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Experimental investigation of the optimal heat rejection pressure for a transcritical CO_2 heat pump water heater

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HIGHLIGHTS

- Experimental investigation of the optimal heat rejection pressure has been presented.
- The optimal heat rejection pressure influence factor has been introduced.
- Obtaining high COP at the lowest refrigerant outlet temperature has been addressed.
- New correlation to predict the optimal high pressure was obtained.

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ABSTRACT

The system performance of a transcritical CO_2 heat pump is significantly influenced by the heat rejection pressure due to the nature of the transcritical refrigeration cycle. It has received wide attention in the scientific community. In this article, an experimental investigation of the optimal heat rejection pressure for a transcritical CO_2 heat pump water heater is presented. It is found that the optimal heat rejection pressure varies with gas-cooler outlet refrigeration temperature at different ambient temperatures. The further experimental results show that the Coefficient of Performance (COP) at the optimal heat rejection pressure decreases substantially with increasing gas-cooler outlet refrigeration temperature in a range from 25 to 45 °C. Based on the experimental data, a simple correlation of the optimal heat rejection pressure in terms of gas-cooler outlet refrigeration temperature is obtained. The analysis shows that the deviation of the correlation is within ±5%, and the predicted COP at the optimal heat rejection pressure is within 6%.

1. Introduction

As a natural refrigerant, carbon dioxide (CO_2) has been attracting increasing attention to replace chlorofluorocarbon (CFC) and hydro-chlorofluorocarbon (HCFC) refrigerants in the application areas of refrigeration, heat pump and air-conditioning [1–5]. Compared to the conventional CFC, HCFC and HFC refrigerants, CO_2 has lots of technical advantages which include environmental friendliness (zero Ozone Depletion Potential and very low direct Global Warming Potential), low cost, easy availability, non-flammability, non-toxicity, compatibility with various common materials and compactness due to high operating pressures [6].

Lorentzen et al. [2–4] and Riffat et al. [5] through their pioneering studies have proved that the use of CO_2 as a refrigerant can provide an efficient and environmentally attractive technology for air-conditioning, hot water heating and steam production, by operating the system in the transcritical region. Since then, a lot of theoretical and experimental research to develop an energy efficient CO_2 transcritical system has been carried out by researchers in various applications. Cavallini et al. [7] studied two stage transcritical CO_2 cycle optimization and Rozhentsev et al. [8] discussed the special design features of CO_2 air-conditioners in air-conditioning. Nekså et al. [9,10] and some other researchers [11–13] studied the application of the transcritical CO_2 cycle in heat pump water heaters and some of their results were quite good. Richter et al. [14] and Stene et al. [15] experimentally investigated the air to air transcritical CO_2 heat pump system for combined space heating and hot water heating. Sarkar et al. [16] studied the

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transcritical CO_2 heat pump cycle for simultaneous cooling and heating. The application of the transcritical CO_2 cycle was further extended into the automotive industry [17,18]. The experimental results from the prototypes showed that it is possible to obtain a similar level of energy efficiency with respect to R134a.

