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Use of R290/R170 in lieu of R22/R23 in Cascade Refrigeration Cycle

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ABSTRACT

R22/R23 have been predominantly used in cascade refrigeration cycles. Even though the ODP of R22 is not as high as CFCs, it still will be phased out following the Montreal Protocol and its amendments because of the chlorine atoms. Hydrocarbons, such as R170 and R290 are natural working fluids. Thermodynamic analysis on the cascade refrigeration cycle adopted R290/R170 under the evaporation temperature from -80℃ to -55℃ and the condensation temperature from 30℃ to 40℃ are processed. System performances, such as the maximum COP, the cascade evaporating temperature, the ratio of refrigerants flow rate between high and low temperature circuits and their variations are compared with that of the R22/R23 under the same conditions. Results show that the performances of the two cascade refrigeration cycle are approximately the same. So the R290/R170 can be used as the substituting refrigerants to R22/R23 in the cascade refrigeration cycle.

1. INTRODUCTION

Cascade system consists of two separate single-stage vapor compression refrigeration cycles. For the high-temperature circuit (HTC) and low-temperature circuit (LTC) the refrigerants of R22 and R23 are typically chosen (Keumnam, 2001). The evaporation temperature of the system can be reached -80℃ to -90℃. As is generally known, R22 will be phased out following the Montreal Protocol and its amendments because of the chlorine atoms, and R23 is a single HFC compound, it has no chlorine content, no ozone depletion potential, but has a high Global Warming Potential (GWP) and a long lifetime. Therefore, for low-temperature refrigeration, development and study of alternative refrigerants that have not only zero ozone depletion potential (ODP) but also low GWP are a pressing need in these days. Natural refrigerants, such as HCs (hydrocarbons), ammonia (R717), carbon dioxide (CO_2) and so on, are the most earth-friendly substances. Not to mention that their ODP is 0, their GWP is also vanishingly small, they are most expected to be alternative refrigerants.

The HTC can normally be charged with R717 (Lee *et al*., 2006), propane (R290) (Niu and Zhang, 2007a), propylene (R1270) (Bhattacharyya *et al*., 2005), ethanol (Bansal and Jain, 2007). R717 is a naturally available refrigerant with few application constraints such as toxicity and flammability. The disadvantage of R1270, R290 and ethanol is their high flammability. The evaporating and condensing pressures of ethanol are also much below the ambient pressure, which lead to air leakage into the system. However, the risk associated with toxic and flammable refrigerants can be

highly minimized by confining the HTC to the plant room area. Several researchers have evaluated the thermodynamic performance of the two-stage cascade refrigeration system uses these refrigerants for the HTC.

CO_2, as a natural working fluid, has many advantages when used in LTC (Niu and Zhang, 2007b, Sergio *et al*., 2004, Christensen and Bertilsen, 2003), but it has some disadvantage such as high pressure and high freezing point (-56.56℃), which prevents it from operating in vapor compression cycles intended for used at lower temperature. For R170 (ethane), the standard boiling point and freezing point are -88.598℃ and -182.8℃ respectively, are lower than CO_2 and closed to R23, can be considered as the refrigerant for LTC (Wang *et al*., 2005, Ma *et al*., 2003).

In the present study, thermodynamic analysis and comparison between R290/R170 and R22/R23 under the same working conditions were carried out to prove the potential of R290/R170 as a promising substitute.

2. THERMOPHYSICAL AND ENVIRONMENTAL CHARACTERISTICS

Table 1 lists some physical and environmental properties of R22, R290, R23 and R170. From table 1, it can be seen that R170 and R23 have quite similar normal boiling point temperature and can get quite similar evaporating temperature. Figure 1 shows the saturation characteristics curves in the temperature range -100℃ to 60℃ of refrigerants list in table 1. The saturation characteristics curves of R170 and R290 are relatively close to R23 and R22 respectively.

