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Modeling and simulating the transcritical CO_2 heat pump system

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ABSTRACT

In this paper, a mathematical model for steady-state simulation of transcritical CO_2 water-to-water heat pump system with an expander has been developed. It is used to simulate the performance of transcritical CO_2 system with CO_2 expander prototype. Simulated results are compared with experimental data to verify the accuracy of the simulation model. The comparison results show the average deviation of about 15% for COP_c(cooling coefficient of performance) and COP_h(heating coefficient of performance), about 17% for cooling and heating capacity at experimental high pressure ranges. With this model, which has been validated in a limited high pressure range, the influence of water mass flow rate and water inlet temperature of both evaporator and gas cooler on the performance of transcritical CO_2 expander system is analyzed. The results show that decreasing inlet temperature and increasing mass flow rate of cooling water cannot only increase the system performance but also reduce the optimal heat rejection pressure, at which the maximum COP (coefficient of performance) can be obtained. For chilling water, increasing its inlet temperature and mass flow rate is favorable for increasing the system performance, while the optimal heat rejection pressure does not vary very much.

1. Introduction

Nowadays, the environmentally friendly natural refrigerant CO_2 and its corresponding transcritical CO_2 cycle, in which the heat rejection process takes place in the supercritical region and the evaporation process happens in the subcritical region, have attracted considerable attention. Many previous studies discussed the use of CO_2 in automobile air conditioners, heat pump water heaters and environmental control units [1–6]. All the above studies indicate that due to a larger energy loss in the throttle valve, the system efficiency of the trancritical CO_2 cycle is very low and the total global warming impact is therefore relatively high. As to experimental research, the transcritical CO_2 heat pump system operates with a slightly lower heating COP than that of R410A heat pump system [7]. Therefore, several measures have been introduced to improve the performance of trancritical CO_2 system [6,8–11], among which application of an expander in place of throttle valve is one of the most effective alternative. But some technical problems will be met when an expander is applied. On the one hand, the structure and the optimization design of expander should be suited to the two-phase flow demand; on the other hand, how to combine the expander and compressor together and recover the work is another difficult problem [9]. Thus, performance testing of a trancritical CO_2 system with an expander is inconvenient, high cost and time-consuming. Consequently, accurate numerical simulation of the system to predict effects of operating parameters on the steady-state performance will be very useful [12].

Up to now, computer simulation for transcritical CO_2 system with different types of component models [13], CO_2 heat pump water heaters heating performance and comparison with R22 system [14] and CO_2 air-to air residential air conditioner with simulation and test verification [15] have been developed. With the development of study on CO_2 heat transfer and system performance, the different numerical models for specific transcritical CO_2 systems mostly based on their own test prototype have been put forward and improved in recent years. Sarkar et al. [12,16,17] studied the performance of a transcritical CO_2 heat pump prototype system for simultaneous cooling and heating of water based on experimental test and numerical simulation through continuous improvement of their numerical model. The performance of an air-to-water CO_2 heat pump water heating system [18] and the influence of a daily change in a standardized hot water demand on the system performance [19] were analyzed numerically.

As stated above, many simulation studies on the transcritical CO_2 cycle have been carried out, among which most focused on the

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Nomenclature

A	heat transfer area (m^2)
COP	coefficient of performance
d	tube diameter(m)
G	mass flow rate (kg/s)
h	specific enthalpy (kJ/kg)
N	compressor revolution speed (rpm)
P	pressure (pa)
Q	heat exchange capacity (kW)
t	temperature (°C)
Δt	temperature difference (K)
U	overall heat transfer coefficient (W/m^2 K)
V	compressor volume swept (m^3/h)
W	power (kW)

Subscripts

1	compressor suction state
2	compressor discharge state
3	expander suction state
4	expander discharge state
c	cooling, gas cooler
com	compressor
d	discharge
e	evaporator
exp	expander
h	heating
i	inlet
is	isentropic
j, N	unit
m	logarithm mean, mechanical
r	CO_2 side
s	suction
th	theoretical
v	volume
w	water side

Greek symbol

α	heat transfer coefficient
η	efficiency
ρ	density
λ	heat conductivity

water heating application and a few on the air conditioning heat pump. However, the expander model was not taken into account in these simulation models of throttle valve systems. Due to the complexity of expander with many small parts, it is difficult to create a detailed simulation model. Therefore, in this paper, a simplified method based on the principle of an overall efficiency similar to that of compressor model is adopted to set up the expander model based on the measured data. In addition, the heat transfer correlations for gas cooler and evaporator are both selected with comparison to the experimental data [20]. Then, a steady-state mathematical model for transcritical CO_2 water-to-water heat pump system with expander has been developed in this paper. Validation of the mathematical model with experimental data from our test rig is presented. Finally, effects of operating parameters such as, water inlet temperature and water mass flow rate of both gas cooler and evaporator on system performance have been studied.

2. Modeling the transcritical CO_2 heat pump system with expander

A typical transcritical CO_2 cycle consists of a compressor, a gas cooler, an evaporator and an expansion device, which in this study is an expander, as shown in Fig. 1. Besides the four major components mentioned above, which will be modeled for the simulation, others may be added to control the system's operating conditions or to maintain system security. A high pressure accumulator is installed after the gas cooler to store the surplus refrigerant and sustain stable operating pressure. A low pressure receiver is added just after the evaporator to store liquid and allow only vapour to enter the compressor. A generator is connected to the expander to generate electricity to supply power for some indication loads, from which the recovery work from the expander can be obtained. Two water tanks with electric heater provide constant inlet temperature of water for gas cooler and evaporator. One mass flow meter is used to measure the refrigerant mass flow rate. Two water pumps and rotameters are applied to control and measure the water flow rate of cooling and chilling water.

In the following, the characteristics of the four main components and their model creation will be introduced in detail.

2.1. CO_2 compressor model

The compressor model is set up by using the method of overall efficiency principle. The refrigerant CO_2 mass flow rate through the compressor is obtained as follows:

$$G_r = \rho_1 \eta_v V_{th} \frac{N}{60} \tag{1}$$

where G_r is the mass flow rate of the refrigerant, ρ_1 is the CO_2 density at compressor suction state, V_{th} is the compressor theoretical volume swept, N is the compressor revolution speed and volumetric efficiency η_v is calculated using the fitted correlation coming from experimental data [21].

The compression work of the compressor can be calculated using the following formula:

$$W_{com} = \frac{G_r \left(h_{2,is} - h_1\right)}{\eta_{is} \times \eta_m} \tag{2}$$

where W_{com} represents the compression work of the compressor; the CO_2 compressor isentropic efficiency η_{is} comes from the experimental data of our test rig [22]; h_1 denotes the specific

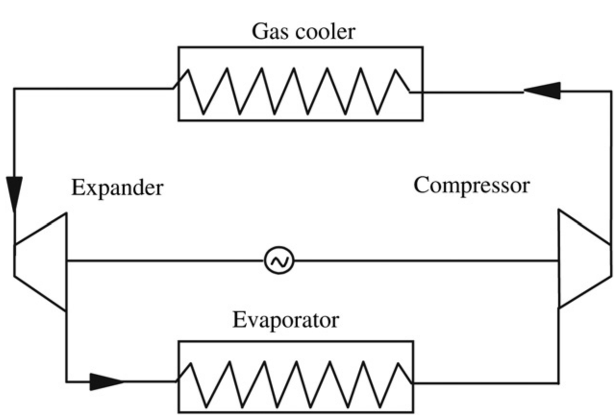

Fig. 1. Schematic of transcritical CO_2 heat pump system with an expander.