PERFORMANCE EVALUATION OF HEAT PUMP SYSTEM USING R744/R161 MIXTURE REFRIGERANT

by

Xian-Ping ZHANG [a,b], Xin-Li WEI [b], Xiao-Wei FAN [c*], Fu-Jun JU [c], and Lei YANG [c]

[a] School of Civil Engineering, Henan Institute of Engineering, Zhengzhou, Henan, China
[b] School of Chemical Engineering and Energy, Zhengzhou University, Zhengzhou, Henan, China
[c] School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou, Henan, China

Original scientific paper
DOI: 10.2298/TSCI1405673Z

As an efficient and energy conservation technology, heat pumps working with R22, which are scheduled to be phased out by Montreal Protocol, are widely used in China at present. The global deteriorating ecology environment would accelerate the phase-out time of R22 in developing countries. Therefore, as a matter of urgency, an eco-friendly substitute should be investigated in order to replace R22. Under this context, and with a consideration of the environmental protection, R744/R161 mixture refrigerant is proposed. R744/R161 mixture refrigerant's condensation pressure is reduced and its flammability and explosivity are suppressed. A thermodynamic model is developed, and under the given working conditions, the performances of subcritical heat pump system using R744/R161 mixture of variable mass fraction are discussed and compared with those of the R22 system. The optimal mass fraction of R744/R161 is given, which corresponds to a maximal heating coefficient of performance. The simulation results show that R744/R161 mixture can work as a competitive alternative to R22 in heat pump system.

Key words: *CO_2 (R744), R161, heat pump, environmental conservation, mixture*

Introduction

Due to its excellent characteristics in efficiency and energy conservation, heat pump is widely used [1]. In china R22 (HCFC22) still works as the dominantly-used refrigerant of heat pump systems. The high-GWP (global warming potential) gases, HFC such as R134a, R410A, and R407C could be the relatively short-term alternatives since the utilization of a large majority of such substances may destroy the environment [2]. Therefore, the eco-friendly refrigerant with low GWP is a potential substitute with the consideration of environmental protection. R161 (HFC161) has an ozone depletion potential (ODP) of zero, an atmospheric life of 0.21 year which is very lower than that of R22, and a GWP of 12 which is even smaller than natural refrigerants hydrocarbons [3]. However, its application as a pure working fluid is challenged by its flammability with LFL (lower flammability limit) of 3.8% which is slightly larger than hydrocarbons. Meanwhile, R744 has been validated to be a successful refrigerant in transcritical heat pump except for its high heat rejection pressure [4, 5]. In the mixture of R161 and R744, R744 plays an antiflaming role in reducing the flammability and explosivity, and in the same time, the heat rejection pressure can be decreased compared with pure R744 in a transcritical cycle. Hence, R744/R161 binary mixture is proposed as a potential alternative to R22.

* Corresponding author; e-mail: xwfan@zut.edu.cn

In fact, R161-based mixtures have already drawn the researchers' attention in China. Chen *et al.* conducted theoretical and experimental investigations on a series of R161-based mixture to replace R22 and other HFC refrigerants [6-8]. Xie *et al.* studied the functions of flame retardants, R22, R134a, and R125 on R161 and the critical ratios are obtained [9]. Due to the flammability of R161, only a few studies can be obtained from other countries outside China. For R744/HFC mixture, the published literatures refer to cascade system. Nicola *et al.* simulated the behavior of a cascade cycle using mixtures of R744 and HFC (R744/R125, R744/R41, R744/R32, R744/R23) as the low-temperature-circuit working fluids and the results show that the R744-based mixture can be an attractive alternative [10]. However, currently, no published literature on R744/R161 mixture has been involved to heat pump system.

Based on the previous studies by our research team, R744/R161 mixture is proposed to replace R22 in heat pump applications [11]. The heating coefficient of performance (*COP*)--based system are investigated in a subcritical cycle, and compared with that of R22. The optimum mass fraction is obtained under the given working conditions.