Table 1: Physical and environmental characteristics of selected refrigerants

refrigerants	R22	R290	R23	R170
Standard Boiling Point(℃)	-40.76	-42.09	-82.1	-88.8
Freezing Point(℃)	-160	-187.7	-155	-183
Critical Temperature(℃)	96.0	96.70	25.6	32.2
Critical Pressure(MPa)	4.97	4.25	4.83	4.89
ODP	0.05	0	0	0
GWP	1780	About 20	12000	About 20
Atmospheric Lifetime, in years	12		260	

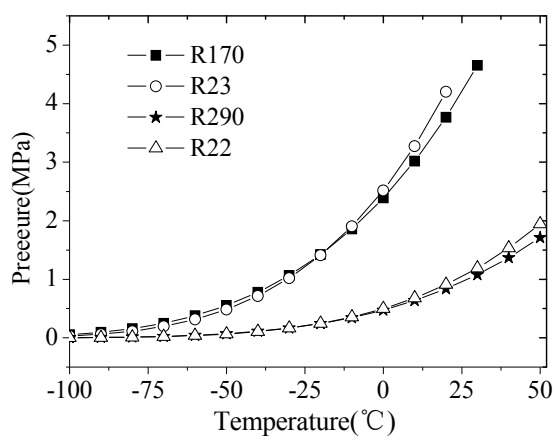

Figure 1: Saturation characteristic of selected refrigerants

3. THERMODYNAMIC ANALYSIS OF A CASCADED REFRIGERATION CYCLE

The cascade system, illustrated in Figure 2, which consists of two separate circuits, each using a refrigerant appropriate for its temperature range. The two circuits are thermally connected by the cascade condenser, which is the condenser of the LTC and the evaporator of the HTC. Figure 3 shows the cascade pressure-enthalpy diagram.

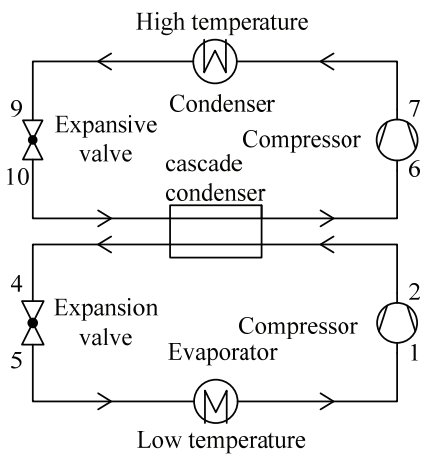

Figure 2: Cascade refrigeration cycle

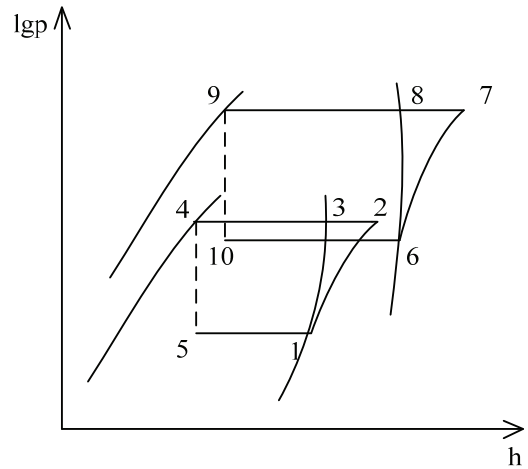

Figure 3: Cascade pressure-enthalpy diagram

The thermodynamic analysis of the two-stage cascade refrigeration system was performed based on the following general assumptions:

(1) adiabatic compression with an isentropic efficiency of 0.8 for both high- and low- temperature compressors,
(2) negligible pressure and heat losses/gains in the pipe networks or system components,
(3) isenthalpic expansion of refrigerants in expansion valves, and
(4) negligible change in kinetic and potential energy.

