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Z. Zhang
Xi'an Jiaotong University

T. Qu
Xi'an Jiaotong University

Y. Yu
Xi'an Jiaotong University

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THE STUDY OF USING CARBON DIOXIDE AS THE ALTERNATIVE OF R502 IN INDUSTRIAL REFRIGERATION APPLICATIONS

Zaoxiao Zhang Tianfei Qu Yongzhang Yu
School of Chemical Engineering, Xi'an Jiaotong University
Xi'an City, Shaanxi Province, 710049, The People's Republic of China
(Fax: 86-29-3237910, E-mail: zhangzx@xjtu01.xjtu.edu.cn)

ABSTRACT

This paper presents the simulation study and comparison of CO_2 and R502 as refrigerants. At first, as a single stage vapor compression refrigeration cycle's refrigerant, CO_2 can be used in subcritical and transcritical situations. The performances are studied completely. The results show that CO_2 has the same or better performance compared to R502's in certain temperature ranges.

Finally CO_2 and R502's performances in a CO_2 liquefying system are discussed in detail. It is promising to use CO_2 as the alternative of R502 in this case, either in performance or in economics.

NOMENCLATURE

e_{q41}	exergy of the cooling capacity kJ/kg
h	enthalpy kJ/kg
T_{amb}	ambient temperature K
T_e	evaporating temperature K
η_e	exergy efficiency
w	work input for compressor kJ/kg
t_c	condensing temperature ℃
p	pressure MPa

INTRODUCTION

More than ten years ago, the Montreal Protocol, a real landmark decision to our global environmental protection was agreed by the main industrial nations. Since then, an extensive research work has been done in seeking the alternatives of CFCs and HCFCs. By now, substantial progress has been made in this field. The refrigerants R134a, R407c, R404a, etc. were regarded as the main alternatives of R12, R22 and R502 respectively. These new refrigerants have been produced commercially. However, these alternatives do not meet the demands of the long term alternatives. Almost every new alternative has a high greenhouse effect or some other defects. But the natural refrigerants such as CO_2, NH_3, etc. are very excellent in environmental protection[2],[4]. Therefore using natural refrigerants is becoming more and more important once again.

CO_2, as a refrigerant, can be obtained easily from the natural world. It has been used in many refrigeration machines in history. But the low critical temperature limited its applications, especially when freons were produced in 1930s. Because CO_2 has a high environmental protection performance, it has been noticed recently. More and more researches have been carried out by using CO_2 as the alternatives of freons[3],[5]. It is proved that CO_2 supercritical heat rejection results in a large temperature glide and therefore can be used in heat recovery and heat pump applications. Many studies have investigated the benefits and disadvantages of using CO_2. Much has been written about the thermodynamic performance. And the applications are still very little. This paper will focus on the analysis of CO_2 as refrigerant applying in a CO_2 liquefying system of a winery, and replacing the traditional refrigerant for certain industry fields.

THERMODYNAMIC CYCLE PERFORMANCE ANALYSIS

Considering both the Ozone Depletion Potential(ODP) and Global Warming Potential(GWP) completely, the natural fluids like NH_3, CO_2, C_3H_8 and water turn out to be promising alternatives of CFCs and HCFCs. But natural fluids also have some obvious shortcomings. Therefore they can be used only in a limited situations. Due to the ongoing phaseout of R502, some natural fluids are applying in the field of R502 refrigeration. The thermodynamic properties of several refrigerants are presented in Table 1.

Table 1 Selected Properties of Some Refrigerants

Refrigerant	R502	R22	R404a	R717	R290	R744
Natural fluid	No	No	No	No	No	No
ODP$^{(1)}$	0.283	0.055	0	0	0	0
GWP$^{(2)}$	3.74	0.36	0.94	0	negligible	negligible
Critical temperature (℃)	82.2	96.2	72.1	132.4	96.8	31.1
Critical pressure(MPa)	4.075	4.99	3.23	11.27	4.25	7.38
Flammable or explosive	No	No	No	Yes	Yes	No
Toxic/irritating decomposition product	No	No	No	Yes	No	No
Relative volumetric refrig. Capacity$^{(3)}$	0.87	1	1.20	1	0.80	5.22

(1) relative to R11 (2) relative to R11 (3) 0 ℃ refrigerant latent heat

It shows in Table 1 that CO_2 has obvious advantages over others in the respects of environmental protection, safety, cost and volumetric capacity. Two main CO_2 cycles can be realized in the situations of different pressure ratios according to varying environmental conditions because the CO_2 critical temperature is close to the ambient temperature. The cycles are discussed as follows.

Subcritical Cycle

The first kind of CO_2 cycle is the same as the ordinary vapor compression cycle when the condensing temperature is about 10 ℃ below the critical point. This is shown as processes 1-2-3-4-1 in Fig.1. And processes 1-1′-1″-2′-3-4-1 is also a CO_2 refrigeration cycle but using two stage compression with the same refrigeration capacity as processes 1-2-3-4-1.

