BINARY BLEND OF CARBON DIOXIDE AND FLUORO ETHANE AS WORKING FLUID IN TRANSCRITICAL HEAT PUMP SYSTEMS

by

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As an eco-friendly working fluid, carbon dioxide or R744 is expected to substitute for the existing working fluids used in heat pump systems. It is, however, challenged by the much higher heat rejection pressure in transcritical cycle compared with the traditional subcritical cycle using freons. There exists a worldwide tendency to utilize blend refrigerants as alternatives. Therefore, a new binary blend R744/R161 in this research is proposed in order to decrease the heat rejection pressure. Meanwhile, on mixing R744 with R161, the flammability and explosivity of R161 can be suppressed because of the extinguishing effect of R744. A transcritical thermodynamic model is developed, and then the system performances of heat pump using R744/R161 blend are investigated and compared with those of pure R744 system under the same operation conditions. The variations of heat rejection pressure, heating coefficient of performance, unit volumetric heating capacity, discharge temperature of compressor and the mass fraction of R744/R161 are researched. The results show that R744/R161 mixture can reduce the heat rejection pressure of transcritical heat pump system.

Key words: *carbon dioxide, R161, heat pump, blend, transcritical*

Introduction

With the stricter requirement for environmental protection, natural refrigerant, carbon dioxide, or R744, has regained its new life after the first widespread applications in the early 20^{th} century [1]. However, for transcritical heat pump system, it is challenged by the much higher heat rejection pressure than the traditional freon one in subcritical cycle [2]. The theoretical and experimental researches have proved that on mixing suitable second component with carbon dioxide, the heat rejection pressure can be reduced [3-6]. From the perspective of environmental protection, extensive application, or the economic pressures during refrigerant replacement process, certain freons have been investigated as the second components. Dai *et al.* [7] theoretically analyzed the system performance of a heat pump water heater using R744 blends with ten low-GWP (global warming potential $<$ 300) refrigerant including R161, R41, R32, *etc.* The results show that the addition of second freon to R744 can decrease the heat rejec-

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tion pressure, and R744/R41, R744/R32 are recommended because of robust performance and relatively high coefficient of performance (*COP*), respectively. Dai *et al*. [8] also investigated blends of R744 with seven low-GWP working fluids (R161, R32, R134a, *etc.*) used in a transcritical Rankine cycle to recover low-grade heat energy. Blend R744/R161 is recommended for small capacity instruments due to its high efficiency. Nicola *et al.* [9] theoretically investigated the performance of a cascade refrigeration cycle using binary blends of R744 and four HFC (R125, R41, R32, and R23) as the low-temperature working fluid. The results show that the R744-based blends are attractive option at temperature approaching –73 °C.

From the environmental protection point of view, fluoro ethane or R161 is eco-friendly although it belongs to hydrofluorocarbon, which is the main reason why R161 is chosen as the second component in this research. R161 is an low-ODP (ozone depletion potential = 0), low-GWP (12), relatively low-atmospheric-life (0.21 year) gas [10]. However, lower flammability limit of R161 is 3.8% which is slightly larger than that of hydrocarbons. On mixing R161 and R744, this disadvantage can be alleviated due to the extinguishing effect of R744.

In the previous study by our research team, R744/R161 blend is modeled to replace HCHC22 in subcritical heat pump applications [11]. For transcritical heat pump system using R744/R161 blend, Dai *et al.* [7] presented a result under different working operation conditions from this research. Under the given operation, the variations of heat rejection pressure, the heating COP_t, unit volumetric heating capacity, discharge temperature and mass fraction of R744/R161 are investigated in this study to present a comprehensive assessment of R744/R161 used in heat pump system.

Cycle analysis and model

Assumptions for the model

The analysis is carried out on the basis of the following main assumptions. The component of blend is pure working fluid, and the effect of lubricant upon the refrigerant is neglected; the system runs under steady state; the pressure drop and heat loss in heat exchangers and connecting pipes are negligible; the heat exchangers are of counter-flow type, and the second heat transfer fluid is water; the compressor isentropic efficiency is set to 0.70; the pinch point heat transfer temperature difference in both heat exchangers is 7 °C.

Given conditions for the model

According to Chinese National Standards, the typical inlet and outlet temperature of heat source are set to 20 °C and 15 °C for water-loop, while the inlet and outlet temperatures of heat sink are set to 17 °C and 65 °C, respectively [12].

