ENERGY EFFICIENT CASCADE SYSTEM WITH CO_2 REFRIGERANT

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IMPROVEMENT OF ENERGY EFFICIENT BY CASCADE SYSTEM WITH CO_2 REFRIGERANT
DEVELOPMENT of CO2-CO2 CASCADE REFRIGERATION SYSTEM

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Abstract

Global warming is commonly issue in worldwide. From point of global warming point of view, alternate HFC refrigerant to natural refrigerant is one of the means to reduce global warming gas which is used to refrigeration system in food store such as supermarket and convenience store. Carbon dioxide (hereinafter CO_2) is one of the dominant candidates as low Global Warming Potential (hereinafter GWP) refrigerant. However, CO_2 refrigerant has lower efficiency for refrigeration because of low critical temperature. In addition, CO_2 refrigerant has higher system pressure than HFC refrigerant. Therefore typical cascade refrigeration system is equipped HFC refrigerant in higher temperature cycle. This report indicate the potential of CO_2-CO_2 cascade system even CO_2 refrigerant itself has lower efficiency than HFC refrigerant. And this report shows optimization of discharge pressure, suction pressure and internal heat exchanger are important to get better performance.

Keywords

CO_2, Carbon dioxide, Coefficient of performance, Cascade.

Introduction

The showcase that is installed into most of supermarkets and convenience stores are operated with refrigeration system, which is equipped HCFC or HFC refrigerant at this moment. However this HCFC and HFC refrigerant has high GWP. Therefore, alternate refrigerant from HCFC and HFC to Low-GWP refrigerant is required. Some configurations of refrigeration system which uses CO_2 refrigerant are studied as solution for reducing global warming gases. [1]

As well known, CO_2 refrigerant has lower efficiency at high ambient temperature. The refrigeration system is operated at super critical condition when ambient temperature exceeds 30.98^{o}C. Therefore controlling discharge pressure is important to get better Coefficient of Performance (hereinafter COP).
This report shows optimized pressure setting and configuration of internal heat exchanger in CO_2-CO_2 cascade refrigeration system. And this report shows possibility to use CO_2 refrigerant in high ambient temperature condition in CO_2-CO_2 cascade refrigeration system.

Optimization of Cascade System.

Configuration of CO2 Cascade System.

A cascade system is structured from higher temperature cycle and lower temperature cycle, both cycles being combined thermodynamically by a cascade heat exchanger (Fig. 1). Both refrigeration systems have compressor, gas cooler, expansion valve, evaporator, and internal heat exchanger (hereinafter IHX). The lower temperature cycle has additional heat exchanger between compressor and gas cooler as pre- cooler. Exhaust heat from lower temperature cycle is transferred to evaporator in higher temperature cycle.

Figure 2 shows *p-h* diagram of the CO_2-CO_2 cascade system.

CO_2-CO_2 cascade system which uses CO_2 refrigerant for both higher temperature cycle and lower temperature cycle has not been studied in the past, because of general acceptance of CO_2 refrigerant's lower efficiency at high ambient temperature condition due to lower critical temperature. However controlling the discharge pressure of CO_2 refrigeration system can make a significant improvement of COP. Both higher and lower temperature CO_2 refrigeration cycle has IHX to improve the efficiency. The effect of IHX is studied in this report.

