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The Entropy Analysis on NH_3/CO_2 Cascade Refrigeration Cycle

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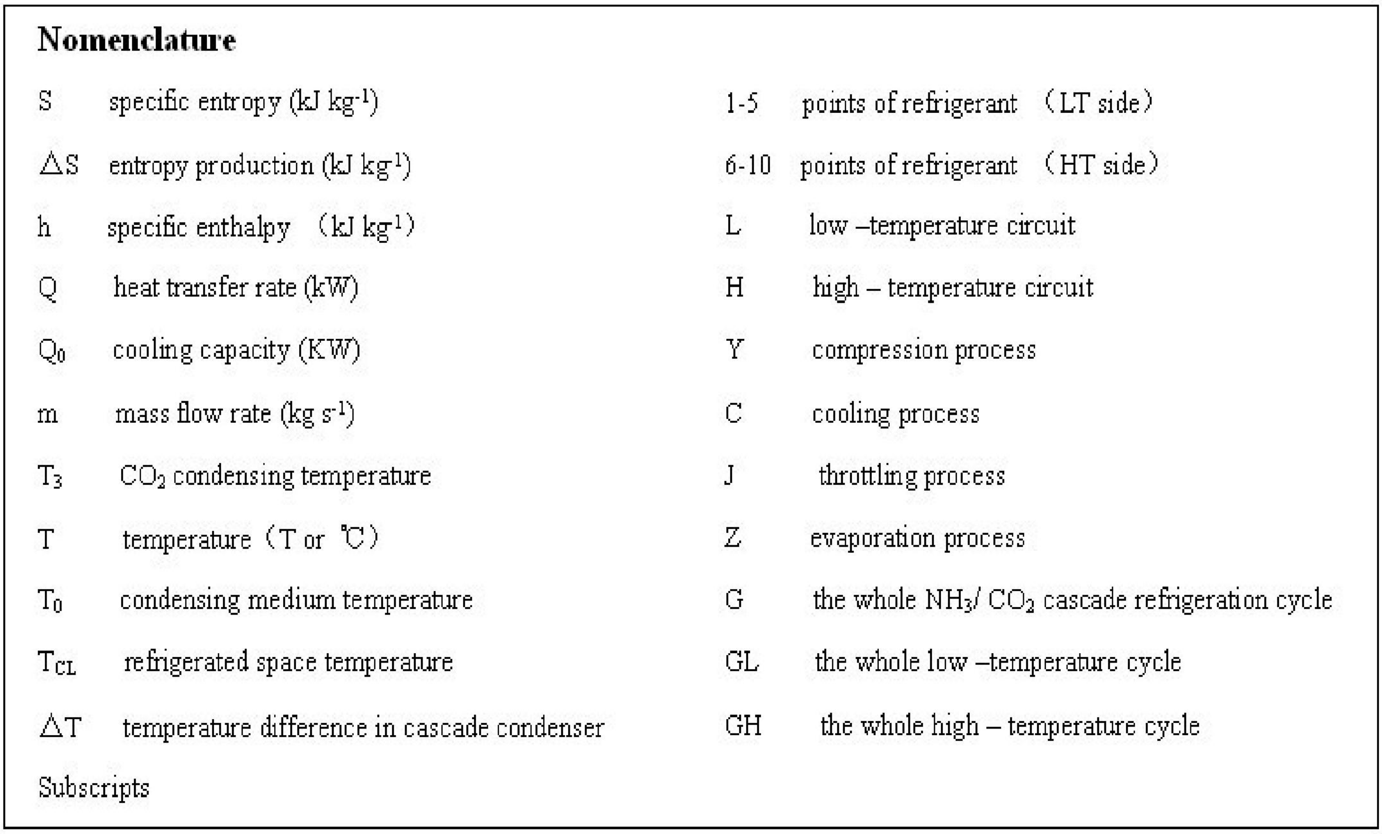
ABSTRACT

This paper introduces a cascade refrigeration cycle that uses natural refrigerants of CO_2 and NH_3 at low temperature. It introduces the character of CO_2 and NH_3, besides analyzes the cascade refrigeration cycle. The optimal intermediate temperature of NH_3/CO_2 cascade refrigeration cycle is determined by the entropy production minimization method. We analyze the four processes entropy production in both CO_2 cycle（LT side）and NH_3 cycle（HT side） and research how the total entropy production changes in the conditions of different T_0 , different T_{CL} and different $\triangle T$. We also find that in order to enhance the efficiency of NH_3/CO_2 cascade refrigeration cycle，it is necessary to reduce $\triangle T$. It can be concluded that NH_3/CO_2 cascade refrigeration cycle has a good future.

