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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.

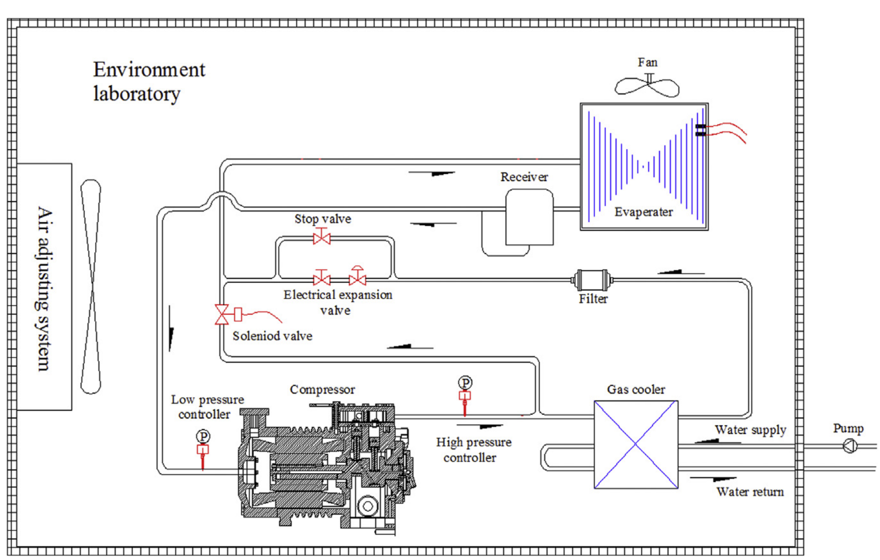

Fig. 1. Schematics of a transcritical CO_2 heat pump water heater.

Fig. 2. Experimental transcritical CO_2 heat pump water heater.

The entire CO_2 heat pump water heater system was located in a psychrometric room. This psychrometric room is specially designed such that the outdoor conditions, mainly temperature and humidity, can be simulated for the heat pump performance testing. The ambient temperature can be varied in the range of −20–45 °C with a constant relative humidity ranging from 20% to 85%. The hot water temperature, at the inlet and outlet of the gas cooler exchanger, ranges from 15 °C to 75 °C. In our experiment, the relative humidity is maintained at 60% and the ambient temperature varies from −15 °C to 30 °C, whilst the hot water outlet temperature is maintained at 65 °C.

The gas-cooler of the CO_2 heat pump water heater, and the connecting water pipes of the test system, are well insulated to minimize heat loss from both water and refrigerant. The maximum shift of energy balance between the water and refrigerant is estimated within 5%. The thermal load drawn from the test system has an uncertainty of about ±2% [24], and the uncertainties of the system COP is estimated at approximately ±3%. The allowed errors for both dry and dew point temperature are ±0.2 °C. All data is collected during the system steady state, which is identified by

Table 1
Characteristics of the CO_2 heat pump components.

Compressor	Semi-hermetic reciprocating compressor; swept volume 10.7 m^3/h.
Gas-cooler	Tube-in-tube heat exchanger; counter flow; smooth tube; heat transfer area (CO_2 side) 3.2 m^2.
Evaporator	Finned-tube heat exchanger; heat transfer area 75 m^2.
Fan	Axial; air flow rate 12,000 m^3/h.
Expansion valve	Electrically expansion valve and regulating valve.
Receiver	Inner volume 0.125 m^3.

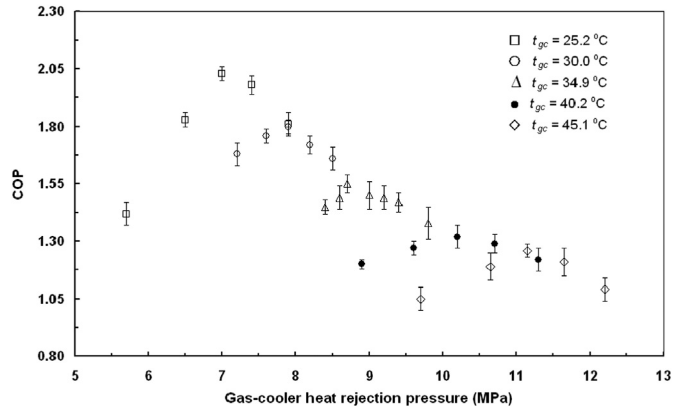

Fig. 3. COP at an ambient temperature of −15 °C for different gas-cooler refrigerant outlet temperatures.

readings without change (within acceptable tolerances) for at least 5 min. The average of the latest 5 readings during steady state is selected to represent the state condition.