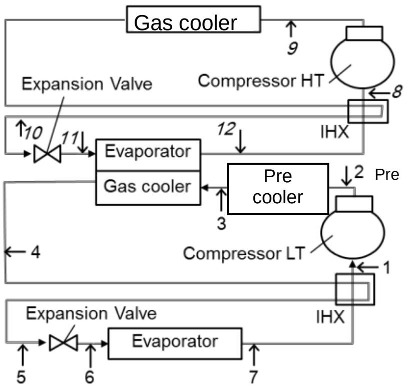

Fig.1 Configuration of CO_2-CO_2 cascade system

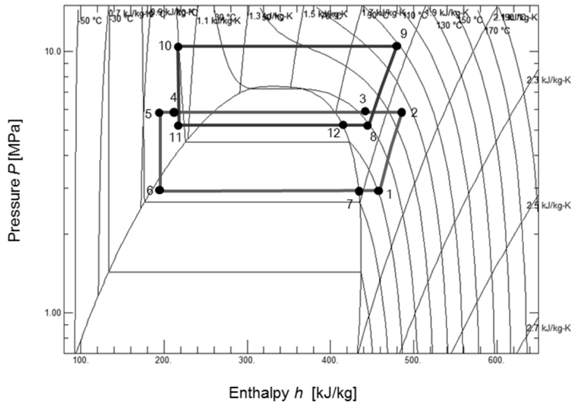

Fig.2 P-h diagram of CO_2-CO_2 cascade system

Calculation of System Efficiency

The system efficiency of cascade refrigeration system is shown by formula (1) to (5).

The total rate of heat transfer Q_{LT} can be expressed by mass flow of refrigerant in lower temperature cycle (M_{LT}) and enthalpy difference between evaporator inlet (Fig. 2 point 6,h_6) and outlet (Fig. 2 point 7, h_7) of lower temperature cycle. The operation of higher temperature cycle depends on enthalpy difference at cascade evaporator (Fig. 2 point 12, h_{12} and point 11, h_{11}) and heat load at cascade heat exchanger (Fig. 2 point 3, h_3 and point 4, h_4) of lower temperature cycle. In formula (2), capacity of higher temperature cycle is equivalent with heat load from lower temperature cycle.

Total COP of the CO_2-CO_2 cascade refrigeration system is shown by formula (5).

$$Q_{LT}=M_{LT}\cdot(h_7-h_6) \qquad (1)$$

$$Q_{HT}=M_{HT}\cdot(h_{12}-h_{11}) = M_{LT}\cdot(h_3-h_4) \qquad (2)$$

$$W_{LT}=M_{LT}\cdot(h_2-h_1)/\eta_{LT} \qquad (3)$$

$$W_{HT}=M_{HT}\cdot(h_9-h_8)/\eta_{HT} \qquad (4)$$

$$COP=Q_{LT}/(W_{LT}+W_{HT}) \qquad (5)$$

Internal Heat Exchanger

The IHX is installed to increase the COP. The configuration of IHX depends on operating condition [3]. However, the configuration of IHX is not changeable. Therefore, the configuration should be decided by concerning annual operating condition.

The percentage of ambient temperature range (Table 2) is calculated by environment data at Milan area for 8 years that was given by Climate Zone.com. [2]

Figure 3 shows annual COP by heat transfer ratio on IHX. The maximum heat transfer rate (Fig.2 point 7-1 equivalent point 4-5) is set to enthalpy difference between h_1 to h_7 (T_1=-3.3 to 22.0°C). The heat transfer ration with 0% gets highest COP. This result says, IHX is not needed for Middle temperature area such as Milan.

Temperature range [°C]	Number of Month			Total ratio [%]
	-of average temperature	-of maximum temperature	-of minimum temperature	
below 10	4	2	6	20.3
10 to 20	5	5	6	81.3
20 to 30	3	5	0	67.7
30 to 40	0	0	0	0

Table 2. Number of Month at several temperature range

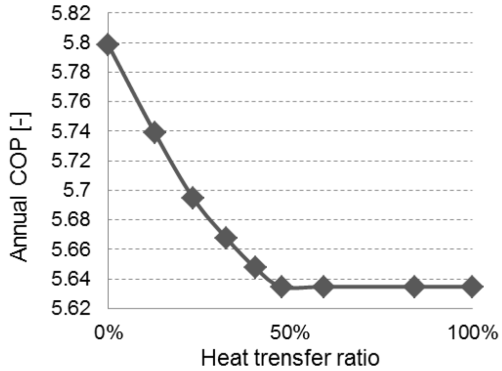

Fig.3 Annual COP vs IHX heat transfer ratio

Pressure Setting. Calculation Result

As a result of calculations, the pressure setting for both refrigeration cycle of high pressure and low pressure that gives highest COP are given in figure 4.