Modelling methodology

The schematic diagram of transcritical heat pump system using R744/R161 blend is shown in fig. 1, and the temperature-entropy (*T-s*) diagram is illustrated in fig. 2. The state points in fig. 2 are corresponding to those in fig. 1, and state point 6 is the bubble point under evaporation pressure. The thin lines in fig. 2 represent the refrigerant subcycle while the dotted lines in fig. 2 represent the heat sink and heat source.

For the tanscritical cycle, the heating COP_t is calculated by:

$$COP_t = \frac{q}{w} = \frac{h_2 - h_3}{h_2 - h_1} \tag{1}$$

where q [kJkg^{-1}] and w [W] are the unit mass heating capacity and the electric power of compressor, respectively, and h [kJkg^{-1}] is the specific enthalpy of refrigerant.

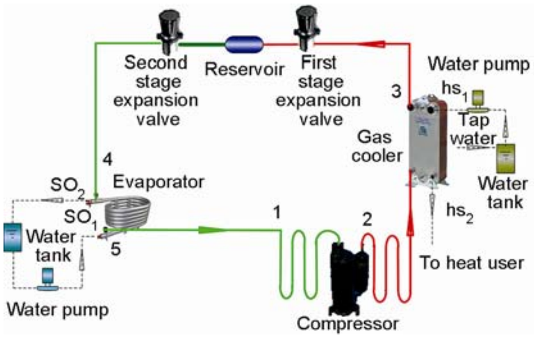

Figure 1. Schematic diagram of transcritical heat pump system

The unit volumetric heat capacity [kJm^{-3}] for transcritical cycle is defined by:

$$q_{\upsilon t} = \frac{q}{\upsilon_1} = \frac{h_2 - h_3}{\upsilon_1} \tag{2}$$

where υ_1 [m^{3}kg^{-1}] is the specific volume at state point 1.

Based on the above descriptions, a simulation code for transcritical R744/R161 blend heat pump systems using engineering equation solver (EES) is developed [13]. The properties of refrigerant are from REFPROP 9.0 which is called by an interface program EES_REFPROP to carry out the necessary property calculations [14, 15].

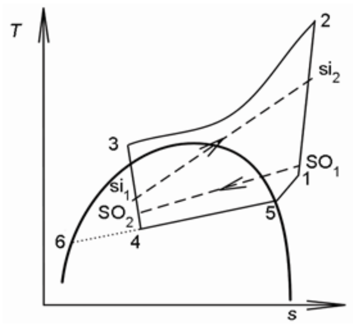

Figure 2. *T*-*s* diagram

Results and discussions

The critical pressure of R744/R161 blend is shown in fig. 3. When R161 is added into R744, the critical pressure is decreased gradually, which may be beneficial to tanscritical system performance with a low mass fraction of R161. The variation of R744/R161 system performances and the mass fraction of R744 are shown in fig. 3. For a given mass fraction of R744/R161, it can be observed that the optimum heating COP_t is increased and then decreased within the R161 mass fraction range of 0.00-0.29. The reason is that the mass specific heating capacity is increased sharply and then slowly, and the compressor power is increased gradually. So the heating COP_t undergoes a raise process at first. When the heat rejection pressure becomes greater than a certain point, the increase in heating capacity cannot compensate that in compressor power, thus resulting a drop in heating COP_t. The system performance shows the same characteristics as that of subcritical cycle when the R161 mass fraction is greater than 0.29. As the optimum COP_{opt} locus shown in fig. 4, the heating COP_t is decreased gradually with the mass fraction of R161. Meanwhile the heat rejection pressure is decreased when the R161 mass fraction is increased. At the mass fraction of 0.98 for R744, the optimum heating COP_t is decreased by 2.39% while the optimum heat rejection pressure is decreased by 5.0% compared to pure R744 system. At the mass fraction of 0.90, 0.85 for R744, the optimum heating COP_t is decreased by 12.54%, 15.32% whereas the optimum heat rejection pressure is decreased by 17.50%, 25.00%. Averagely, within the R161 mass fraction range of 0.00-0.29, the heat rejection pressure can be decreased by 19.17% comparing with the pure R744 system whereas the heating COP_t is decreased by 11.70%.