The experimental system is fully instrumented to evaluate its performance as a whole, and that of its individual components. The temperatures are measured with matched four-wire PT100 temperature sensors with an accuracy of ±(0.1% of range + 0.2% of reading). The pressures in the system are measured with pressure transducers (±0.5% of full scale, 16 MPa accuracy). The mass flow rate of water is measured by an Admangse solenoid mass flow meter (±0.3% of full scale accuracy). The electrical power input is monitored using a digital power meter QT1600 with an accuracy of ±(0.1% of range + 0.05% of reading). All the pressure, temperature, flow rate and power readings are continuously monitored by a calibrated Agilent HP34970 data acquisition system.

2.2. Test procedure

The COP of transcritical CO_2 systems is highly influenced by the heat rejection pressure which depends on the gas-cooler refrigerant outlet temperature and the evaporation temperature [6,19–21]. Therefore, the test procedure was designed to investigate the optimal heat rejection pressure at fixed gas-cooler refrigerant outlet and evaporation temperatures. The gas cooler refrigerant outlet temperature is dependent on the external water inlet temperature, and hence it is adjusted according to the water inlet temperature at a fixed water outlet temperature, 65 °C. The evaporation temperature is determined by the ambient conditions. As a heat pump water heater has to work at different external ambient temperatures, it is more practical to study the effect of the ambient temperature on the system performance and heat rejection pressure for control purposes. Therefore, in our experiments, an optimal heat rejection pressure investigation was conducted at different ambient temperatures instead of evaporation temperatures. However, according to the literature [23], the evaporation temperature variation is small at a given ambient temperature during the steady operation. The optimal heat rejection pressure in the gas-cooler is defined when the highest system COP is achieved. Therefore, the actual experimental tests were performed for a fixed gas-cooler refrigerant outlet temperature at a fixed ambient condition (fixed temperature and relative humidity) while varying the heat rejection pressure at the gas-cooler.

3. Results and discussion

The experimental tests were conducted at five different gas-cooler refrigerant outlet temperatures and four ambient

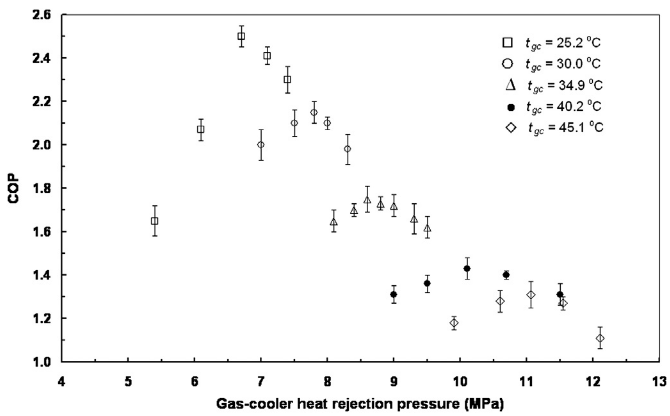

Fig. 4. COP at an ambient temperature of 0 °C for different gas-cooler refrigerant outlet temperatures.

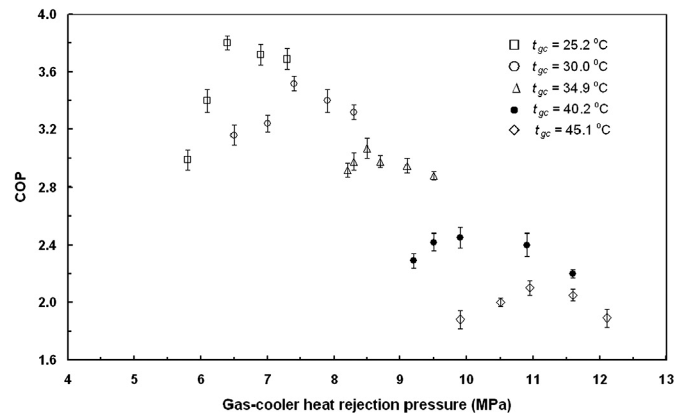

Fig. 6. COP at an ambient temperature of 30 °C for different gas-cooler refrigerant outlet temperatures.

temperatures which covered typical China weather conditions and application of water heaters. At each temperature condition, more than five steady-state data points were measured. The experimental results concerning system COP and optimal heat rejection pressure of the CO_2 heat pump water heater are presented and discussed below.