INTRODUCTION

Global environmental problems，such as global warming and depletion of the ozone layer，have become more and more severe by the use of synthetic refrigerants (CFC, HCFC and HFC). In order to keep sustainable development of environment, searching efficient, green and friendly refrigerants has become a common concern of the international community. Natural working fluid was regarded as the final plan to solve environmental problems by G. Lorentzen the former president of the International Institute of Refrigeration [1]. When the required T_{CL} is very low, we can use cascade refrigeration system. The cascade refrigeration system consisted by two single-stage compression refrigeration system usually uses R22 and R13 as refrigerant in most regions of the world. However R22 and



Nomenclature

S	specific entropy (kJ kg^{-1})
$\triangle S$	entropy production (kJ kg^{1})
h	specific enthalpy （kJ kg^{1}）
Q	heat transfer rate (kW)
Q_0	cooling capacity (KW)
m	mass flow rate (kg s^{-1})
T_3	CO_2 condensing temperature
T	temperature（T or ℃）
T_0	condensing medium temperature
T_{CL}	refrigerated space temperature
$\triangle T$	temperature difference in cascade condenser

Subscripts

1-5	points of refrigerant （LT side）
6-10	points of refrigerant （HT side）
L	low –temperature circuit
H	high – temperature circuit
Y	compression process
C	cooling process
J	throttling process
Z	evaporation process
G	the whole NH_3/ CO_2 cascade refrigeration cycle
GL	the whole low –temperature cycle
GH	the whole high – temperature cycle

R13 not only destroy atmospheric ozone layer, but also have serious greenhouse effect. Under the "Montreal Protocol", R13 has been forbidden currently, and R22 only can be used before 2030 in some countries.

Therefore, refrigerant friendly to environment is needed to meet the requirement of low-temperature refrigeration. W. R. Kitzmiller once promoted the program of NH_3/CO_2 cascade refrigeration cycle in 1932, high pressure level with NH_3 as refrigerant, low-level with CO_2 as refrigerant. CO_2 has good heat transfer performance, rather large cooling capacity by using latent heat and small viscosity at low temperature compared with other low-pressure refrigerant [2]. The research of Pettersen A. and Jakobsen shows that when using CO_2 instead of NH_3 at low-level, the size of compressor will reduce to the original 1 / 10 compared with NH_3/NH_3 system, and T_{CL} can reach to - 50℃—- 45℃, even reach to - 80℃ through the dry ice for powder effect. At present, Europe has established a few of cascade refrigeration system with low-temperature using CO_2 as refrigerant in the supermarkets. Operation conditions indicate that it is technically feasible. This system can also be applied to low-temperature freeze-drying process.

THE PHYSICAL PROPERTIES OF CO_2 AND NH_3

As a refrigerant, CO_2 has some special advantages. Mainly in: (1) CO_2 is harmless to environment and a substance naturally existing in nature (ODP = 0, GWP = 1). (2) CO_2 has excellent economy. (3) CO_2 has good security, and chemical stability. It is safe, non-toxic and non-combustible, adapting to mechanical parts materials using a variety of oil. Even at high temperature, it does not decompose to produce harmful gases. (4) CO_2 has good thermal physical properties, suiting to the refrigeration cycle and equipment. It has larger latent heat of evaporation and has greater cooling capacity(0 ℃, the cooling capacity per unit volume of CO_2 is 1.58 times of NH_3, 5.12 times of R22 and 8.25 times of R12) [3]. At the same time, its dynamic viscosity is low. 0℃, the dynamic viscosity of CO_2 saturated liquid is only 5.2% of NH_3 and 23.8% of R12. CO_2 has high thermal conductivity and small ratio of liquid density and vapor density; refrigerant between circuits is more easily distributed after throttling. CO_2 has excellent flow and heat transfer characteristics, so the size of the compressor and the system can be significantly reduced to make the whole system compact.

NH_3 has been used for 120 years and still applies to large-scale industrial systems in many countries. The advantage is ODP=0, GWP=0, with excellent thermodynamic properties, cheap price and convenient leak detection. It is the most vital refrigerant used in standard refrigeration equipment with reciprocating or rotary compressor and cooling capacity higher than 25KW. And in the appropriate equipment, even more small-capacity NH_3 refrigerator has gradually appeared in the market. Most consideration about NH_3 is its safety, mainly about its toxicity and flammability, followed by pungent smell. In fact, its toxicity is only 1/10-1/50 of the toxicity of chlorine; its ignition limit is 15.5% (volume ratio), 3-7 times of the usual hydrocarbon and natural gas, while the heat of combustion is less than half of them. About 100 years historical experience shows that NH_3 has low accident rate. NH_3 has a strong pungent smell. Therefore, we can easily identify the leak. In addition, NH_3 is lighter than air, so it is easy to escape from the roof to outside. When NH_3 and water is contacted, NH_3 can be quickly absorbed by water. This performance can be used to eliminate the NH_3 vapor in the air, greatly reducing the accident.