Cycle analysis and simulation

Modelling of the cycle

The schematic diagram of heat pump system using R744/R161 mixture as refrigerant in a subcritical cycle is illustrated in fig. 1, and the corresponding temperature-entropy (*T*-*s*) diagram is showed in fig. 2. The dotted lines in fig. 2 represent the second heat transfer fluids.

The heating *COP* of the subcritical heat pump system is defined as:

$$COP_{\mathrm{h}} = \frac{q_{\mathrm{h}}}{w_{\mathrm{c}}} = \frac{h_2 - h_3}{h_2 - h_1} \tag{1}$$

where q_{h} [kJkg^{-1}] is the unit mass heating capacity, w_{c} [W] – the compressor electric power, and h [kJkg^{-1}] – the specific enthalpy.

The unit volumetric heat capacity $q_{\upsilon\mathrm{h}}$ [kJm^{-3}] is given by:

$$q_{\upsilon\mathrm{h}} = \frac{q_{\mathrm{h}}}{\upsilon_1} = \frac{h_2 - h_3}{\upsilon_1} \tag{2}$$

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

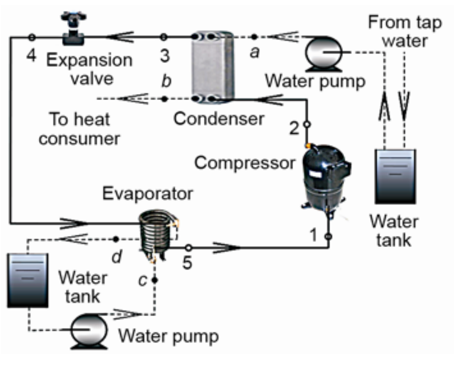

Figure 1. Schematic diagram of subcritical heat pump system

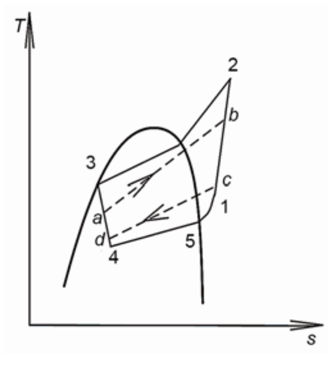

Figure 2. *T–s* diagram

Simulation conditions

In order to simplify the simulations, the following assumptions have been made: the system works at steady-state; both R744 and R161 are all considered as pure fluids, and the lubricant effect on the properties of pure or mixture refrigerants of various mass fractions is negligible; pressure drops in heat exchangers and connecting pipes, and heat transfer between the system and the ambient have been neglected; the compressor isentropic efficiency is 0.70; the pinch point temperature in both heat exchangers is 7 °C.

Based on the above hypothesis, a simulation code for subcritical R744/R161 heat pump systems using the engineering equation solver (EES) and the reference fluid thermodynamic and transfer properties (REFPROP 9.0) was developed [12, 13].

Results and discussions

The inlet and outlet temperature of heat sources are set to 20 °C and 15 °C for water-loop, 15 °C and 10 °C for ground-water, 10 °C and 5 °C for ground-loop, while the inlet and outlet temperatures of heat sink are set to 15 °C and 55 °C according to the Chinese National Standards [14].

The variation of system performances of heat pump using R744/R161 and the mass fraction of R744 are shown in fig. 3. For visual comparison, the COP_h of R22 are also graphed in horizontal lines. It should be noted that the mass fractions of R744 must be lower than 90.0%, above which the blend R744/R161 will have a low critical temperature under the given working conditions. In order to obtain the more accurate result, the calculation internal is designed to be thick next to the turning points. It can be seen that the system performances for different kinds of heat sources show the similar trends. When the mass fraction of R744 is increased, the heating COP_h increases firstly and then decreases. The reason can be observed from fig. 4 when water-loop is taken as an example. The mass heating capacity increases with mass fraction of R744 in the beginning while the compressor electric power slightly decreases, and so COP_h tends to increase at first. Then, the compressor electric power slightly increases while mass heating capacity shows a more flat increase, resulting in a drop for COP_h. After the optimum point, the mass heating capacity gradually decreases with a more greater gradient, and meanwhile the compressor electric power gently decreases. Therefore, COP_h continually drops but increases a little when the mass fraction is within the range of 85~90%. There exists an optimum mass fraction of 20/80 for R744/R161, and the parameters of heat sources have little influence upon the mass fraction. For different kinds of heat sources, the COP_h of mixture are all greater than those of R22 by 15.04%, 13.98%, 13.00%, and the mean rate-of-increase is 14.01%.

