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Experimental investigation on a heat pump water heater using R744/R290 mixture for domestic hot water

Fujun Ju[a,b], Xiaowei Fan[b], Yaping Chen[a,*], Tuanjie Wang[b], Xiangyang Tang[b], Amin Kuang[b], Shengfei Ma[b]

[a] *Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, China*
[b] *School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou 450007, China*

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ABSTRACT

The natural eco-friendly mixture of R744/R290 was investigated to replace R22 in a fully instrumented water-water heat pump test rig. The test results show that the R744/R290 mixture with optimum concentration of 12%/88% (M_{opt}) is the suitable working medium for heat pump water heaters because of its higher *COP* and heating capacity than those of R22 under variable conditions as well as the nominal working condition. The heat pump system with M_{opt} can supply higher temperature hot water and promote compressor lifetime in substitution of R22. The test results also reveal that the heating *COPs* of heat pump system with M_{opt} are 4.98–11.00% higher than those of R22 at the heat sink outlet temperature ranging from 45 °C to 65 °C, and the heat sink outlet temperature has obvious effect on the system efficiency but little on the heating capacity.

1. Introduction

The building sector accounts for about 40% of the total energy consumption and domestic hot water supply has become the main contributor to residential building energy consumption [1]. Heat pumps, as efficient energy conversion and emission reduction means, can be adopted to supply domestic hot water efficiently instead of electric water heaters and gas water heaters. However, one of the challenges for heat pumps is to find the appropriate substitutes for the conventional refrigerants such as R22, R134a, R410A and R407C, which have been in prohibition or phase-out in conventional heat pumps or refrigerators for their higher ODP (ozone depletion potential) or GWP (global warming potential) effects [2,3]. With the increasing awareness of environment protection, one of attractive solutions to avoid high environmental impacts of the traditional refrigerants is the use of the natural refrigerants, such as hydrocarbons (HCs), R744 (carbon dioxide) and ammonia or their mixtures [4].

Among the natural refrigerants, HCs (hydrocarbons) offer environmental friendliness (null ODP and negligible GWP), non-toxicity, availability and high compatibility with mineral or synthetic oil [5,6]. R290 and R600a were used as refrigerants before the invention of CFCs (chlorofluorocarbons). In recent years, R600a has been successfully used in domestic refrigerators in China, Germany and other European countries [7]. R290 is technically valuable for replacement of R22 in heat pump water heater system, tumble dryers and heat pump type air condition system because of better energy efficiency, higher compatibility with material and lubricant oils and lower cost [8–12]. It is safe to use HCs as refrigerants in the allowable quantity, but if the charge quantity exceeds the danger threshold, some safety measures must be taken to reduce the risks in operation because of their high flammability [13].

In recent years, R744 (CO_2) has regained attention as a promising alternative for its favorable features such as environmental friendliness, safety (non-toxicity and non-flammability), availability, and good compatibility with lubricants and materials, good thermodynamic and transport properties [14]. Due to the low critical temperature of 31.1 °C, the transcritical R744 cycle technology was developed by Lorentzen and has been applied in refrigeration, air-conditioning and heat pump applications, especially the domestic heat pump water heaters [15–17]. However, there exist two main drawbacks for the R744 transcritical cycle: significantly high operating pressure and the low system energy efficiency mainly related to large throttling loss in expansion process.

At present, there is no perfect pure refrigerant that meets all the requirements [18]. However, by mixing purposefully two or more pure refrigerants, a desired mixture might be obtained which can eliminate or alleviate the undesired properties of pure refrigerants. For example, the zeotropic blend of R744/R290 has been proposed as the potential

* Corresponding author. Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University Nanjing 210096, China.
E-mail address: ypgchen@sina.com (Y. Chen).

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replacement in various heat pump, air conditioning and refrigeration systems. The aim is simply to mitigate the flammability of R290, but the benefits are multiple that the operating pressure of R744 system is reduced and the system efficiency is improved by taking advantage of the temperature glide.

Fan et al. [19] conducted a simulation study on the performance of a heat pump water heater system using R744/R290 as the substitute for R22 and indicated that the mixture with mass concentration 20%/80% of R744/R290 has the best performance, which presents respectively 12.62% and 34.24% increments in heating *COP* (coefficient of performance) and volumetric heating capacity with respect to those of R22. Dai et al. [20] theoretically investigated the feasibility of binary blends of R744 with ten low-GWP refrigerants used as substitutes in heat pump water heater system and discovered that the mixture R744/R290 presents the promising results at two optimum concentrations for higher heating *COP*. Hakkaki-Fard et al. [21] performed a numerical simulation study on the feasibility of R744 blends used as a substitute for R410A in a cold climate air-source heat pump and concluded that the heating *COP* of heat pump with R744/R290 (5%/95%, by mass) is higher but the heating capacity is low in comparison with that of R410A; while the results are opposite with R744/R32 (20%/80%, by mass). Zhang et al. [22] theoretically and experimentally studied the performance of a transcritical system with R744/R290 mixture and the results demonstrated that both volumetric heating capacity and the heating *COP* of the R744/R290 (95%/5%, by mass) are comparable to those of pure R744 with a decrease of heat rejection pressure, but the heat rejection pressure is still very high. Kim et al. [23] performed an experimental study on the air conditioning system using blend of R744/R290 and demonstrated that the addition of R290 to R744 can promote the system energy efficiency and reduce the discharge pressure, with better temperature matching in the heat exchangers. Kim and Kim [24] conducted theoretical and experimental investigations on the performance of an autocascade refrigeration system with R744/R290 blend. Niu and Zhang [25] and Di Nicola et al. [26] experimentally and theoretically investigated the performance of R744/R290 for cascade refrigeration systems respectively.