The COP of the system is defined in Equation (1).

$$COP = \frac{Q_E}{W_H + W_L} \tag{1}$$

Where, the capacity of the evaporator (Q_E), Compressor power consumption for HTC and LTC (W_H and W_L) are respectively given in Equations (2), (3) and (4).

$$Q_E = m_L\left(h_1 - h_5\right) \tag{2}$$

$$W_H = m_H\left(h_7 - h_6\right) \tag{3}$$

$$W_L = m_L\left(h_2 - h_1\right) \tag{4}$$

The heat transfer in the cascade heat exchanger (Q_{CAS}) is defined in Equation (5).

$$Q_{CAS} = m_L\left(h_2 - h_4\right) = m_H\left(h_6 - h_{10}\right) \tag{5}$$

So mass flow ration (m_H/m_L) can be gained from Equation (5), see Equation (6).

$$\frac{m_H}{m_L} = \frac{h_2 - h_4}{h_6 - h_{10}} \tag{6}$$

And the COP can also be defined by substituting Equations (2), (3), (4) and (6) in Equation (1), see Equation (7).

$$COP = \frac{(h_1 - h_5)(h_6 - h_{10})}{(h_2 - h_4)(h_7 - h_6) + (h_2 - h_1)(h_6 - h_{10})} \tag{7}$$

4. RESULTS AND DISCUSSION OF THE ANALYSIS

In both circuits of the R290/R170 and R22/R23 cascade system have the same heat losses of cascade condenser is 0 kW, and isentropic efficiency of compressors in both cycles, η=0.8.

4.1 Effect of Condensing Temperature

Figure 4 and 5 depict the variation of COP, mass flow ratio and mass flow of HTC and LTC for change in condensing temperature (T_C). Condensing temperature was varied from 30℃ to 40℃, while the other temperatures such as temperature difference in cascade condenser, cascade evaporating temperature ($T_{CAS,E}$=-30℃), evaporating temperature (T_E=-75℃ and -60℃ in figure 4, T_E=-80℃ in figure 5), subcooling and superheat were held constant. As expected, a rise in condensing temperature resulted in a decrease in COP for both of R290/R170 and R22/R23 cascade system. Although the COP of R22/R23 for the same given conditions is higher than R290/R170, lower evaporating temperature (see figure 4 T_E=-75℃) has little effect on the two systems. As can be seen from figure 5, the mass ratio increased with a rise in condensing temperature, R290/R170 shows higher mass flow ratio than R22/R23, however the mass flow of R290 and R170 is approximately a half of R22 and R23 respectively.

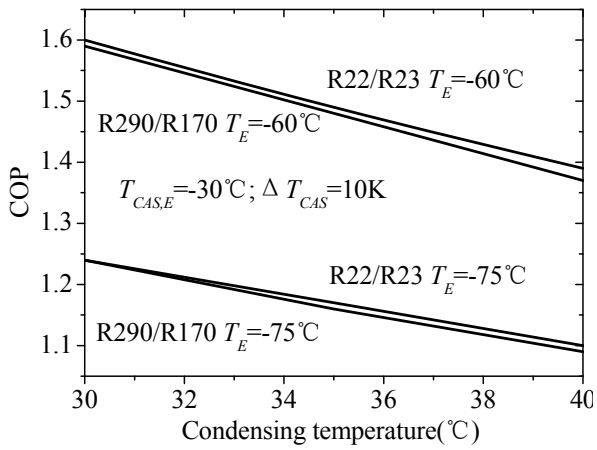

Figure 4: Effect of condensing temperature on system performance

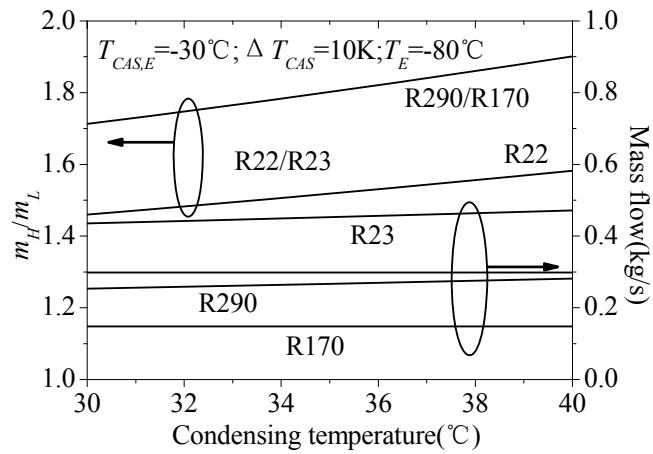

Figure 5: Effect of condensing temperature on mass flow of HTC and LTC and their ratio