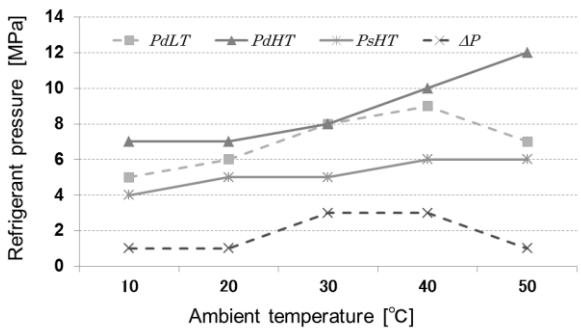

Fig.4 Optimized pressure for cascade system

Ambient temperature from 10°C (T_a=10) to 40°C (T_a=40) the discharge pressure at lower temperature cycle that gives highest COP is increased by ambient temperature. However at ambient temperature 50°C (T_a=50), the highest COP is given by discharge pressure (P_{dLT}) at 7MPa. The reason of this change comes from isentropic efficiency of compressor. The isentropic efficiency of this compressor has peak at compression ratio 2.3 (Pd/Ps) and this isentropic efficiency decreased sharply above compression ratio 2.5.

Smaller pressure difference between Suction pressure of lower temperature cycle (P_{dLT}) and discharge pressure of higher temperature cycle (P_{dHT}) provides smaller compression ratio of compressor. This smaller compression ratio makes effort to improve volumetric efficiency of the compressor. However highest COP at 30°C (T_a=30) and 40°C (T_a=40) are given from pressure difference (ΔP) at 3MPa. Because increased discharge pressure at lower temperature cycle makes effort to exhaust heat by pre-cooler. Thus, heat load on higher temperature cycle is reduced.

The COP of CO_2-CO_2 cascade system at several ambient temperatures are compared with typical refrigeration system that is equipped R404A (Fig.5)

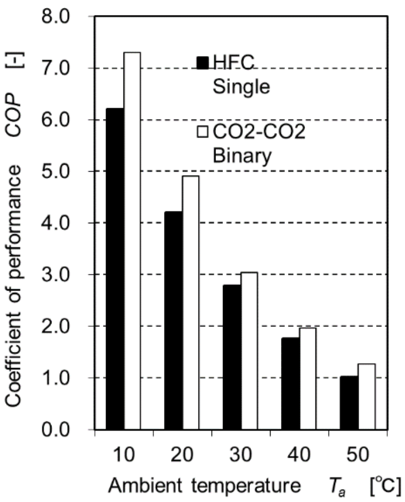

Fig.5 Compared COP with HFC single refrigeration system and CO_2-CO_2 cascade system

CO_2-CO_2 cascade system has better efficiency from 10% to 20% than R404A refrigeration system. The advantage is bigger at lower ambient temperature side. This means annual efficiency of CO_2-CO_2 cascade system is around 20% better than typical R404A refrigeration system, because average ambient temperature is below 20°C at most of city around the world. [2]

The difference of COP at higher ambient temperature (above 30°C) is smaller than lower ambient temperature side. This result is examined based on optimized cascade system at middle ambient temperature area (Tokyo). Therefore, heat transfer ratio of IHX is set to 0%. However higher heat transfer ration is required at higher ambient temperature area. Thus, different configuration of CO_2-CO_2 cascade system is needed for higher ambient temperature area.

Experimental Result

The refrigeration system was installed to test facility (Fig.6) and connected to actual refrigeration showcase that was same as typical convenience store in Japan (Fig.7). The efficiency was measured by input power of compressor and mass flow meter of refrigerant. The test condition is shown in table 3.

Fig. 6 CO_2 Cascade system

Fig.7 Showcases

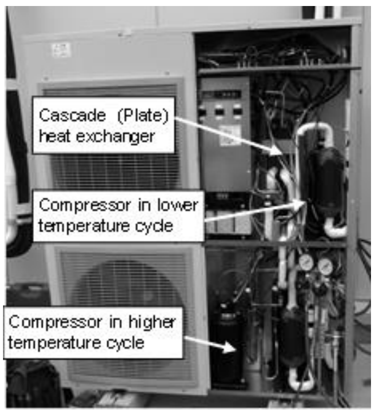

Fig.8 Inside of CO_2-CO_2 cascade system

Figure 8 shows inside of CO_2-CO_2 cascade system which was installed to test facility.