Transcritical Cycle

At times the ambient temperature is above the CO_2 critical point, the CO_2 compression discharge pressure is higher than its critical pressure. Then CO_2 is cooled under isobaric condition and its temperature drops to the point well below the critical condition. Finally CO_2 flows into the evaporator after passing through the expansion valve. This is the transcritical cycle which is attracting more and more attentions in automobile air-conditioning and heat pump applications[6]. It is proved[1] that the performance of CO_2 transcritical cycle can be improved greatly by recovering the expansion work during expansion process 3″-4″. But the amount of work recovered is largely limited by the expansion machines which demands too high to design the expansion machines. Therefore this limits its applications.

In order to study the feasibility of substituting CO_2 for R502 in industry fields, a single-stage vapor compression cycle with refrigerants CO_2 and R502 is simulated and calculated theoretically. In simulations, the cycle's condensing temperature is t_c=30 ℃. The exergy of the refrigeration capacity is defined as

$$e_{q41}=(h_1-h_3)(T_{amb}/T_e-1) \tag{1}$$

And the exergy efficiency of the cycle is

$$\eta_e=e_{q41}/w \tag{2}$$

The theoretical cycle's simulation results are presented in Fig.2-Fig.6.

Fig.2. shows the changes of the volumetric refrigeration capacity of CO_2 and R502 with evaporating temperatures. And the coefficient of performances (COP) are shown in Fig. 3.

The changes of refrigerant mass flow rate with the evaporating temperature are shown in Fig.4. It indicates that the CO_2 mass flow rate is equal to R502's when the evaporating temperature is about -21 ℃ and the other operating conditions are the same.

The performance of subcooling cycle for CO_2 and R502 are shown in Fig. 5. It can be seen that COP of CO_2 cycle increases rapidly when subcooled, that is about 3% increase in COP per degree of liquid refrigerant subcooled, but that of R502 is only about 1%.

The changes of exergy efficiency for CO_2 and R502 with evaporating temperature are shown in Fig. 6. The exergy efficiency of the two fluids is close to each other in a wide temperature range. And the R502's exergy efficiency is 1.3% higher compared to CO_2's.

It can be concluded from the analysis above that the liquid subcooling affects the CO_2's COP greatly. The COP of CO_2 subcooled cycle is close to that of R502's in a certain temperature range. In this case, CO_2 can be considered to replace R502.

The CO_2 cycle's discharge temperature is high due to its large adiabatic index. The applications of two stage or multistage compression can contribute to decrease the discharge temperature and increase COP obviously as shown in Fig. 7.

THE APPLICATION OF CO_2 REFRIGERATION IN A CO_2 LIQUEFYING SYSTEM

The Introduction Of CO_2 Liquefying System

CO_2 is widely used in food-reservation, beverage industry et al. as by-product of some industry processes. CO_2 is usually recovered and liquefied for storage through a low temperature refrigeration system. The refrigerant is usually R502 or R22 in the system. The liquefying process scheme is shown in Fig. 9. The liquid storage temperature is about -20 ℃ to -30 ℃ and its pressure is about 1.6 MPa. The R502 refrigeration system's evaporating temperature should be kept below -25 ℃. It indicates that the refrigeration system is the key equipment for CO_2 liquefying.

With the phaseout of R502, safe refrigerants need to be introduced into CO_2 liquefying systems. In this case, it is convenient to use CO_2 refrigeration cycle because CO_2 is both refrigerant and product. It will have advantages such as system operating, maintenance and refrigerant charging. The new liquefying scheme is shown in Fig.10. It shows that liquid refrigerant CO_2 is mixed with the CO_2 vapor after expansion to reduce the heat transfer temperature difference.

Performance Analysis Of CO_2 Liquefying System Using CO_2 Refrigeration

Because of the low critical point, it is hard to maintain CO_2's condensing temperature well below the critical. So two improved schemes are chosen. The first is subcritical single stage compression cycle which use the proper cooling medium .The second is transcritical single stage cycle in which CO_2 vapor is subcooled to a temperature below critical point before expansion. The compressor work input for these two schemes is compared in Fig.8.

It can be concluded that the compressor work input of the first scheme equals to that of old R502 liquefying system when evaporating temperature is about -11 ℃. In this case CO_2 replaces R502 completely. Because the CO_2 compressor is very compact, the CO_2 compressor is well made in this pressure ratio range, therefore CO_2 refrigeration can be applied in this field, especially when CO_2 refrigeration performance is excellent in the proper evaporating temperature range. The compressor work input of the second scheme is larger than the other schemes' because of its higher pressure ratio. This can be improved by recovering the expansion work. Yet the application of the transcritical cycle in low temperature refrigeration is limited.

