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Performance Research on Heat Pump Using Blends of R744 with Eco-friendly Working Fluid

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Abstract

In order to protect the environment and save energy, new refrigerants with zero ozone depleting potential, low global warming potential have been investigated by more and more researches to substitute HCFCs/ HFCs for eco-friendly working fluid. Among alternatives, non-azeotropic mixtures are becoming the more potential and important candidates. In this research, the transcritical system performances of water heater heat pump using R744/DME (dimethyl ether) binary mixture as working fluid were theoretically analyzed. On mix R744 with DME in a smaller mass fraction, both the optimum heat rejection pressure and the heating coefficient of performance (COP) are decreased. The mean relative reduction rate of optimum heat rejection pressure, however, is greater than that of heating COP. Also, the influence of superheat degree at the inlet of compressor upon the optimum heat rejection pressure and the heating COP is also discussed. The results show that the R744/DME can work as a promising alternative to replace with current widely-used Freons.

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Keywords: Heat pump; R744; Eco-friendly working fluid; Mixture; Transcritical

1. Introduction

The globe is facing a more and more severe environmental crisis, and it is generally considered in the field of heating, ventilating and air conditioning that the application of natural working fluid could be the most complete and ideal solution to replace HCFC/HFC which is widely used in domestic markets [1]. Among natural working fluids,

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R744 (CO_2), R290 (propane), R600a (isobutane) have already come to commercial application stage to work as suitable alternatives in refrigeration and air conditioning systems [2,3]. RE170 (DME or Dimethyl Ether) with good thermal properties and compatibility with common lubricating oil, is currently under research and development level partly because of its flammability [4,5]. Chen et al. [6] tested the flammability of DME/R134a binary and DME/R1234yf/R134a ternary mixture with different volume ratios, and the results show that DME/R134a reaches its critical flammability ratio when the volume ratio of R134a to DME is about 5. The paper also presents the critical suppressive line of DME/R1234yf/R134a.

Due to the high discharge pressure of transcritical heat pump using R744 as working fluid, it is effective to mix R744 with appropriate refrigerant in order to decrease the high side operation pressure, and then achieve lower initial investment and safer operation condition [7]. The current open publications mostly refer to mixture of R744 and hydrocarbon [8-10], however a few literature mainly by Japanese researchers are involved in R744/DME mixture.

Koyama et al. [11] experimentally investigated the system performance of transcritical heat pump using R744/DME binary mixture (mass fraction: 90/10) and compared with pure R744. The results show that the discharge pressure of R744/DME is decreased by about 2.0 MPa for both heating and cooling modes while the system COP remain unchanged, but the discharge temperature tends to increase for R744/DME system. Onaka et al. [12] theoretically analyzed the system performance of transcritical heat pump cycle for high R744 mass fraction in mixtures and subcritical one for low R744 mass fraction. The results show that there exists an optimum COP at a certain pressure for each mixture and the heat rejection pressure decreases with increase of DME fraction. Also the COPs of the R744/DME and pure DME are higher than that of pure R744. Bi et al. [13] theoretically analyzed the transcritical refrigeration performance of R744/DME mixture without consideration of the secondary heat transfer fluid, and the results show that when the mass fraction of DME is below 10, the direct refrigerant charge could be available. The optimum heat rejection pressure of R744/DME binary mixture is decreased by 3.0 MPa compared to that of pure R744. Our research team [14] has investigated the system performance of subcritical heat pump using R744/DME as working fluid, and come to a conclusion that under the conventional condensation pressure an optimal R744/DME mass fraction is 28/72 for water heater application, 3/97 for space heating application.

Afroz et al. [15] tested the heat transfer coefficients and pressure drops of R744/DME (mass fraction: 39/61, 21/79) during horizontal smooth in-tube condensation, and the heat transfer coefficient and pressure drop is increased with the DME fraction in the mixture. Onaka et al. [16] carried out the experimental research to compare the in-tube evaporation heat transfer coefficient of R744/DME (mass fraction: 10/90, 25/75) with pure R744. The results show that the heat transfer coefficient of R744/DME is decreased when DME is added into R744. Zhang et al. [17] numerically investigated the flow and heat transfer performance of R744/DME (mass fraction of DME: 21-39) mixture in a horizontal tube at 8.0 MPa, and the optimum mass fraction of R744/DME is 70/30 at which the heat transfer performance can be improved. Liu et al. [18] numerically simulated the flow and heat transfer characteristics of R744/DME, and the results show that the mixtures have better heat transfer performances than that of pure R744 under the given condition.

Due to its good thermophysical properties, eco-friendly characteristics, zero ozone depleting potential (ODP) and very low global warming potential (GWP), R744/DME binary mixture is currently considered as one of the promising alternatives [19]. In this research, the system performance of transcritical heat pump using R744/DME binary mixture is theoretically assessed based on certain Chinese national standards in order to investigate the comprehensive characteristics of R744/DME mixture, and also to decrease the high heat rejection pressure when pure R744 works as the working fluid.

