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Simulation Study on Performance of Transcritical Carbon Dioxide Heat Pump Water Heater and Simulating Gas Cooler

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Abstract
In this paper, a set of CO_2 heat pump water heater experimental device is designed. The finite volume method is used to establish the simulation model of the air cooler. The simulation model is verified with 20 groups of experimental data, and the relative error is less than 15%. The simulation studies the influence of the CO_2 inlet parameters of the air cooler on the heat transfer performance of the air cooler.
The results show that under the same CO_2 inlet parameters (temperature, pressure, mass flow rate), the heat transfer coefficient at the CO_2 side first increases and then decreases along the tube length, and there is a peak value of the heat transfer coefficient. When the CO_2 inlet pressure drops, the peak value of heat transfer coefficient will gradually move backward, and the smaller the pressure is, the higher the peak value is, and the heat transfer coefficient at the water side is basically unchanged. With the increase of inlet pressure, the required length of heat exchange tube decreases.
Keywords: *CO_2heat pump water heater;heat transfer performance; spiral corrugated tubes*

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I. INTRODUCTION

Air source heat pump is a renewable energy equipment driven by electric energy. It can force the surrounding air as a low level heat source to provide high-quality heat energy that can be used. Generally, thermal heat pump can obtain 3 or more heat by consuming 1 share of electric energy, so heat pump is an energy product with high efficiency and energy conservation. The transcritical CO_2 heat pump water heater is one of the air source heat pump water heaters. With CO_2 as the refrigerant, the critical temperature of CO_2 is only 304.21K, so its heating cycle is different from that of conventional refrigerants. Its heat release process operates in the supercritical area, and the temperature drops throughout the process, while the phase state remains unchanged. And its temperature drop just matches the temperature rise of water. This temperature slip just matches the required variable temperature heat source. It belongs to a special Lorentz cycle [1] [2]. When it is used to heat water, it has a high heat transfer coefficient.

1.1Casing air cooler

Because of its mature processing technology, low cost and high safety factor, many researchers choose the tubular air cooler to study the performance of CO_2 heat pump system. At present, the types of casing type air coolers are: conventional casing, large casing with multiple small tubes, integrated casing, etc. The research direction of the casing type air cooler mainly focuses on how to improve the heat transfer performance of the air cooler, reduce the overall size and weight of the heat exchanger, improve the system performance and reduce the weight of the unit. The structure is shown in Figure 1.

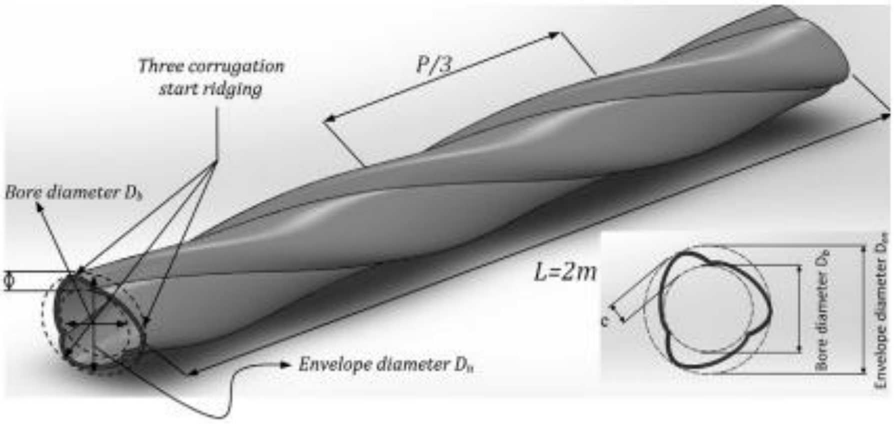

Figure 1Three head spiral bellows structure studied by Kareem

1.2 CO_2 thermophysical property analysis

At normal temperature and pressure, CO_2 is colorless and tasteless, chemically stable, nonflammable, non combustion supporting, and non-toxic at low concentrations. As a refrigerant, it has its unique property advantages. The critical temperature and pressure are 304.13K and 7.377MPa. The temperature and pressure of the three-phase point are -56.6℃and0.52MPa.The refrigeration capacity perunit volume is 22546kJ/m3, which is 5 to 8 times that of conventional refrigerants. The compression ratio (2 to4) of the CO2 refrigeration cycle is lower than that of synthetic refrigerants. The volumetric efficiency of the compressor is relatively high.Thisshown in Figure 2.

Supercritical CO_2 fluid has the dual characteristics of gas and liquid in physical properties, and its density is close to that of liquid; The viscosity and diffusion coefficient are close to the gas state, so it has good fluidity and transmission characteristics.