4.2 Effect of Evaporating Temperature

The variation of system performance, mass flow of HTC and LTC and their ratio for changing in evaporating temperature in LTC (T_E) was show in figure 6 and 7. Evaporating temperature was varied from -55℃ to -80℃ by keeping condensing temperature (T_C=30℃ and 40℃ in figure 6, T_C=40℃ in figure 7), temperature difference in cascade condenser, cascade evaporating temperature ($T_{CAS,E}$=-35℃), subcooling and superheat constant. The increase in evaporating temperature resulted in much higher performance of the both systems than condensing temperature. Although the performance of R22/R23 for the same given conditions is higher than R290/R170, lower condensing temperature has little effect on the two systems. The mass flow ratio decreased with an increase in evaporating temperature (see figure 7). The other results of mass flow and mass flow ratio are the same with condensing temperature change.

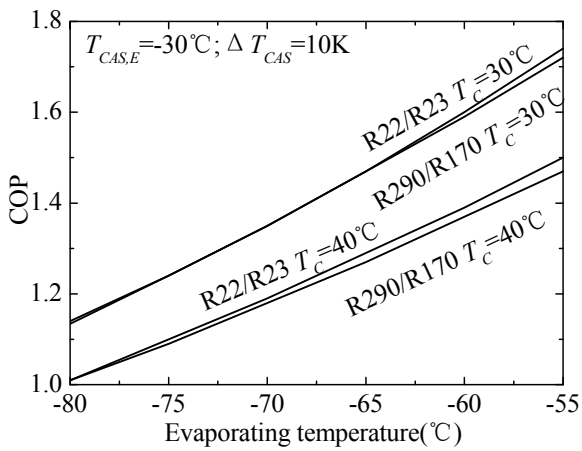

Figure 6: Effect of evaporating temperature on system performance

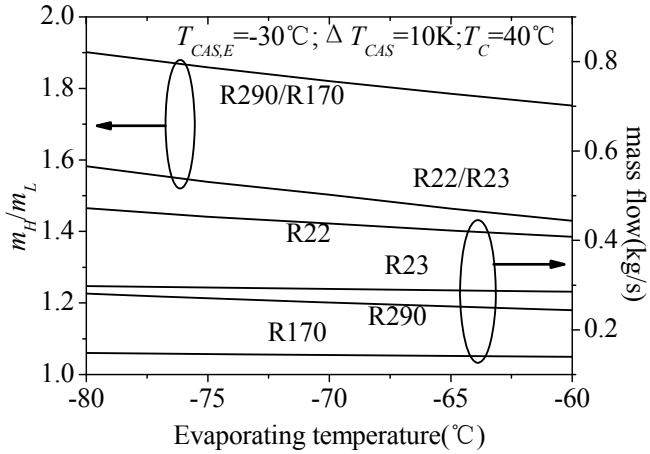

Figure 7: Effect of evaporating temperature on mass flow of HTC and LTC and their ratio

4.3 Effect of Cascade Evaporating Temperature

The variation of cascade evaporating temperature ($T_{CAS,E}$) on both cascade systems (see figure 8 and 9) was studied by keeping the other operating parameters constant. These parameters include condensing temperature (T_C=35℃), evaporating temperature (T_E=-80℃ in figure 8 and T_E=-60℃ in figure 9), temperature difference in cascade condenser (ΔT_{CAS}=10K). The cascade evaporating temperature was varied from -50℃ to -15℃. Figure 8 and 9 shows that there were an optimum cascade evaporating temperatures at which the COP of the both systems were maximum. For the specified operating conditions in figure 8 and 9 the maximum COP (COP_{MAX}) and its corresponding cascade evaporating temperature for R22/R23 and R290/R170 cascade system has listed in table 2. When the cascade evaporating temperature is higher than -31.4℃ and -21.7℃, the COP of R290/R170 cascade system is higher than R22/R23 at the operating conditions of T_E=-80℃ and T_E=-60℃ respectively.

