evaporator Δt rise. The NH_3/CO_2 cycle has the maximum COP, while the $R404a/CO_2$ cycle has the minimum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle are almost identical.

Fig.5 shows the variation of COP with condensing temperature of LTC t_3 of five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycle at $\Delta t = 5°C$, $t_1 = -50°C$, $t_7 = 40°C$. It shows that at given condition, the COP of five different cascade refrigeration cycles decreased with the Condensing temperature of LTC t_3 rise. The NH_3/CO_2 cycle has the maximum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle are almost identical, while the $R404a/CO_2$ cycle has the minimum COP.
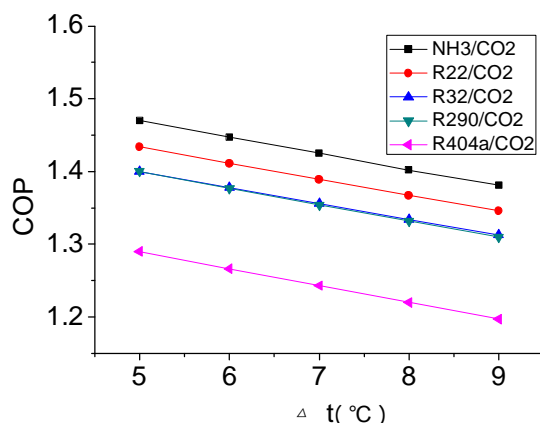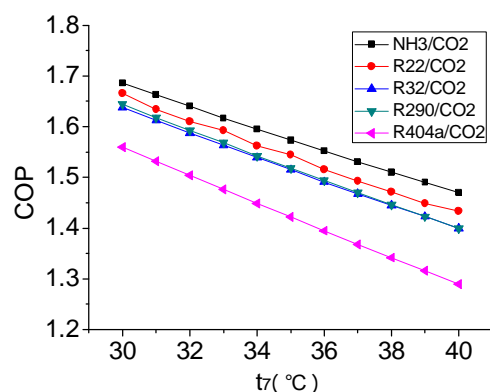

Fig.4 Variation of *COP* with Δt Fig.5 Variation of *COP* with t_3

Conclusions

Thermodynamic analysis of five different (NH_3/CO_2, $R22/CO_2$, $R32/CO_2$, $R290/CO_2$, $R404a/CO_2$) cascade refrigeration cycles have been present here.

(1) The COP of five different cascade refrigeration cycles increased with the evaporating temperatures t_1 rise, while it decreased with the heat-transfer temperature difference of condenser-evaporator Δt and condensing temperature of LTC t_3 rise. And then the NH_3/CO_2 cycle has the maximum COP, while the $R404a/CO_2$ cycle has the minimum COP, the COP of $R32/CO_2$ cycle and $R290/CO_2$ cycle is almost identical.

(2) It shows that at given condition, different cascade refrigeration cycles except $R404a/CO_2$ cycle have a best COP with the condensing temperature t_7 rise. The NH_3/CO_2 cycle has the maximum COP, but the COP of $R404a/CO_2$ cycle growing very fast with the condensing temperature t_7 rise. It has the minimum COP when the condensing temperature t_7 is less than -10°C, but it almost have the same COP as NH_3/CO_2 cycle when condensing temperature t_7 is 0°C.

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