The CO_2 subcritical cycle discussed above is applied in a CO_2 liquefying system of a winery. The CO_2 liquefying load is 270kg/h, and well water is used as cooling medium which is below 15 ℃. The condensing temperature is kept at 20 ℃ The CO_2 liquid refrigerant is subcooled to 15 ℃ in an internal heat exchanger before expansion. A single-stage open type compressor is used and its power input is 5.5kw. The suction pressure is 2.57MPa, and discharge pressure 5.73MPa, and the cycle's COP is 3.6. The performance is approved in 6 months operating test.

CONCLUSIONS

R502 is widely used as an excellent refrigerant in low evaporating temperature applications. R404a is just a temporary alternative of R502. It is feasible to use natural fluid CO_2 as the alternative of R502 in certain industry refrigeration in both technique and economics, especially for commercial refrigeration and gas liquefying applications. CO_2 refrigeration system designed properly can replace R502 system without much difficulty, therefore it should be widely applied.

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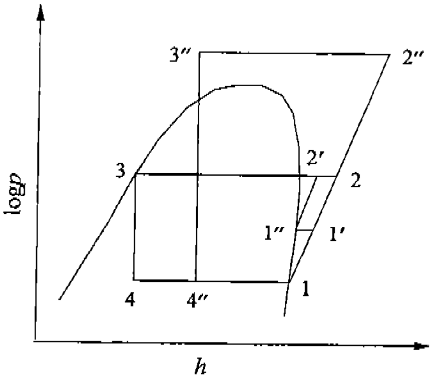