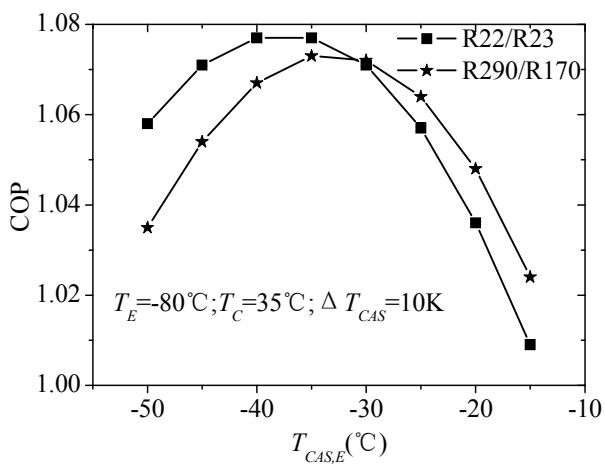

Figure 8: Effect of cascade evaporating temperature on system performance (T_E=-80℃)

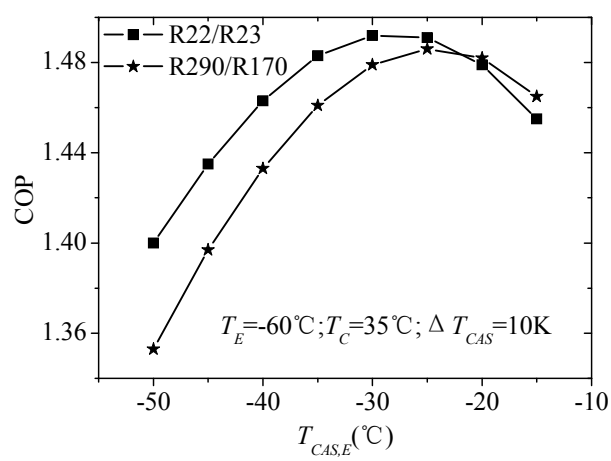

Figure 9: Effect of cascade evaporating temperature on system performance (T_E=-60℃)

Table 2: the COP_{MAX} and its corresponding $T_{CAS,E}$ for R22/R23 and R290/R170 cascade system in figure 8 and 9

Cascade system	Figure 8				Figure 9			
	COP_{MAX}	$T_{CAS,E}$(℃)	COP	$T_{CAS,E}$(℃)	COP_{MAX}	$T_{CAS,E}$(℃)	COP	$T_{CAS,E}$(℃)
R22/R23	1.078	-37.7	1.073	-31.4	1.492	-28.3	1.483	-21.7
R290/R170	1.074	-33.5			1.485	-24.4		

The variation of the COP_{MAX} of the systems for other conditions was also analyzed (see figure 10). The evaporating temperature was varied from -80℃ to -55℃. It was observed that the COP_{MAX} increases with increasing evaporating temperature and decreasing condensing temperature for the two systems. The COP_{MAX} of R22/R23 system is higher than R290/R170 system by about only 1.19% on the condition of condensing temperature and evaporating temperature is 40℃ and -55 ℃ respectively, but showed negligible difference with decreasing condensing temperature and evaporating temperature.