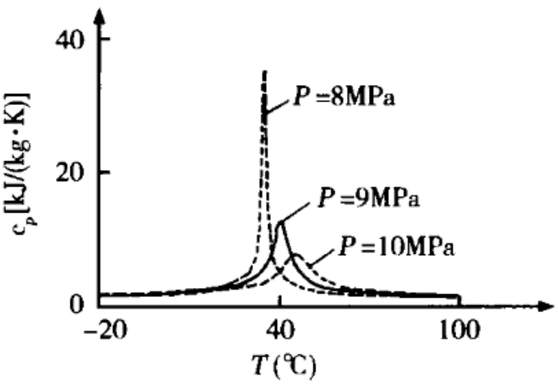

Figure 2 Correlation analysis of heat transfer of carbon dioxide spiral tube air cooler

The bare tube heat transfer correlations were selected. The experimental correlations for the supercritical fluids Dittus Boelter [3] and Gnielinski [4] are the two with the highest accuracy and approval. Most of the forced convection heat transfer correlations for supercritical carbon dioxide are modified by the Dittus Boelter correlation (D-B correlation) or Krasnoshchekov and Protopopov [5] (P-K correlation). The modification methods include physical property modification, dimensionless modification and piecewise function modification, extending the original subcritical heat transfer correlation to the field of supercritical fluid.

1. Dittus Boelter correlation

When 104<Re<1.2 × 105, when a flat smooth pipe is in a turbulent area, the Dittus Boelter correlation can be used:

$$Nu_r = \frac{h_r D_h}{l_r} = 0.023 Re_{Dh}^{0.8} \Pr^{0.3} \quad (1$$

2. Gnielinski Correlation:

The Gnielinski formula can be used for the convection heat transfer coefficient of the straight pipe:

$$Nu_f = \frac{(f_D/8)(Re_f - 1000)Pr_f}{1+12.7(f_D/8)^{0.5}(Pr_f^{2/3} - 1)} \quad (2$$

The definition formula of CO_2 side Nusselt is: Nu_c; Darcy friction factoris calculated by Filonenko formula:

$$f_D = 1.82(\lg Re_c - 1.63)^{-2} \quad (3)$$

3. Krasnoshchekov and Protopopov correlation

$$Nu = Nu_0 (\frac{m_b}{m_w})^{0.11} (\frac{k_b}{k_w})^{-0.33} (\frac{\overline{c_p}}{c_{pb}})^{0.35} \quad (4)$$

II. ESTABLISHMENT OF SIMULATION MODEL OF AIR COOLER

2.1Simulation principle of air cooler

In the heat release process of the air cooler, CO_2 crosses the critical point from the supercritical state to the subcritical state, and the physical properties near the critical point will change dramatically. In order to ensure the accuracy of the mathematical model, this paper uses the distributed parameter method to model, divide the entire air cooler into hundreds of micro element segments along the length of the tube, calculate the heat exchange in each micro element segment, and take the outlet parameters of the previous segment of CO_2 and water as the inlet parameters of the next micro element segment, Since the length of the micro element segment is small, the average of the inlet temperature and the assumed outlet temperature is taken as the qualitative temperature of each micro element segment for calculation.

The model makes the following assumptions:

(1) Both CO_2 flow and water flow are one-dimensional uniform flow;

(2) The axial heat conduction along the tube length is ignored, that is, there is no heat transfer between the micro segments;

(3) Ignore heat loss;

(4) Ignore the influence of lubricating oil and non condensable gas.

Under the above assumptions, the tubular air cooler can be represented as shown in Figure 3:

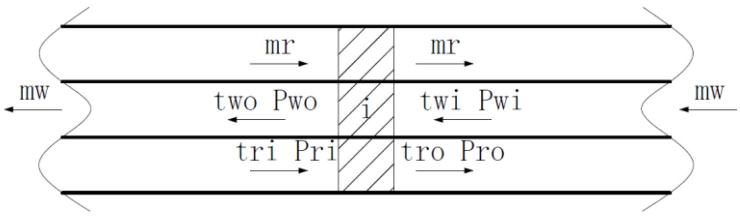

Fig. 3 Microelement segment calculation model

Taking the i-th micro element segment as an example, the input parameters are the mass flow of CO_2, m_r, the CO_2 temperature t_r, i and pressure $P_{r, i}$ at the micro element inlet, the mass flow of water, m_w, the inlet temperature $t_{w, i}$ and the pressure $P_{w, i.}$ The output parameters are CO_2 outlet temperature $t_{r, o}$ and pressure $P_{r,i}$, water outlet temperature $t_{w, o}$ and pressure $P_{r, o}$. The specific process of heat exchange is: the enthalpy values $h_{r, i}$, $h_{r, o}$ of CO_2 inlet and outlet can be obtained according to the temperature and pressure of CO_2, so the heat exchange at CO_2 side in the whole process is:

$$Q_{r,i} = M_r (h_{r,i} - h_{r,o}) \quad (5)$$

The heat of the water side in the i-th micro element is:

$$Q_{w,i} = m_w c_{p,m} (t_{w.o} - t_{w,i}) \quad (6)$$

According to the heat exchange calculation formula, the heat exchange between the two fluids can be expressed as:

$$Q_i = K_i A_i \Delta T_{m,i} \quad (7)$$

2.2Correlation fitting of heat transfer and flow in tubes

Reference [6] obtained the basic form of the heat transfer and friction coefficient calculation criterion formula of spiral grooved tubes through the similarity theory and dimensional analysis method. In this paper, the similarity theory and multiple regression method are used to process the experimental data to obtain more reliable forced convection heat transfer criterion correlations and friction coefficient criterion correlations in spiral grooved tubes.

The similarity theory adopted in this paper is an analytical method for solving the similar flow field by using mathematical analysis method. Starting from the differential equation and boundary conditions of the flow field, based on the dimensional homogeneity in the equation, the solution of the practical problem is obtained by using mathematical methods such as similarity transformation. For the research of spiral grooved tubes, it is generally believed that the spiral tubes take p/d and e/d (pitch p, groove depth e) as the characteristic dimensions, so in this paper, several dimensionless numbers, p/d, e/d, Re and Pr, are selected as the relationship variables of the criterion formula of heat transfer Nu in the tubes. The expression is:

$$Nu = F_1(p/d, e/d, Re, \mathrm{Pr}) \tag{8}$$

P/d, e/d and Re are selected as the relationship variables of the criterion formula for the friction resistance coefficient f in the pipe, and the expression is:

$$f = F_2(p/d, e/d, Re) \tag{9}$$

The formula for calculating Nu and f is arranged as a power function, where the exponent of Pr is taken as 1/3 of the empirical value, and the expression is:

$$Nu = e^{m_1}(p/d)^{m_2}(e/d)^{m_3} Re^{m_4}\,\mathrm{Pr}^{1/3} \tag{10}$$

$$f = e^{n_1}(p/d)^{n_2}(e/d)^{n_3} Re^{n_4} \tag{11}$$

III. RESEARCH ON SIMULATION RESULTS

3.1Effect of CO_2 inlet pressure

The CO_2 pressure will affect the level of the quasi critical temperature. In the air cooler, the higher the CO_2 inlet pressure is, the higher the critical temperature is. However, the higher the inlet pressure is, the higher the requirements for the process of the compressor and air cooler are also put forward. This paper simulated and analyzed the heat transfer performance of the air cooler when the inlet temperature of the air cooler is 98 ℃, the CO_2 mass flow rate is 30g/s, the inlet and outlet water temperature is 17 ℃/65 ℃ and the water flow rate is 130L/h, and the CO_2 inlet pressure is P_{ri}=10MPa, 10.5MPa, 11MPa and 11.5MPa respectively. The simulation results are shown in Figures 4 .

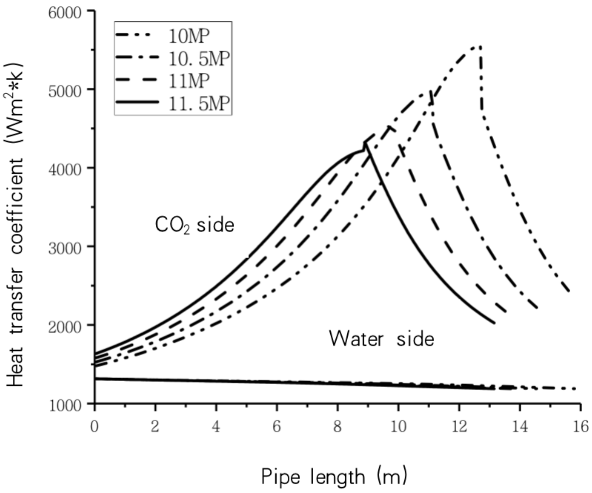

Fig. 4 Heat transfer coefficient varies with inlet pressure

It can be seen from Figure 4that under the same pressure, the heat transfer coefficient at the CO_2side first increases and then decreases along the tube length, with a peak value of the heat transfer coefficient, and the heat transfer coefficient at the water side is basically unchanged. The peak value of CO_2 side heat transfer coefficient will gradually move backward with the pressure drop, and the smaller the pressure is, the higher the peak value will be. When the inlet pressure Pri=10MPa, 10.5MPa, 11MPa and 11.5MPa, the required length of heat exchange tubes is 15.8m, 14.55m, 13.7m and 13.15m respectively, and the required length of heat exchange tubes decreases with the increase of pressure.