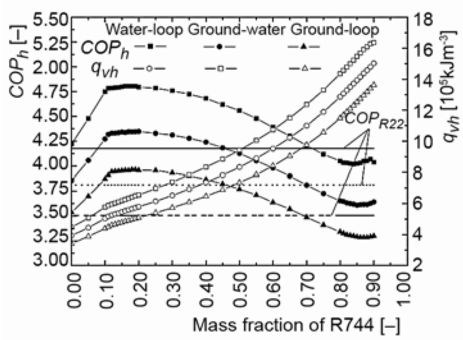

Figure 3. Variation of system performances and mass fraction of R744

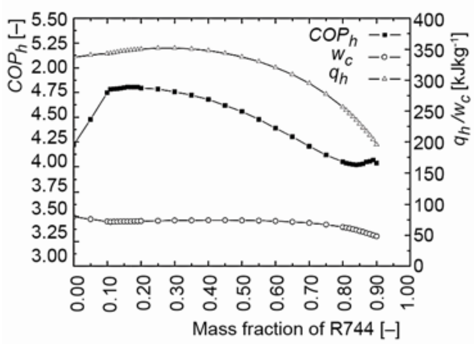

Figure 4. Variation of COP_h, w_c, q_h, and mass fraction of R744

Compared with R22 system, the volumetric heating capacities of R744/R161 for three kinds of heat sources are increased by 32.26%, 33.86%, and 32.54%, with a mean of 32.89%. It means that the system using R744/R161 mixture can be more compact.

The variation of condensation pressure, P_c, of mixture of R744/R161 and mass fraction of R744 is shown in fig. 5 for water-loop heat source. The condensation pressure of R744/R161 at optimum mass fraction is 2.452 MPa, which is a little lager than that of R22 and considerably lower than that of pure R744. Therefore, heat pump using mixture R744/R161 can work under the conventional pressure without redesigning the components and fearing for the operation safety.

When the mass fraction of R744 is increased, the discharge temperature, t_d, of the mixture R744/R161 increases firstly and then decreases, which is shown in fig. 6. At the optimum mass fraction, the t_d of R744/R161 is lower than that of R22. It is beneficial to steady operation for heat pump system.