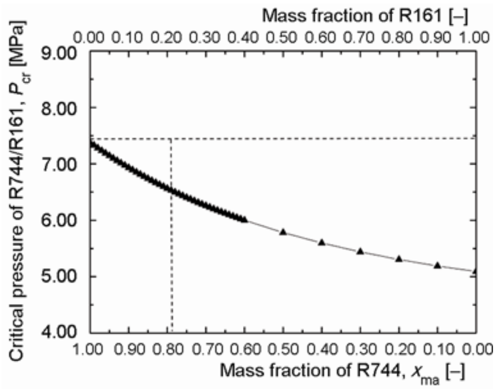

Figure 3. Variation of critical pressure and mass fraction of R744

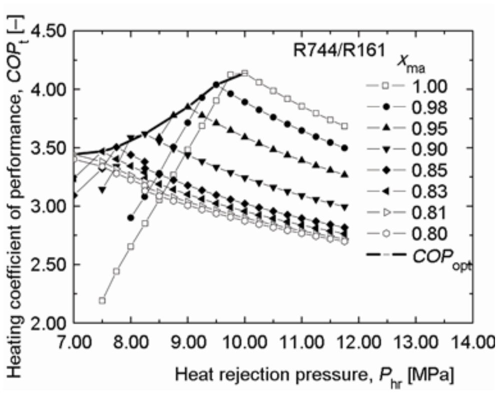

Figure 4. Variation of system performances and mass fraction of R744

The variation of unit volumetric heating capacity of R744/R161 blend and mass fraction of R744 is shown in fig. 5. As the heat rejection pressure is increased, the volumetric heating capacity is increased sharply and then slowly. It tends to decrease for each mass fraction of R744/R161. At mass fraction of 0.85, the optimum volumetric heating capacity is decreased by 38.21% compared to pure R744 system. Within the R161 range of 0.00-0.29, the mean decrease is 29.32%, which means the transcritical system using pure R744 can be more compact.

For discharge temperature of compressor, it can be seen from fig. 6 that the temperature at optimum state is gradually increased with the mass fraction of R161, which is not beneficial to steady operation for heat pump system. For a certain mass fraction of R744/R161, the discharge temperature is gradually increased with the heat rejection pressure because of the increased compression ratio.

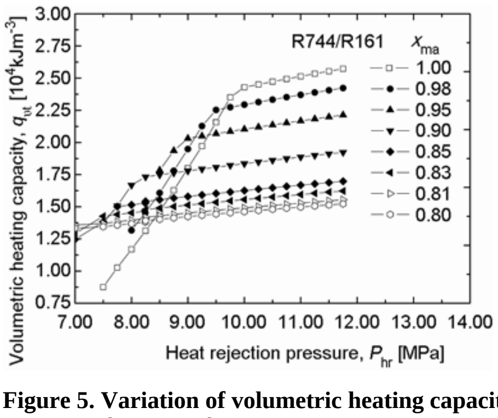

Figure 5. Variation of volumetric heating capacity and mass fraction of R744

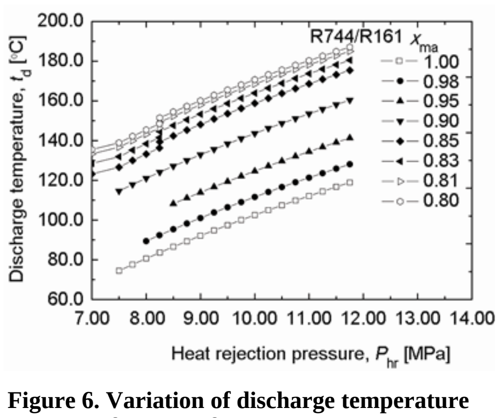

Figure 6. Variation of discharge temperature and mass fraction of R744

Conclusions

Based on the pinch point temperature difference between refrigerant and second heat transfer fluid in evaporator and gas cooler, a thermodynamic simulation code for a transcritical heat pump water heater using blend is developed. According to Chinese National Standards, the given working conditions are set, and then the system performances of R744/R161 blend are investigated and compared with that of pure R744 system. Within the

R161 mass fraction range of 0.00-0.29, the simulation results show that on mixing R161 with R744, the heat rejection pressure can be averagely decreased by 19.17% in comparison with the pure R744 system. Also, the heating COP_t is decreased by 11.70%, and unit volumetric heating capacity is decreased by 29.32%. The discharge temperature of R744/R161 is greater than that of pure R744. Therefore, a comprehensive consideration should be taken when the mass fraction of R744/R161 is determined. The simulation results could provide useful references on the following experimental research of R744/ R161 heat pump system.

Acknowledgments

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