Fig.1 Different R744 refrigeration cycles

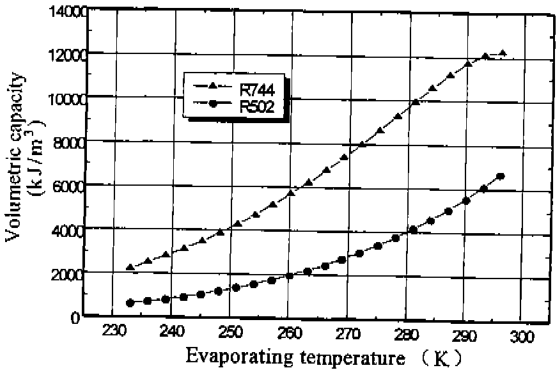


Fig.2 Volumetric capacity of R744 and R502 cycles

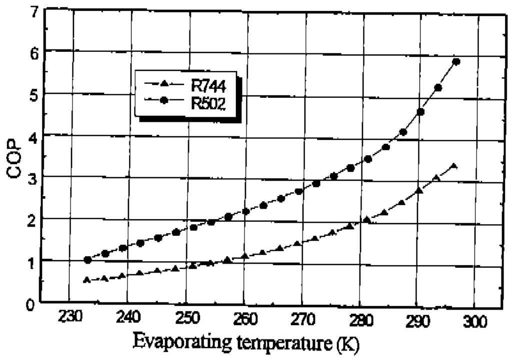


Fig.3 COP of R744 and R502 cycles

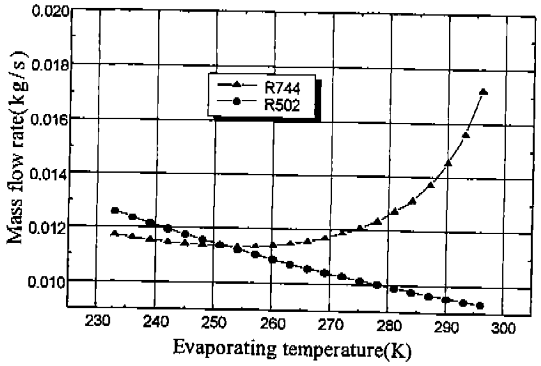


Fig.4 Mass flow rate of varying evaporating temperature

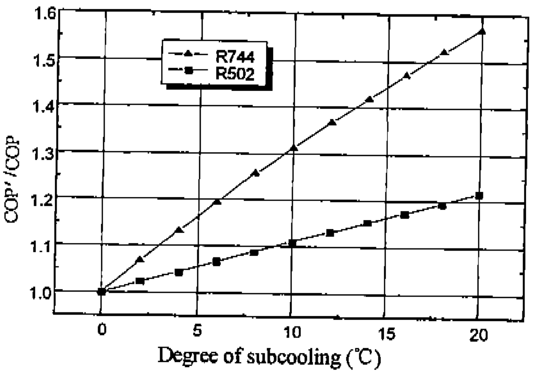


Fig.5 COP changing of subcooled cycles

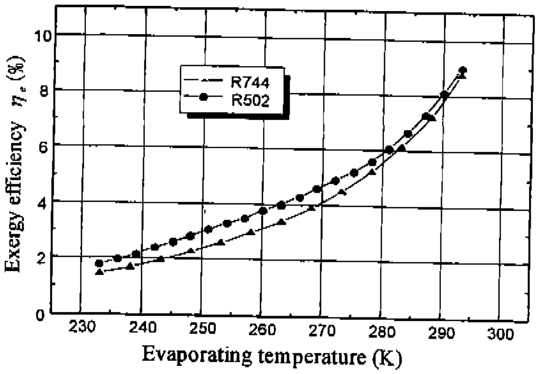


Fig.6 Exergy efficiency of R744 and R502 cycles

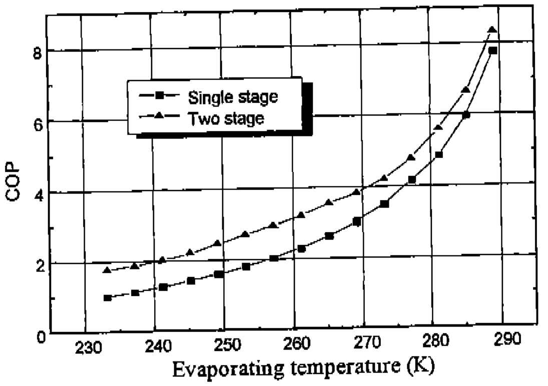


Fig.7 COP of a two-stage compression R744 cycle

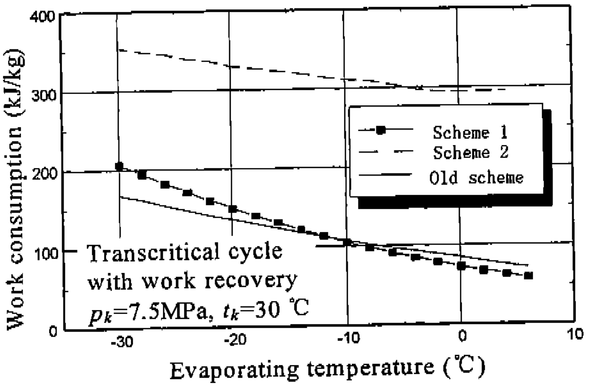
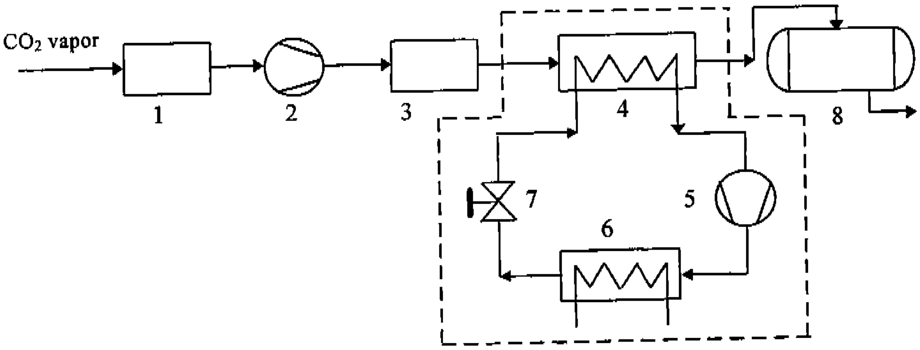
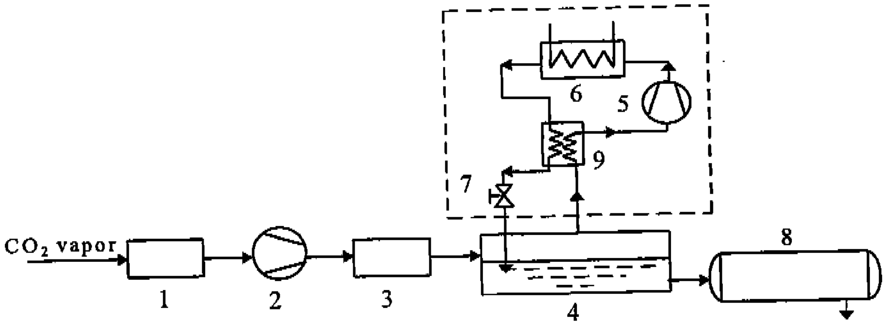


Fig.8 Work consumption with varying evaporating temperature



1. filter 2.CO_2 compressor 3.dryer 4.CO_2 condenser/R502 evaporator
5.R502 compressor 6.R502 condenser 7.expansion valve 8.CO_2 liquid storage tank

Fig.9 Old liquefying scheme with refrigerant R502



1. filter 2.CO_2 compressor 3.dryer 4. condenser/evaporator
5. CO_2 single stage compressor 6.CO_2 condenser 7.expansion valve
8.CO_2 liquid storage tank 9. internal heat exchanger

Fig.10 New liquefying scheme