THE ENTROPY ANALYSIS OF NH_3/CO_2 CASCADE REFRIGERATION CYCLE

Theoretical analysis

NH_3/CO_2 cascade refrigeration cycle is composed of NH_3 high-temperature cycle and CO_2 low-temperature cycle [4]. Fig. 1 schematically depicts the cascade refrigeration cycle. Fig.2 is the corresponding temperature-entropy diagram. In Fig. 2, l-2-3-4-5-1 is cycle of low-temperature part (CO_2), and 6-7-8-9-10-6 is the cycle of the high temperature part (NH_3) .The evaporation of NH3 and the condensation of CO_2 complete in a "cascade condenser"; and this equipment insulates environment using insulation materials. Therefore, evaporation heat of NH3 is equal to the condensation heat of CO_2, and temperature difference in cascade condenser(△T) is 5-8℃.

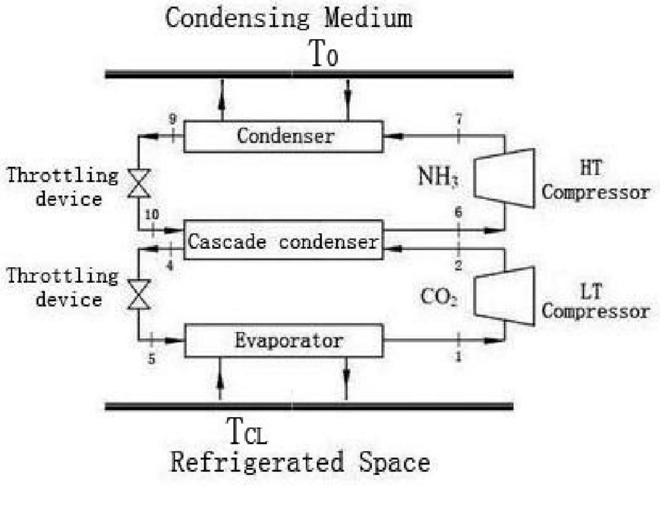


Fig.1 Schematic diagram of CO_2/NH_3 cascade refrigeration cycle

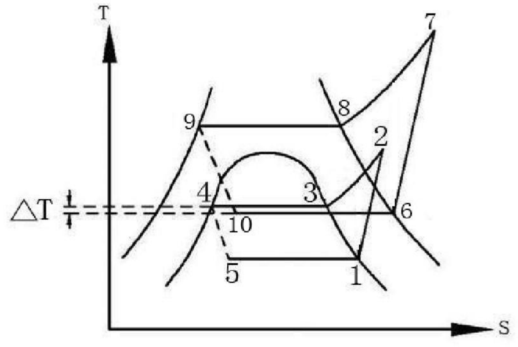


Fig.2 The temperature-entropy diagram of CO_2/ NH_3 cascade refrigeration cycle

Theoretical cycle is calculated as follows

The relation of the mass flow between HT circuit and LT circuit:

If the mass flow of LT part of CO_2 is m_L and cooling capacity is Q_0, then

$$m_L = \frac{Q_0}{h_1 - h_5} \tag{1}$$

Heat transfer rate of cascade condenser is,

$$Q_{KL} = Q_0 \frac{h_2 - h_4}{h_1 - h_5} \tag{2}$$

The mass flow of HT circuit is,

$$m_H = \frac{Q_{KL}}{h_6 - h_{10}} = \frac{Q_0(h_2 - h_4)}{(h_6 - h_{10})\ (h_1 - h_5)} \tag{3}$$

The entropy production [5] of LT circuit:

The compression process: $\Delta S_{YL} = m_L(s_2 - s_1)$ (4)

The cooling process: $\Delta S_{CL} = m_L(s_4 - s_2) + \frac{Q_{LZ}}{T_6}$ (5)

Where, $Q_{LZ} = m_L(h_2 - h_4)$

The throttling process: $\Delta S_{JL} = m_L(s_5 - s_4)$ (6)

The evaporation process: $\Delta S_{ZL} = m_L(s_1 - s_5) - \frac{Q_0}{T_{CL}}$ (7)

The entropy production of HT circuit:

The compression process: $\Delta S_{YH} = m_H(s_7 - s_6)$ (8)