3.2Effect of CO_2 inlet temperature

When the inlet and outlet temperature of the water side is constant, increasing the CO_2 inlet temperature can increase the heat exchange per unit length and reduce the required air cooler tube length, but increasing the CO_2 inlet temperature requires increasing the compressor power consumption, so the balance point between the CO_2 inlet temperature and the compressor power consumption should be sought during actual operation. When the CO_2 inlet temperature is too high, problems such as excessive exhaust pressure and pressure ratio, reduced compressor efficiency, and mechanical wear will occur. This section simulated and analyzed the heat transfer performance of the air cooler when the CO_2 inlet pressure is 11MP, the mass flow rate is 30g/s, the inlet and return water temperature is 17 ℃/65 ℃, and the inlet water flow rate is 130L/h, and the CO_2 inlet temperature is T_{ri}=90 ℃, 95 ℃, 100 ℃ and 105 ℃ respectively.

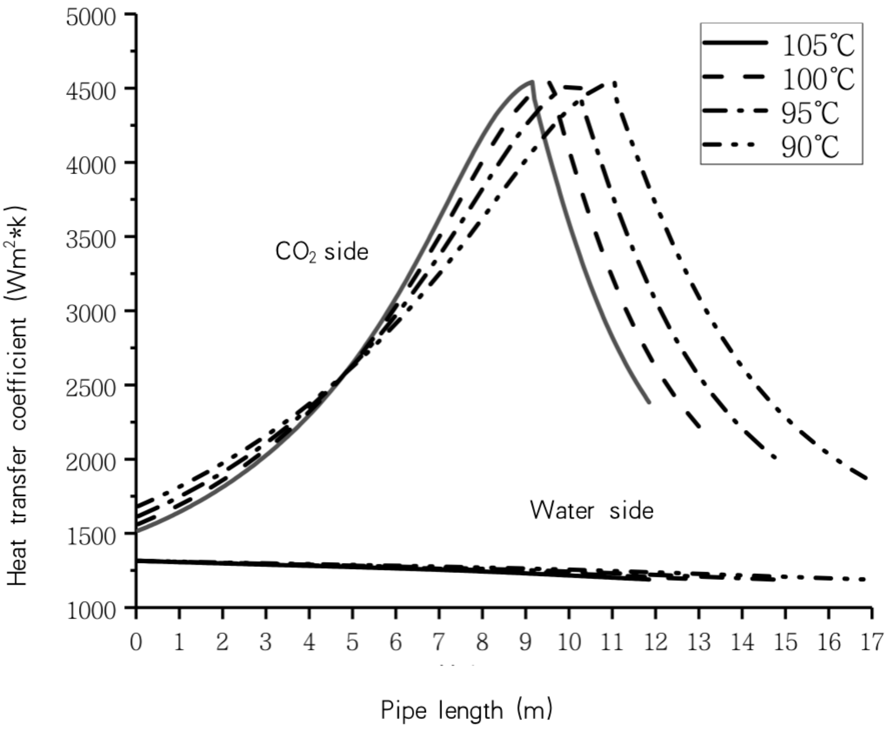

Fig. 5 Heat transfer coefficient changes with inlet temperature

It can be seen from Figures 5 that at the same temperature, the heat transfer coefficient on the CO_2 side first increases and then decreases along the tube length, and there is a peak value of the heat transfer coefficient. The peak value will gradually move back with the temperature drop, but the peak value is basically unchanged. The micro element heat transfer Qi will increase with the increase of the inlet temperature, and the increase is in close proportion to the increase of the temperature. The heat exchange tube length decreases with the increase of temperature. When the CO_2 inlet temperature is Tri=90 ℃, 95 ℃, 100 ℃ and 105 ℃ respectively, the heat exchange tube length is 16.9m, 14.75m, 13.1m and 11.85m.

3.3Impact of CO_2 mass flow

Increasing the mass flow of CO_2 can effectively improve the heat exchange of the system. However, when the mass flow exceeds a certain value and continues to increase, the heat exchange at the evaporator side reaches the maximum value, and the compressor power consumption will continue to increase. At this time, the system performance starts to decline. In addition, excessive mass flow will lead to serious liquid entrainment in the compressor suction, reducing the compressor efficiency, and there will also be potential safety hazards. This paper simulated and analyzed the heat transfer performance of the air cooler under the conditions that the inlet pressure of the air cooler is 11MP, the inlet temperature is 98 ℃, the inlet and return water temperature is 17 ℃/65 ℃, and the water flow rate is 130L/h, and the CO_2 mass flow rate Mr is 30g/s, 40g/s, 50g/s, and 60g/s respectively.