2. Method

A simulation code using Engineering Equation Solver (EES) [20] was developed for transcritical R744/DME heat pump water heater. In order to carry out the necessary property calculations, in the code, REFPROP 9.1 [21] which provides the most accurate thermodynamic and transport property data was called by the property subroutines that linked with an interface program EES_REFPROP [22].

The system consists of a compressor, a gas cooler, an expansion valve and an evaporator as shown in Figure 1. For the sake of simplification, the following assumptions were made: the system operates at a steady state for each working condition; pressure drops in all the heat exchangers including gas cooler and evaporator, and connecting pipes were neglected; evaporation process and heat rejection process for mixtures are isobaric ones; heat transfer between the system and the ambient are not taken into account; the pinch point temperature difference for both gas cooler and evaporator are designed as a constant value of 7℃.

The heat sink and heat source temperatures are determined according to Chinese National Standard GB/T23137-2008 [23]. The heat sink inlet and outlet temperatures are 17℃ and 65℃while the inlet and outlet temperatures of heat source are 20℃and 15℃. The mass fraction of DME in transcritical system is partly determined by the critical pressure of R744/DME binary mixture shown in Figure 2. It can be seen that when DME is added into R744, the critical pressure, P_{cr}, is increased firstly and then at the DME mass fraction of about 24%, the critical pressure begins to be constantly decreased. On the one hand, the optimum heat rejection pressure is inclined to decrease on mix DME with R744 according to the published literature, but on the other hand, the critical pressures increased at first. Therefore, for transcritical cycle, the maximum and optimum mass fraction of DME can be expected to be a smaller one, which is exactly the point of this research. The critical temperature, t_{cr}, is increased with the mass fraction of DME as illustrated in Figure 2.

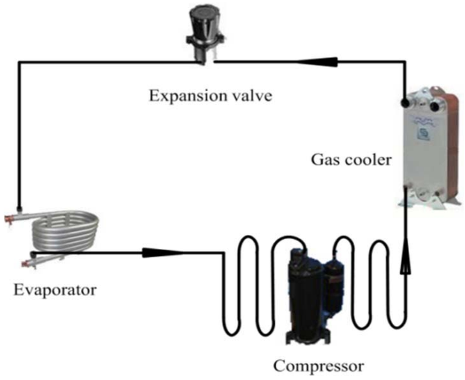

Fig. 1. Schematic diagram of R744/DME based heating system

The heating $\mathrm{COP_h}$ of the system is defined as

$$\mathrm{COP_h} = \frac{q_{\mathrm{h}}}{w} \tag{1}$$

where q_{h}(kJ/kg) is the unit mass heat capacity, and w (kJ/kg) is the compressor power.

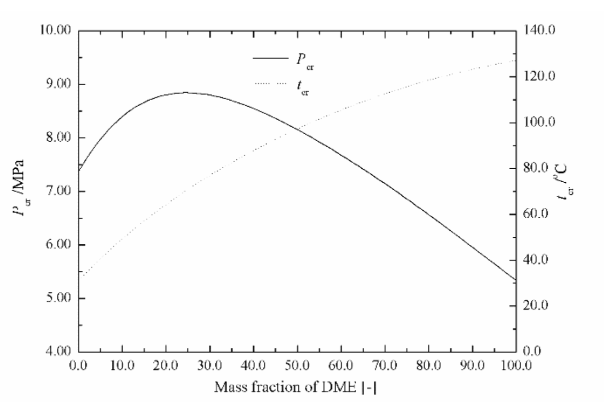

Fig. 2. The critical pressure and temperature of R744/DME binary mixture

3. Result and discussion

The system performance of R744/DME binary mixtures in a transcritical cycle is shown in Figure 3. It should be pointed that the degree of superheat at the inlet of compressor is 10℃ in consideration of practical operation condition. The mass fraction interval of DME is set to 1% in order to investigate the interrelation of optimum heat rejection and critical pressure. As the heat rejection pressure is increased, the heating COP$_h$ is increased firstly and then decreased for pure R744. Since COP$_h$ is defined as the ratio of heating capacity to compressor power, the counterweight of these two parameters results in the curve of COP$_h$. When the mass fraction of DME is less than or equal to 6%, the same system performance is inherited. Furthermore, once R744 is mixed with DME and then works in a transcritical cycle, the optimum heat rejection pressure which refers to the maximum heating COP$_h$ tends to decrease. When the mass fraction of DME is greater than 6%, the COP$_h$ constantly drops with the increase of the heat rejection pressure which is same as the conventional refrigeration system. The typical points, mass fraction of 7%, 24% at which the critical pressure of mixture tends to decline, 50%and 66% below which the critical pressure of mixture is lower than that of pure R744 is illustrated in Figure 3, and the system characteristics is same as the conventional one.