The cooling process: $\Delta S_{LH} = m_H(s_9 - s_7) + \frac{Q_{LH}}{T_0}$ (9)

where, $Q_{LH} = m_H(h_7 - h_9)$,

The throttling process: $\Delta S_{JH} = m_H(s_{10} - s_9)$ (10)

The evaporation process: $\Delta S_{ZH} = m_H(s_6 - s_{10}) - \frac{Q_{LZ}}{T_3}$ (11)

where, $Q_{LZ} = m_H(h_6 - h_{10})$

Analysis of the calculating results

As the part of the HT cycle is cooled under ambient temperature conditions. So the condensing medium temperature(T_0) is 25℃.Condensing temperature can be taken as 40 ℃ .The temperature difference [7] in cascade condenser(△T) is 5℃. Evaporation temperature is -55℃, and cooling capacity(Q_0) is 3.5kw. The isentropic efficiency of compressing process is 0.8;the refrigerated space temperature(T_{CL}) is - 45 ℃ , and CO_2 condensing temperature(T_3) is a known constant.

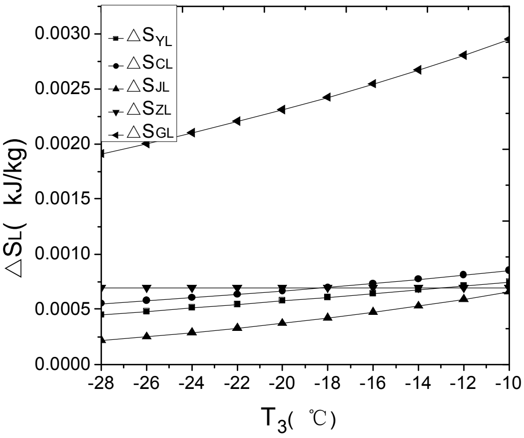


Fig.3 The entropy productions of compressing process, condensing process, throttling process, evaporating process and total entropy production（$\triangle S_{YL}$, $\triangle S_{CL}$, $\triangle S_{JL}$, $\triangle S_{ZL}$, $\triangle S_{GL}$） in LT circuit change with T_3

Fig.3 shows how the entropy productions of compressing process, condensing process, throttling process, evaporating process and total entropy production in LT circuit change withT_3. It can be seen from the figure that the entropy productions of compressing process, condensing process, throttling process increase as T_3 rising. The entropy production of condensing process is the largest, followed is the compressing process. And the change of evaporating process is very small.

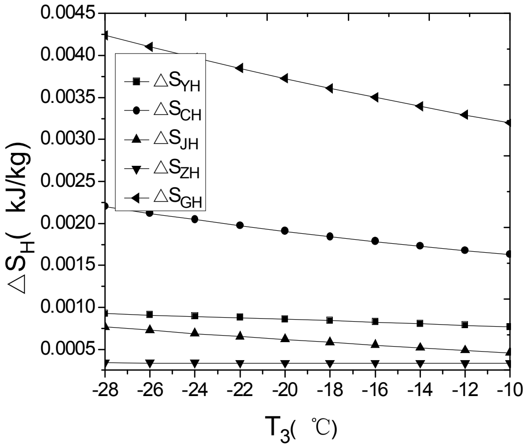


Fig.4 The entropy production of compressing process, condensing process, throttling process, evaporating process and total entropy production（$\triangle S_{YH}$, $\triangle S_{CH}$, $\triangle S_{JH}$, $\triangle S_{ZH}$, $\triangle S_{GH}$） in HT circuit change with T_3

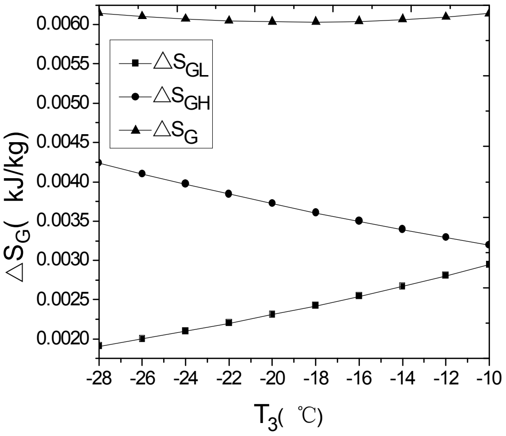


Fig.5 The sum of the entropy production in each circuit and total entropy production($\triangle S_{GL}$, $\triangle S_{GH}$, $\triangle S_G$) change with T_3

Fig.4 shows how the entropy productions of compressing process, condensing process, throttling process, evaporating process and total entropy production in HT circuit change with T_3. It can be seen from the figure that the entropy production of condensing process, throttling process decrease as T_3 rising. The entropy production of condensing process is the largest, followed is the throttling process; the changes of compressing process and evaporating process are nearly constant.