The above studies indicate that R744/R290 has the potential to be a long term substitute in heat pump, air-conditioning and various refrigeration systems, but for heat pump water heater systems using R744/R290 the investigation was only carried out by our research team with theoretical research [19], and the feasibility of R744/R290 as the substitute work medium for heat pump water heater systems needs to be testified by experimental research. Hence, in this paper, the feasibility verification of R744/R290 blend used as a substitute for R22 in an instant heat pump water heater system with large temperature lift of heat sink for domestic hot water supply was experimentally investigated in a water to water heat pump testing rig. The emphasis was on the enhancement in heating *COP* and heating capacity of heat pump using zeotropic blend R744/R290 by replacing the conventional cycle to the Lorenz cycle [27,28].

2. Refrigerant properties

The ODP and GWP of R22 are respectively 0.05 and 1810, while R744/R290 blend presents the excellent environmental performances with null ODP and negligible (< 20) GWP.

Fig. 1 shows the physical characteristics of R22 and R744/R290 blends at six compositions. Some parameters, such as normal boiling point, critical temperature, critical pressure and temperature glide, were computed by using REFPROP 9.1 [29].

The lower critical temperature of the mixture leads to the higher heating capacity due to the lower suction specific volume under the same evaporation temperature but reduced heating *COP* for the excessive superheat at compressor outlet, reduced condensation section and increased flash gas loss at throttle valve outlet. Thus, a modest critical temperature is necessary with consideration of the heating *COP* and heating capacity. It is noted from Fig. 1(a) that the increase of R744 in the mixture leads to the lower critical temperature for its lower critical temperature of 31.1 °C. R744/R290 blends at six compositions perform the slightly lower critical temperatures than that of R22, but they still meet the demand in view of the operational condition of the heat pump in this study. It also can be found that the higher critical pressure of R744 results in the rise of critical pressure of the mixtures with the increase of R744. It can be speculated that the discharge pressure of the heat pump system using R744/R290 may increase with the rise of R744 under the same operating conditions, mainly due to the reduced critical temperature and raised critical pressure. Hence, the content of R744 in the blend should be controlled to ensure the acceptable discharge pressure can be obtained.

The normal boiling point of a zeotropic mixture is defined as the arithmetic mean value of the bubble point and dew point under normal atmospheric pressure. It is clear from Fig. 1(b) that the normal boiling point of the R744/R290 blend, as the criterion that judge the applicable temperature zone, decreases with the rise of mass fraction of R744 which has a low normal boiling point of −78 °C. If the system has a leakage, the firstly leaked R744 with lower normal boiling point might reduce the danger. Generally, the refrigerant with lower normal boiling point has the higher discharge pressure under the same operating temperature. It can be predict that the R744/R290 blend will presents the higher discharge pressure in comparison with that of either R290 or R22 because of the lower normal boiling point as shown in Fig. 1(b). In addition, the temperature glide of the R744/R290 blend increases with the rise of mass fraction of R744. The optimum temperature glide can compromise the requirement of temperature variations in both heat exchangers of a heat pump system with improved temperature matching between hot and cold heat transfer fluids. Thus, the use of the mixtures can enhance the *COP* or exergy efficiency of heat pump system by reducing the mean temperature differences between heat transfer fluids [30].

For the binary blend with high temperature glide, the two components of the blend have quite different normal boiling points. Hence, the system is charged firstly with the lower vapor pressure (higher normal boiling point) refrigerant and then the higher one. If the system has a leakage, the component with lower normal boiling point leaks firstly, this results in the variation in mixture concentration. Thus, for system maintenance, the recharge of the mixture may be a challenge.

3. Experiments

3.1. Experimental setup

A fully instrumented water-water heat pump system was developed for a precise performance assessment and comparison of pure R22 and R744/R290 blends. As shown in Fig. 2, the testing apparatus is composed of three closed loops: refrigerant loop, heat sink loop and heat source loop.

The refrigerant loop contains a rolling rotor compressor, a condenser, an expansion valve, an evaporator, a dry filter and two sight glasses. A compressor with a constant speed designed for R22 was used for the tests. In consideration of the safe operation of the compressor, the maximum allowable discharge pressure and discharge temperature of the heat pump are 2.996 MPa and 110 °C respectively and the allowable suction pressure range is 0.296–1.044 MPa, which were provided by the compressor manufacturer. The condenser and evaporator were made of respectively eighteen and eight pieces of 1.2-m premanufactured concentric copper tubes connected together. Compared with the R22 heat pump system, the system was retrofitted with the condenser and evaporator of about 14% and 20% longer tube length, respectively. For the condenser, the outer diameter and the thickness of the outer and the inner tubes are 16.0 mm × 1.5 mm and 9.52 mm × 0.8 mm respectively. For the evaporator, the outer diameter and the thickness of the outer and the inner tubes are