Figs. 3–6 show the measured COP as a function of the heat rejection pressure at various gas-cooler refrigerant outlet and ambient temperatures. The ambient temperature ranges from −15 °C to 30 °C, and the gas-cooler refrigerant outlet temperature varies from 25 °C to 45 °C. It was observed that the system COP followed a similar pattern with the gas-cooler outlet temperature at different ambient temperatures, and it reached a maximum at a certain heat rejection pressure, called the optimal heat rejection pressure. This optimal heat rejection pressure changed substantially with the gas-cooler refrigerant outlet temperature. It increased sharply when the gas-cooler refrigerant outlet temperature increased at each ambient temperature. This proved that the optimal heat rejection pressure largely depends on the gas-cooler refrigerant outlet temperature as reported in literature [6,19–23].

Fig. 7 demonstrates the effect of the ambient temperature on the optimal heat rejection pressure. The optimal heat rejection pressure reduction is defined as the percentage reduction of the optimal heat rejection pressure compared with that under the condition of the ambient temperature of −15 °C. The reduction of the optimal heat rejection pressure with the ambient temperature was large at low gas-cooler refrigerant outlet temperatures. It became negligible at relatively high gas-cooler refrigerant outlet temperatures. However, the maximum reduction of the optimal heat rejection pressure over the entire range of experimental ambient temperatures was less than 8%. After considering the experimental measurement error, this effect is really minor which is consistent with the findings reported by Chen et al. [21] in a similar transcritical CO_2 refrigeration system with internal heat exchangers.

The experimental results also showed that the maximum system COP was highly affected by the gas-cooler refrigerant outlet temperature and the ambient temperature. The variation of the maximum system COP with the gas-cooler refrigerant outlet temperature at various ambient temperatures is shown in Fig. 8. The maximum system COP decreased sharply with the gas-cooler refrigerant outlet temperature ranging from 25 °C to 45 °C at each ambient temperature. For example, at an ambient temperature of 30 °C, the maximum system COP was almost doubled with the gas-cooler refrigerant outlet temperature dropping from 45 °C to 25 °C. The tendency of reduction in the maximum system COP became gentle when the ambient temperature lowered; however, it is still over 30% when the gas-cooler refrigerant outlet temperature dropped from 45 °C to 25 °C at an ambient temperature of −15 °C. This implied that the transcritical CO_2 heat pump water heater system should be designed to have the lowest possible gas-cooler refrigerant outlet temperature in order to achieve the highest system performance.

A few theoretical expressions have been obtained by researchers [6,19–21] to identify the optimal heat rejection pressure in a refrigeration cycle similar to the one analyzed in this paper. Among

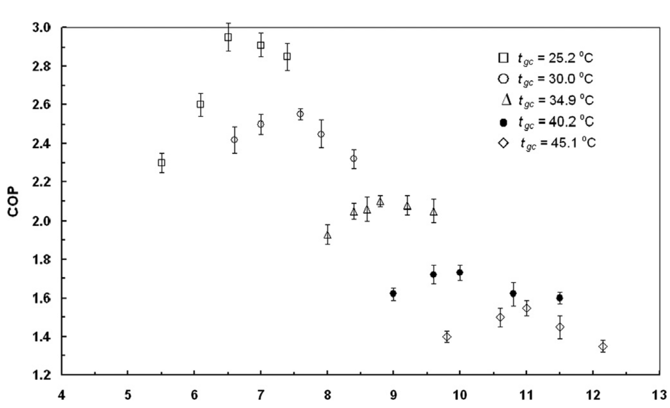

Fig. 5. COP at an ambient temperature of 15 °C for different gas-cooler refrigerant outlet temperatures.

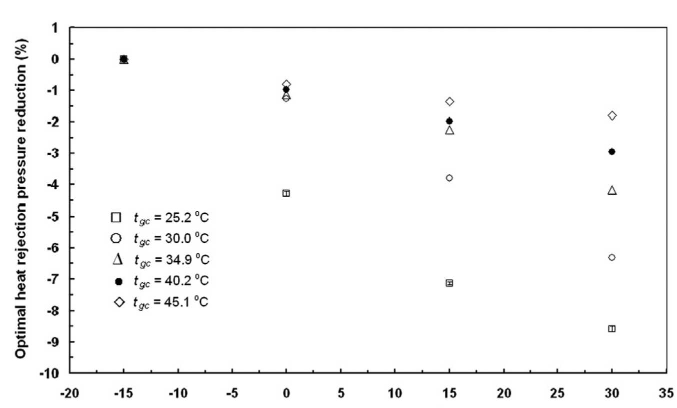

Fig. 7. Reduction of the optimal heat rejection pressure at the ambient temperature for different gas-cooler refrigerant outlet temperatures.