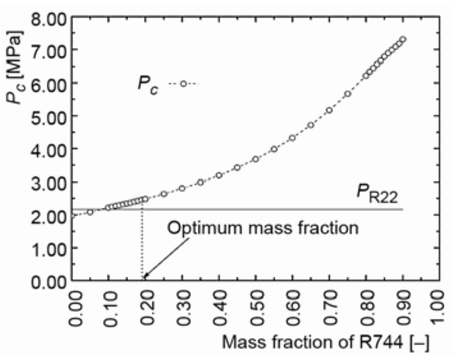

Figure 5. Variation of condensation pressure and mass fraction of R744

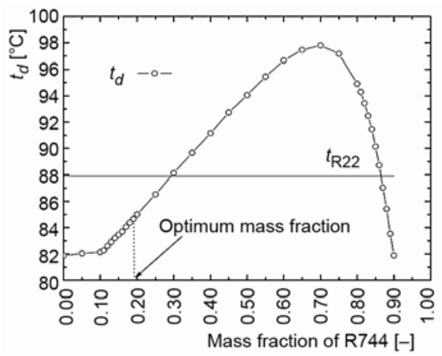

Figure 6. Variation of discharge temperature and mass fraction of R744

Conclusions

A simulation code for the subcritical heat pump is developed on the basis of the heat transfer pinch point during evaporation and condensation processes, then under the given working conditions (according to the Chinese National Standards), the system performances of R744/R161 mixture are investigated and compared with R22 system for different heat sources. The simulation results show that R744/R161 mixture is more superior to R22 in the subcritical heat pump. There exists an optimum mass fraction of 80/20 for R744/R161, at which the heating COP_h is averagely enhanced by 14.01% comparison to R22 system. In addition, the unit volumetric heating capacity is obviously increased by 32.89%. The discharge temperature of R744/R161 is lower than that of R22 while the condensation pressure is slightly larger than that of R22.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51176207), Henan Province Project for the Excellent Youth Scholars of Higher Education of China (No. 2012GGJS-185), Research Funds of Zhengzhou Science and Technology Bureau (No. 121PPTGG357-7), Doctoral Scientific Fund Project of Henan Institute of Engineering (No. D2012006) and the Research Funds of Key Laboratory of Heating and Air Conditioning, the Education Department of Henan Province (No. 2013HAC104).

References

[1] Blarke, M. B., Lund H., Large-Scale Heat Pumps in Sustainable Energy, Systems System and Project Perspectives, *Thermal Science*, *11* (2007), 3, pp. 143-152
[2] Yang, Z., Wu, X., Retrofits and Options for the Alternatives to HCFC-22, *Energy*, *59* (2013), Sept., pp. 1-21
[3] Calm, J. M., Hourahan, G. C., Refrigerant Data Update, *Heating/Piping/Air Conditioning Engineering*, *79* (2007), 1, pp. 50-64
[4] Kim, M. H., *et al*., Fundamental Process and System Design Issues in CO_2 Vapor Compression Systems, *Progress in Energy and Combustion Science*, *30* (2004), 2, pp. 119-174
[5] Sarkar, J., *et al*., Experimental Investigation of Transcritical CO_2 Heat Pump for Simultaneous Water Cooling and Heating, *Thermal Science*, *14* (2010), 1, pp. 57-64
[6] Wang, Q., *et al*., Experimental Studies on a Mixture of HFC-32/125/161 as an Alternative Refrigerant to HCFC-22 in the Presence of Polyol Ester, *Fluid Phase Equilibria, 293* (2010), 1, pp. 110-116
[7] Xuan, Y. M., Chen, G. M., Experimental Study on HFC-161 Mixture as an Alternative Refrigerant to R502, *International Journal of Refrigeration, 28* (2005), 3, pp. 436-441
[8] Han, X. H., *et al*., Cycle Performances of the Mixture HFC-161 + HFC-134a as the Substitution of HFC-134a in Automotive Air Conditioning Systems, *International Journal of Refrigeration, 36* (2013), 3, pp. 913-920
[9] Xie, P. Z., Guo, Z. K., Experimental Research on Combustion Inhibition of R161 (in Chinese), *Refrigeration and Air-Conditioning*, *13* (2013), 3, pp. 51-56, 40
[10] Nicola, G. D., *et al*., Blends of Carbon Dioxide and HFCs as Working Fluids for the Low-Temperature Circuit in Cascade Refrigerating System, *International Journal of Refrigeration, 28* (2005), 2, pp. 130-140
[11] Zhang, X. P., *et al*., Theoretical and Experimental Studies on Optimum Heat Rejection Pressure for a CO_2 Heat Pump System, *Applied Thermal Engineering*, *30* (2010), 16, pp. 2537-2544
[12] Klein, S. A., *Engineering Equation Solver*, Academic Commercial Version 9.433, #2313, 2012
[13] Lemmon, E. W., *et al*., Reference Fluid Thermodynamic and Transport Properties (REFPROP), *NIST Standard Reference Database 23*, Version 9.0, 2013
[14] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China (in Chinese), *Heat Pump Water Heater for Household and Similar Application*, GB/T23137-2008

Paper submitted: October 13, 2013
Paper revised: March 18, 2014
Paper accepted: July 13, 2014