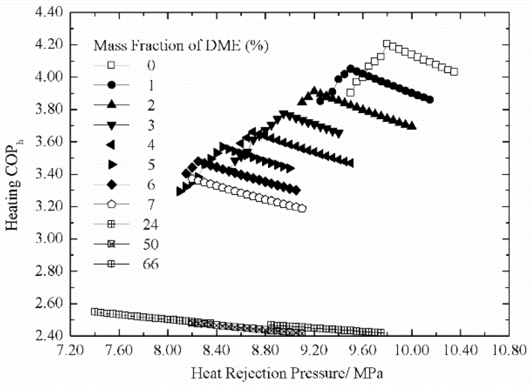

Fig. 3. The system performance of R744/DME binary mixtures in a transcritical cycle

The variation of heat rejection pressure, heating COP$_h$ and mass fraction of DME is illustrated in Figure 4. For pure R744 system, the optimum heat rejection pressure is 9.80 while the maximum heating COP$_h$ is 4.25. When the mass fraction of DME is 6%, the optimum heat rejection pressure is decreased to 8.25 while the maximum heating COP$_h$ is also decreased to 3.48. For relative reduction rate, the optimum heat rejection is 15.82%, and the heating COP$_h$ is 17.24%. So, when the pressure is taken as the main consideration point and at the same time, decreased heating COP$_h$ is acceptable, R744/DME mixture with small mass fraction of DME could be a potential solution.

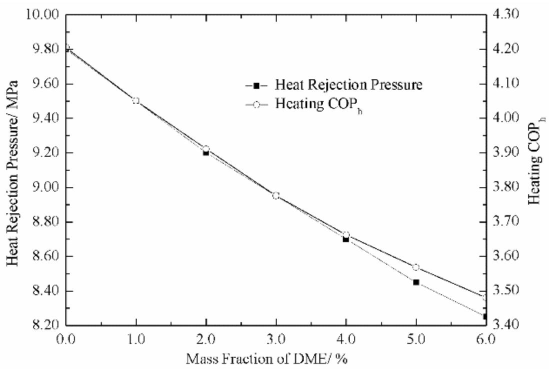

Fig. 4. The variation of optimum heat rejection pressure, heating COP$_h$ and mass fraction of DME

The variation of optimum heat rejection pressure, heating COP_h and superheat degree at the inlet of compressor is given in Figure 5. It is clear that the superheat degree has something to do with the optimum heat rejection pressure and heating COP_h. When the superheat degree is given as 0℃, the maximum mass fraction of DME will be 7%, which is a little greater than that of superheat degree of 10℃. The optimum heat rejection pressure is decreased from 11.00 MPa to 8.5MPa while heating COP_h is decreased from 4.997 to 4.202 with a relative reduce rate of 15.91%. However, the relative reduce rate of optimum heat rejection pressure, 22.73%, is greater. For different superheat degree, the mean relative reduce rate of optimum heat rejection pressure is 19.27% which is also greater than that of heating COP_h, 16.58%. It can be concluded that at certain superheat degree, the drop of optimum heat rejection pressure can compensate the loss of heating COP_h.

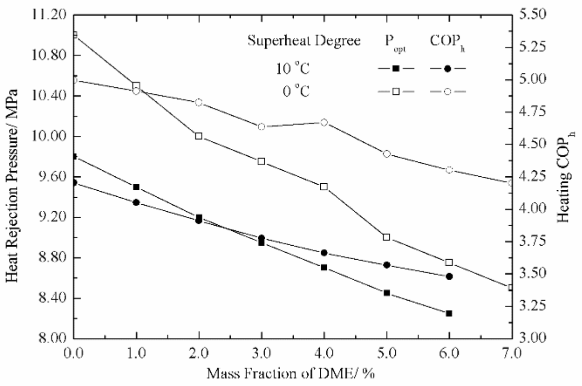

Fig. 5. The variation of optimum heat rejection pressure, heating COP_h and superheat degree

4. Conclusion

A simulation code of transcritical heat pump water heater using R744/DME binary mixture as the working fluid is developed based on the controlled pinch point heat temperature difference in heat exchanger. Through the change of mass fraction of DME, heat rejection pressure and superheat degree at the inlet of compressor, the system performances of the transcritical heat pump were assessed in this research. Two key operation parameters, optimum heat rejection pressure and heating COP_h, are analyzed. The results show that on addition DME to R744, for the DME mass fraction range of 0-6%, the optimum heat rejection pressure is obviously decreased from 9.80 MPa to 8.25 MPa with a mean reduce rate of 19.27% when the superheat degree of 10 °C is given. The heating COP_h is also decreased from 4.205 to 3.48. Comprehensively, the mean reduce rate of optimum heat rejection is greater than that of heating COP_h. Therefore, in practical applications, R744/DME with its reduced pressure characteristics, could work as a promising alternative combined with some measures taken to improve system performance.

Acknowledgements

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