T_a [ºC]	H_a [%RH]	T_{CVS}[ºC]	H_{CVS}[%RH]	T_{sc}[ºC]
2.0	45.0	22.0	35.0	4.0
7.0	50.0	22.0	35.0	4.0
20.0	55.0	25.0	45.0	4.0
28.0	60.0	26.0	50.0	4.0
35.0	65.0	27.0	50.0	4.0
40.0	65.0	27.0	50.0	4.0

Table 3. Test condition for refrigeration system

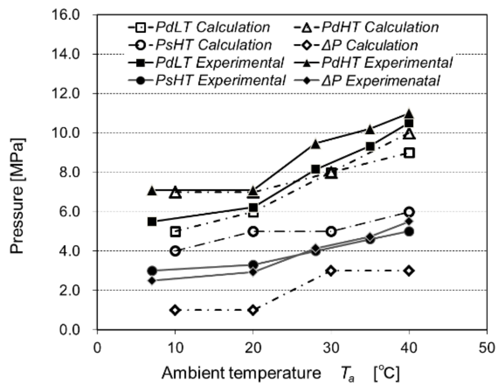

Fig.9 Comparison of optimized pressure between calculation and experimental result of COP on CO2-CO2 binary system

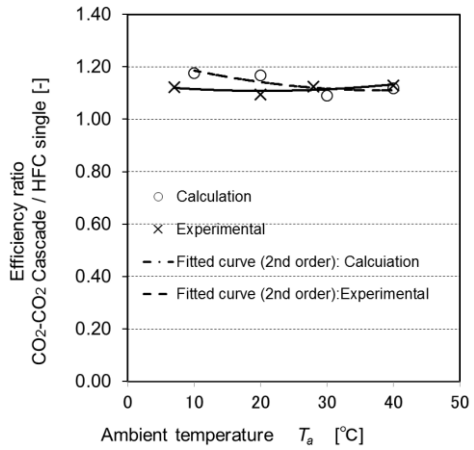

Fig.10 Compared COP between CO2-CO2 refrigeration system and HFC refrigeration system

Optimized pressures are shown in Fig.9. This test result at T_a=below 30ºC is similar with calculation result. However, the result above 30ºC has gap around 1.5MPa. That is assumed this gap comes from pressure drop at gas cooler and pre-cooler because of higher volumetric flow at these condition.

The efficiencies are compared as efficiency ratio between CO_2-CO_2 cascade system and HFC single refrigeration system (fig.9). The calculation result shows better efficiency of CO_2-CO_2 cascade system around 15% to 20%. The test result shows around 15% better efficiency of CO_2-CO_2 cascade system from HFC single refrigeration system.

Conclusions

HFC refrigerant is widely used in refrigeration industry at this moment. The market stock of refrigerant which is charged to refrigeration system is increased because of replacement of CFC and HCFC refrigerant. CO_2 refrigerant is considering as alternative solution to reduce not only global warming gas but also CO_2 emission from energy usage of refrigeration system. Because energy usage of refrigeration system at typical convenience store is around 50% of total energy usage of its store.[4] Therefore reducing energy usage on refrigeration system makes significant effort to reduce total CO2 emission form food store such as convenience store.

CO_2 refrigerant have been not used to higher temperature cycle of cascade system because of its lower critical temperature. However, this report shows the possibility of CO_2-CO_2 cascade system that has better efficiency than existing HFC refrigeration system for retail industry. In addition, optimization of IHX configuration for higher ambient temperature area should be considered to get better efficiency.

Nomenclature

T_a :Ambient temperature [^{o}C]
P_d :Discharge pressure [MPa]
P_s :Suction Pressure [MPa]
h :Enthalpy [kJ/kg]
Q :Rate of heat transfer [W]
W :Power [W]
M :Mass flow rate [kg/hr]
T_n :Refrigerant temperature at point n in T-h diagram [^{o}C]
COP :Coefficient of performance
η :Isentropic efficiency
HT :Higher temperature cycle
LT :Lower temperature cycle
ΔP : Pressure difference between suction on higher cycle and discharge on lower cycle

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