What is common to all transcritical CO_2 cycles is the existence of a gas-cooler which is used to replace the condenser in a conventional refrigerant vapor compression cycle. In the gas-cooler, the temperature and pressure are decoupled due to the supercritical working region, and an optimal heat rejection pressure exists at which the maximum efficiency of the cycle is achieved. A number of theoretical research works have revealed that this optimal pressure is mainly affected by the refrigeration outlet temperature in the gas-cooler and the evaporating temperature. Kauf [19] first developed a simulation model to determine the optimal heat rejection pressure for different operating conditions, as a function of the gas cooler refrigerant outlet temperature. Based on this model, a control function was demonstrated to adjust the high pressure so that the system can be run with a Coefficient of Performance (COP) that deviates from the maximum values by less than 5.8%. Liao et al. [20] further developed a thermodynamic model to analyze the optimal heat rejection pressures for transcritical CO_2 air-conditioning cycles, in which the isentropic efficiency of the practical compressor was considered. They found that the values of the optimal heat rejection pressure mainly depend on the refrigerant temperature at the gas-cooler outlet, the evaporation temperature, and the performance of the compressor. A correlation of the optimal high pressure in terms of these parameters for specific conditions in a transcritical carbon dioxide cycle air conditioning system was then obtained. Chen et al. [21] further studied the optimal heat rejection for a transcritical CO_2 refrigeration system with internal heat exchangers. It is revealed that the optimal heat rejection pressure has a large effect on the design of the system components in order to achieve a maximum system performance. Sarkar et al. [6] proposed a simple expression considering an ideal compression process for a simultaneous heat pump/refrigeration combination cycle. More recently, Cabello et al. [22] and Aprea et al. [23] presented an experimental study on the optimal gas-cooler pressure for a transcritical CO_2 refrigeration plant and split system respectively. Their experimental results showed that the optimal heat rejection pressure largely depended on the CO_2 temperature at the gas-cooler outlet, the evaporation temperature and the ambient temperature. They compared the experimental results, with the predictions from the most commonly used correlations proposed in the above theoretical studies [6,19–21]. Due to the different assumptions applied in the correlations, and in the facilities studied by the authors [6,19–21], the experimental results showed large deviations from the predictions, and the deviations varied with the correlations. Based on the experimental study, it was obvious that the performance of transcritical CO_2 cycles was largely influenced by the heat rejection pressure, and by the effects of operating conditions on the optimal heat rejection pressure change within the transcritical CO_2 systems. Currently no correlation can predict the optimal heat rejection pressure for all different applications of transcritical CO_2 cycles. This motivated us to extend the research work to an air-to-water transcritical CO_2 heat pump water heater for commercial applications.

At present, no research work is reported on this aspect of the air-to-water transcritical CO_2 heat pump water heater for commercial applications. In this article, a prototype for this purpose was set up at the Xi'an Jiaotong University. We experimentally studied the optimal heat rejection pressure of a transcritical CO_2 heat pump water heater at various ambient conditions and refrigerant temperatures at the gas-cooler outlet. The cycle efficiency of the prototype was evaluated for a wide range of gas-cooler pressures at various working conditions. The experimental results were compared with the most commonly used corrections for transcritical CO_2 refrigeration cycles [19,21]. Furthermore, a correlation to predict the optimal heat rejection pressure for such transcritical CO_2 heat pump water heaters at specific conditions was obtained from the experimental data, and the deviation of this correlation was hence discussed.

2. Experimental

2.1. System description

The schematic of a CO_2 heat pump water heater is shown in Fig. 1. The system is mainly comprised of a semi-hermetic reciprocating compressor, a finned-tube evaporator, receivers, filters, expansion valves, a tube-in-tube gas cooler and defrosting system as shown in Fig. 2. More detailed information about the components is listed in Table 1.

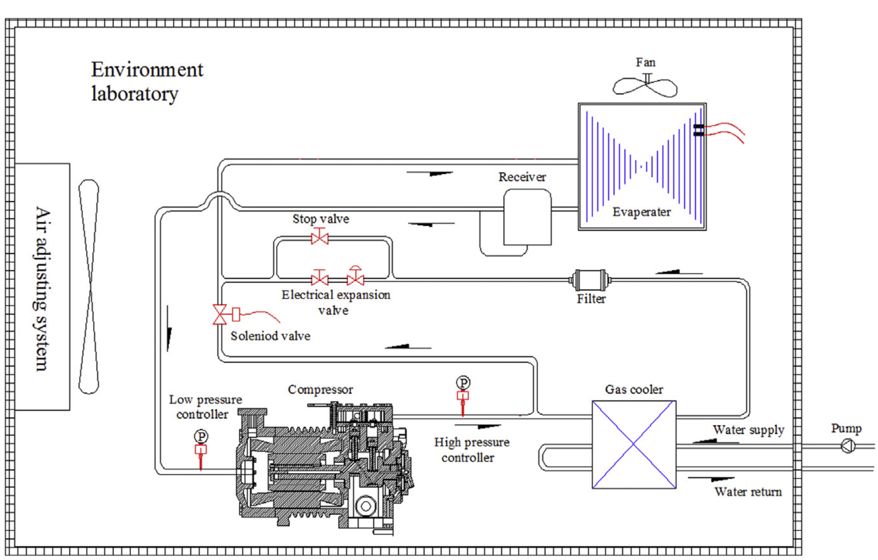

Fig. 1. Schematics of a transcritical CO_2 heat pump water heater.