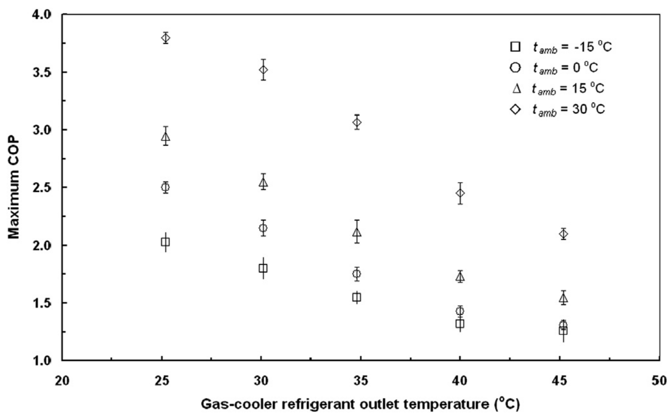

Fig. 8. Maximum COP at the gas-cooler refrigerant outlet temperature for different ambient temperatures.

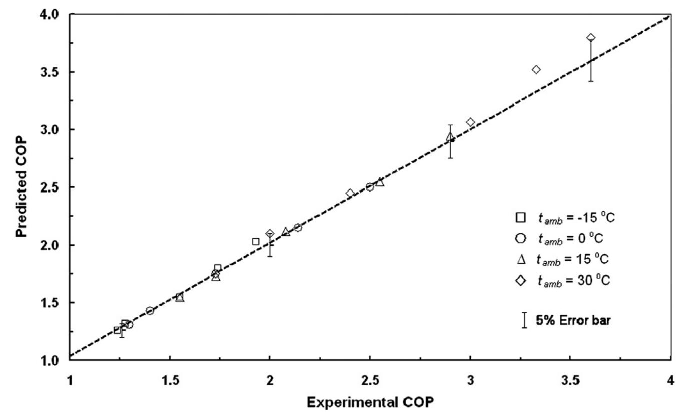

Fig. 10. Deviation of the maximum COP by using our expression to predict the optimal heat rejection pressure.

them, the expressions from Kauf [19] and Chen [21] only consisted of the effect of gas-cooler refrigerant outlet temperature which is consistent with the findings in our testing machine. Therefore, these two expressions were used to compare with our experimental data. The two expressions are listed below:

$$P_{\mathrm{opt}} = 2.6 \cdot T_{\mathrm{gc},o} + 7.54\ (\mathrm{bar}) \quad \text{Kauf [19]} \tag{1}$$

$$P_{\mathrm{opt}} = 2.68 \cdot T_{\mathrm{gc},o} - 6.797\ (\mathrm{bar}) \quad \text{Chen [21]} \tag{2}$$

Where P_{opt} refers to the optimal heat rejection pressure, in bar, and $T_{\mathrm{gc},o}$ is the gas-cooler refrigerant outlet temperature, in °C.