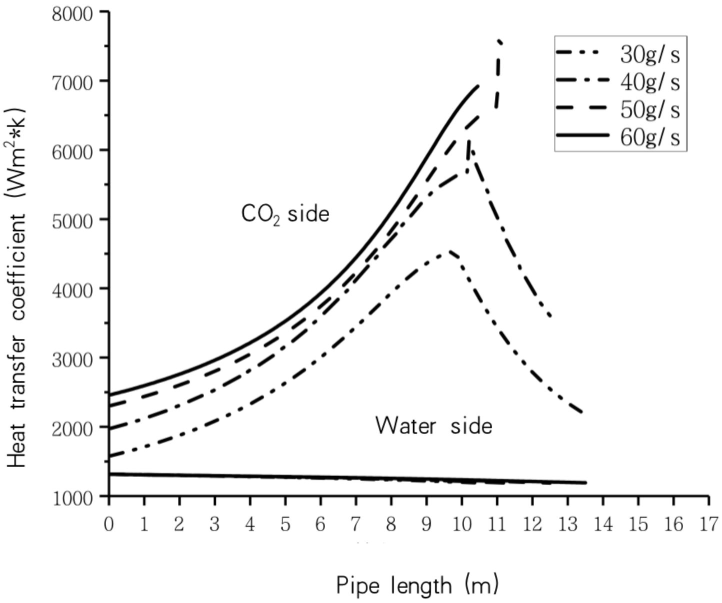

Fig. 6 Heat transfer coefficient changes with mass flow

It can be seen from Figure 6that under the same mass flow rate, the heat transfer coefficient on the CO_2 side still has a peak value along the tube length. When the mass flow rate is greater than 50g/s, the heat transfer has been completed near the peak value, so there is no post drop phenomenon of the heat transfer coefficient. The peak value of CO_2 side heat transfer coefficient increases with the increase of mass flow rate, while the water side heat transfer coefficient is basically unchanged. When the CO_2 mass flow rate Mr is 30g/s, 40g/s, 50g/s and 60g/s respectively, the tube length required for heat exchange is 13.5m, 12.5m, 11.2m and 10.45m respectively, and the required tube length decreases with the increase of CO_2 mass flow rate.

IV. CONCLUSION

The finite volume method is used to establish the simulation model of the casing air cooler of the transcritical CO_2 heat pump water heater. The experimental data are used to fit the correlations of forced convection heat transfer and friction resistance coefficient of supercritical CO_2 in the spiral grooved tube. The correlations are used to establish the simulation model, and the experimental data are used to verify the model. Finally, the effects of CO_2 inlet pressure, temperature and mass flow rate on the heat transfer performance of the air cooler are studied by simulation model. The following conclusions can be drawn:

(1) Using experimental data and multiple regression method, the correlations of forced convection heat transfer and friction resistance coefficient of supercritical carbon dioxide in spiral grooved tubes were fitted. The two formulas were verified with experimental data, and the results showed that the errors of the two formulas were within ± 18% and ± 20% respectively.

(2) The simulation model of air cooler established in this paper is verified by 20 groups of experimental data, and the results show that the relative error of the simulation model is within ± 15%.

(3) The simulation model shows that under the same CO_2 inlet parameters (temperature, pressure, mass flow rate), the heat transfer coefficient at the CO_2 side first increases and then decreases along the tube length, and there is a peak value of the heat transfer coefficient. When the CO_2 inlet pressure drops, the peak value of heat transfer coefficient will gradually move backward, and the smaller the pressure is, the higher the peak value is, and the heat transfer coefficient at the water side is basically unchanged. With the increase of inlet pressure, the heat transfer Qi of micro element section will also increase, and the required heat exchange tube length will decrease.

(4) With the increase of the inlet temperature of the air cooler, the peak value of the heat transfer coefficient on the CO_2 side will move forward, but the value of the peak value is basically unchanged, and the micro element heat transfer Qi will also increase, and the increase in Qi is close to the proportional relationship with the increase in temperature, and the tube length required for heat transfer will also decrease with the increase in temperature.

(5) When the CO_2 mass flow rate is larger, the heat transfer coefficient on the CO_2 side is larger, the peak value is higher, and the micro element heat transfer is larger, so the required heat exchange tube length will also be reduced.

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