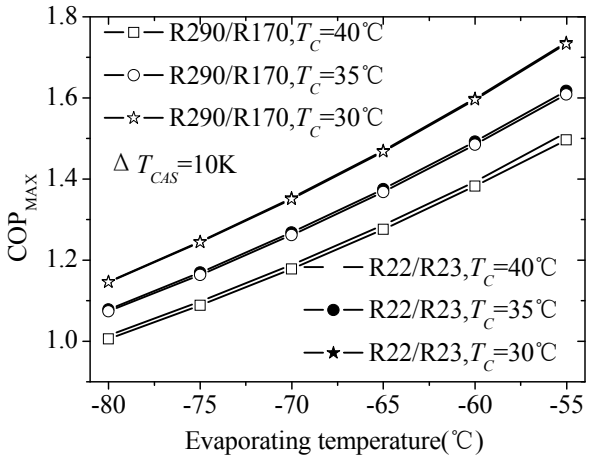

Figure 10: Effect of evaporating temperature on the maximum COP

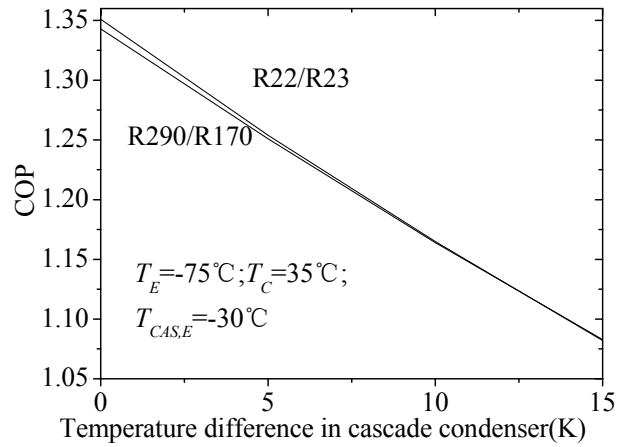

Figure 11: Effect of temperature difference in cascade condenser on system performance

4.4 Effect of Temperature Difference in Cascade Condenser

Figure 11 shows the effect of temperature difference in cascade condenser (ΔT_{CAS}) from 0℃ to 15℃ on system performance, for the operating condition of evaporating temperature (T_E=-75℃), condensing temperature (T_C=35℃) and cascade evaporating temperature ($T_{CAS,E}$=-30℃). It was easily perceived that the COP falls with raising ΔT_{CAS}. The COP of R22/R23 system is higher than R290/R170 by about only 0.6% on the condition of temperature difference in cascade condenser is 0K, and the both system equals in system performance when ΔT_{CAS} is 11.4K.

5. CONCLUSIONS

This paper presents a thermodynamic analysis of R290/R170 and R22/R23 cascade refrigeration systems, operating at evaporating temperature from -80℃ to -55℃, condensing temperature from 30℃ to 40℃, cascade evaporating temperature from -50℃ to -10℃, and temperature difference in cascade condenser from 0K to 15K, as far as the thermophysical and environmental characteristics of R290 and R170 are concerned, the following conclusions are made:

- R290 and R170 are the most earth-friendly substances. Their ODPs are zero and GWPs are about 20.
- The COP and COP_{MAX} of R290/R170 cascade system is very close to R22/R23, especially at lower condensing and evaporating temperature conditions.
- Although the mass flow ratio of R290/R170 cascade refrigeration cycle is higher than R22/R23, the mass flow of R290 and R170 circuits are approximately a half of R22 and R23 respectively due to their higher refrigeration capacity, so the flammability of R290 and R170 will be reduced greatly.
- R290/R170 can be considered as a good substitute for R22/R23 in the cascade refrigeration cycle.

NOMENCLATURE

h	specific enthalpy	(kJ/kg)		**Subscripts**
m	mass flow rate	(kg/s)	C	condenser
Q	rate of heat transfer	(kW)	CAS	cascade heat exchanger
T	temperature	(℃)	E	evaporator

W	power	(kW)	MAX	maximum
Δ	change	(–)	sub	subcooling
η	efficiency	(–)	sup	superheating

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ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China under the project 306004.