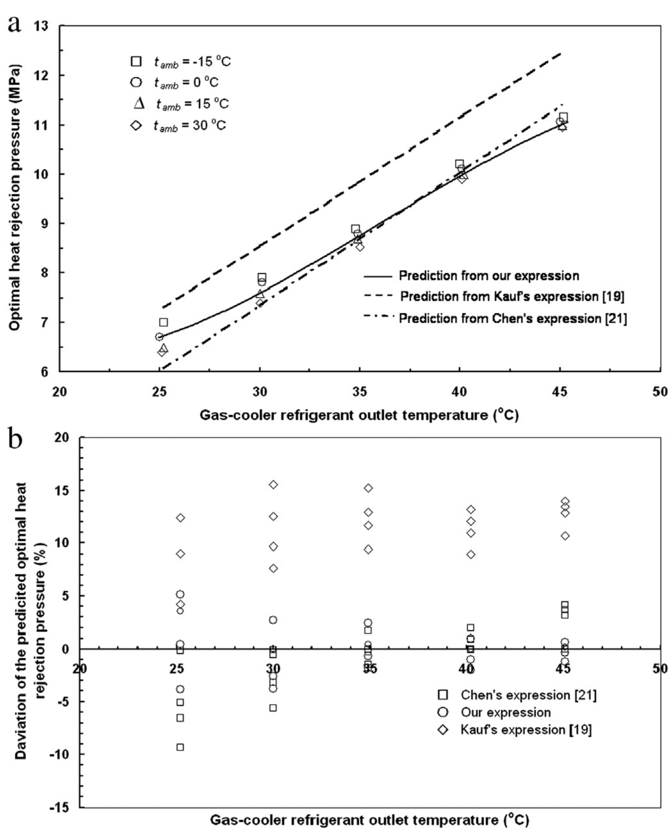

Fig. 9. (a) Comparison between the experimental optimal heat rejection pressure and predicted optimal heat rejection pressure from two commonly used expressions [19,21]. (b) Deviation of the predicted optimal heat rejection pressures at different gas cooler refrigerant outlet temperatures from the three expressions.

The comparison between the predictions from the two expressions and our experimental data is shown in Fig. 9. The predicted optimal heat rejection pressure from Kauf's expression was always much higher than the experimental data and its errors were larger than 10% for all the experimental temperatures as shown in Fig. 9(b). On the contrary, Chen's expression showed a good agreement with our experimental data and the deviation was below 10% over most of the experimental ranges. However, the low gas-cooler refrigerant outlet temperature is out of the application range of Chen's expression. It was found that the deviation is larger than 10% if Chen's expression was still applied for this low temperature. Therefore, a new correction of the optimal heat rejection pressure in terms of gas-cooler refrigerant outlet temperature was obtained by using experimentally fitted polynomial curve from the experimental data. It is expressed as

$$p_{\mathrm{opt}} = 132.3 - 8.4 t_{\mathrm{gc},o} + 0.3 t_{\mathrm{gc},o}^2 - 27.7 \times 10^{-4} t_{\mathrm{gc},o}^3 \tag{3}$$

This correlation is valid for the CO_2 heat pump with gas-cooler outlet temperatures ranging from 25 to 45 °C, and ambient temperatures from −15–30 °C. As shown in Fig. 9(b), the deviation of this correlation is much less than that of Chen's expression for all our experimental temperatures. It has a maximum deviation below 5% at the low gas-cooler refrigerant outlet temperature which is out of the application range of Chen's expression.

Furthermore, if this new correlation was used to obtain the optimal heat rejection pressure, the deviation of the predicted system maximum COP in a real system is less than 6%, as presented in Fig. 10. This indirectly proved that the ambient temperature has negligible effect on the optimal heat rejection pressure. By ignoring this temperature, it can much simplify the analysis without losing the accuracy of the analysis. In addition, due to this optimal heat rejection pressure for different gas-cooler refrigerant temperatures, it is essential to design a precise control system to control the system operation for a transcritical CO_2 heat pump water heater since a small error in heat rejection pressure can cause a large reduction of the system efficiency.

4. Conclusion

In this paper, an experimental investigation of the optimal heat rejection pressure for a transcritical CO_2 heat pump water heater at various operating conditions for commercial applications has been presented. The results showed that the optimal heat rejection pressure was largely influenced by the gas-cooler refrigerant outlet temperature for the transcritical CO_2 heat pump water heater. The ambient temperature has negligible effect on the optimal heat rejection pressure. It was also observed that the system COP at the optimal heat rejection pressure decreased sharply when the gas-cooler refrigerant outlet temperature increased from 25 °C to 45 °C. In order to obtain a high system COP, the system must be designed to operate at the lowest possible gas-cooler refrigerant outlet temperature.

The experimental results were compared with two commonly used expressions for a similar CO_2 system. Chen's expression showed a good agreement with the experimental data within its temperature range. Out of the temperature range of Chen's expression, the error was found to be more than 10%. Therefore, a new correlation to predict the optimal high pressure was obtained using the fitted polynomial curve from experimental data. The deviation of this correlation was also discussed. The comparison showed that the expression has a maximum deviation below 5%. When this expression was used to obtain the optimal heat rejection pressure, the deviations in system efficiency in the real system was shown to be less than 6%. This proved that our expression can best fit the experimental behavior of the system studied in this paper.

Acknowledgements

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