Fig.5 shows how the sum of the entropy production in each circuit and total entropy production change with T_3. It can be seen from the figure that with the raise of T_3, the sum of the entropy production in LT circuit increases, while the sum in HT circuit decreases and the total entropy production first decreases, then increases. So there exists a minimum entropy production. The corresponding temperature of minimum entropy production is called optimum intermediate temperature [6]. The optimum intermediate temperature of the calculating condition is -18℃.

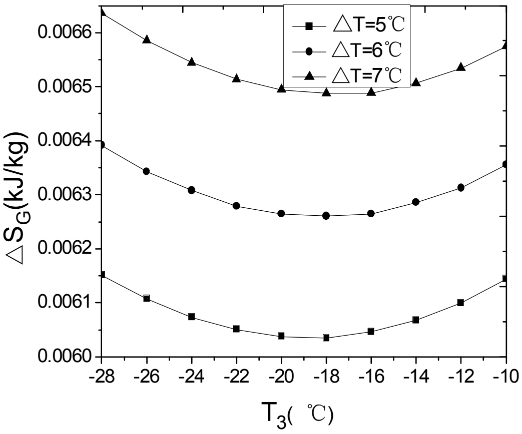


Fig.6 The total entropy production(△S_G) changes with T_3 in different △T

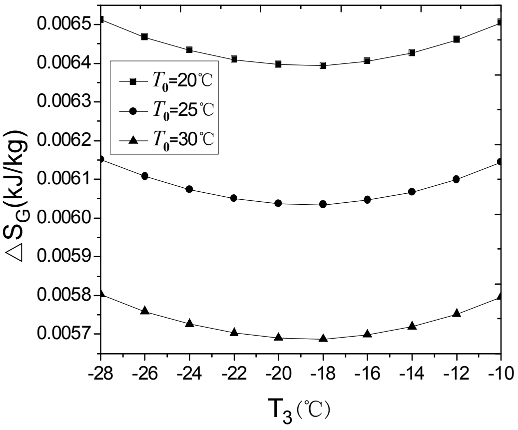


Fig.7 The total entropy production(△S_G) changes with T_3 in different T_0

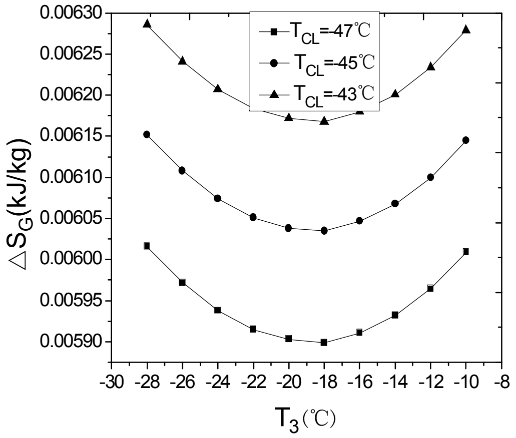


Fig.8 The total entropy production(△S_G) changes with T_3 in different T_{CL}

Figure 6, Figure 7, and Figure 8 separately shows how the total entropy production of NH_3/CO_2 cascade refrigeration cycle changes with T_3 under the conditions of different △T, T_0 and T_{CL}. It can be seen from the three figures, with the increase of T_3, the total entropy production decreases at first and then increases, so there exists a minimum entropy production. As for different △T, the smaller the △T is, the smaller the corresponding total entropy production is. That is, the irreversible loss is smaller. So we should reduce △T.

CONCLUSIONS

The total entropy production of NH_3/CO_2 cascade refrigeration cycle decreases at first and then increases with T_3 increasing, and there is a minimum entropy production. The minimum entropy production can determine the optimal intermediate temperature of NH_3/CO_2 cascade refrigeration cycle. In this paper, the optimal intermediate temperature is about -18℃.

(1) As T_3 increases , the sum of entropy production in LT circuit increases while the sum of entropy production in HT circuit decreases, and the entropy production of condensing process is maximum.

(2) The minimum entropy production increases with △T and T_{CL} increasing, and decreases with T_0 increasing. Among them, the minimum entropy production changes greatest with △T. In order to reduce irreversible loss of NH_3/CO_2 cascade refrigeration cycle, we should first reduce △T.

(3) This paper only analyzes the irreversible loss of NH_3/CO_2 cascade refrigeration system by using entropy , but we need to do further research to optimize the system performance（COP）.

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