Simulation and Experimental Study on the Characteristics of the Gas Cooler in the Simulink CO₂ Heat Pump

F C Xuan¹, J Xie¹,²,³ and Z Gu¹

¹College of Food Science and Technology, Shanghai Ocean University, Shanghai 201306, China
²Shanghai Professional Technology Service Platform on Cold Chain Equipment Performance and Energy Saving Evaluation, Shanghai Engineering Research Center of Aquatic-Product Processing & Preservation, Shanghai 201306, China

E-mail: jxie@shou.edu.cn

Abstract. So as to research impact of inlet temperature of gas cooler on the expression of carbon dioxide hot water unit, the ambient temperature was controlled at 15 °C, and the inlet temperature was adjusted. The exhaust temperature, heating capacity, and system heat exchange capability were calculated. Testing and measuring the change of exhaust temperature, outlet temperature of gas cooler, exhaust pressure, heat exchange capability. Based on simulink simulation tools, a calculation simulation platform of CO₂ heat pump water heaters was established, and a test bench of transcritical CO₂ heat pumps was built. In the experimental simulation, the inlet water temperature was increased from 15 °C to 40 °C, the simulation result of the exhaust temperature increased by 14.2 °C, the heating capacity decreased by 4.69 kW, the heat pump coefficient decreased by 0.66. In the experimental result, the exhaust temperature increased by 18.7 °C, the heating capacity decreased by 4.31 kW, heat pump coefficient decreased by 0.63. The research results can provide some guidelines for the practical application and optimization of transcritical CO₂ heat pump system.

1. Introduction

Environmental problems have always been the focus of global attention. In heat pump systems, the CFCS and HFCS in halogenated hydrocarbons have a destructive effect on the ozone layer, and HFCS will exacerbate global warming. As early as 1997, the amendment of the Montreal protocol pointed out that it was necessary to rely on the development of science and technology, realizing economic and environmental coordination for protecting the ozone layer from being destroyed, and finally eliminate the emissions that destroying the ozone layer. Saving energy, protecting the environment and developing new energy are the eternal themes of the world [1-4]. As a green and environmentally friendly refrigerant, CO₂ has high density, low viscosity, low flow loss, good heat transfer effect, and good thermodynamic properties. Its being used in heat pump systems with unique advantages, and it is an ideal alternative to halogenated hydrocarbon refrigerants. Carbon dioxide heat pump is the trend of hot water production in the future [5-8].

The heat pump is a device that converts low-grade energy into high-grade energy. In the carbon dioxide hot water unit, the CO₂ refrigerant exchanges heat with the cold water for producing high-temperature hot water in the gas cooler. Therefore, heat pumps can be used to replace the using of coal-fired boilers, reducing the use of coals, saving energy, protecting the atmospheric environment,
reducing carbon emissions, and suppressing global warming. The mathematical model and application of CO\textsubscript{2} gas cooler for air-cooled finned tube are introduced in detail. As the number of heat transfer cycles increases the results show that the heat transfer path temperature and heat capacity increase [9]. At present, most scholars stay on the structure of the heat exchanger for the simulation of the gas condenser [10-12], and the inlet water temperature of the gas cooler is only experimental study [13-17]. The calculation and simulation of the working conditions of the gas cooler are few. Therefore, this paper is based on simulation technology, the simulation test is to study by changing the water inlet temperature of the gas cooler, to search the influence of different inlet water temperature on the exhaust temperature, heating capacity and the heating coefficient of the carbon dioxide hot water unit, and comparing the calculation simulation result with the test result analysis. The test provides some guidances for the designing optimization of the carbon dioxide hot water unit.

Energy conservation is an important social consciousness in today's world. We should try our best to reduce energy consumption and increase energy efficiency. According to the definition of energy conservation put forward by the World Energy Council in 1979, it is to take all measures that are doable, economical and practical, environmentally and socially receive to improve the efficiency of energy resources utilization. Carbon dioxide heat pump adopts natural working medium carbon dioxide, which can reduce ozone layer damage and greenhouse effect. In addition, due to the excellent thermodynamic properties of carbon dioxide, it can efficiently refrigerate, reduce power consumption and improve economic benefits.

2. Experimental working principle
Transcritical carbon dioxide heat pump is mainly formed of carbon dioxide compressor, gas cooler, evaporator, throttle valve, regenerator and other components. Its circulation principle is shown in figure 1. CO\textsubscript{2} refrigerant is compressed into high-temperature and high-pressure gas in the compressor, and it enters the gas cooler and exchanges heat with cold water, after being throttled by the throttle valve. CO\textsubscript{2} refrigerant enters the evaporator, and then the carbon dioxide refrigerant absorbs the heat of the surrounding environment, then the CO\textsubscript{2} refrigerant is sucked into the compressor, and is compressed. The system repeatedly circulates for achieving constant hot water.

![Figure 1. Schematic diagram of transcritical carbon dioxide hot water unit](image)

3. The establishment of mathematical models
According to the operating characteristics of the transcritical carbon dioxide hot water unit, the formulas according to the following two assumptions are established. As is shown in the following formulas (1) ~ (6), and the mathematical model of the compressor, gas cooler, evaporator, and hot water storage tank are established [18].

(1) The mathematical model of the CO\textsubscript{2} compressor is a steady-state model, and the mathematical
models of the gas cooler and evaporator are lumped parameter models;  
(2) Ignoring the energy loss of refrigerant in various parts and pipelines;

3.1. Mathematical model of CO₂ compressor

Discharge temperature of compressor:

\[ T_{\text{dis}} = T_{\text{suc}} \left( \frac{P_{\text{dis}}}{P_{\text{suc}}} \right)^{\frac{k-1}{k}} \]  \[ (1) \]

Where \( P_{\text{dis}} \) is the out pressure of compressor, MPa; \( P_{\text{suc}} \) is the entrance pressure of compressor, MPa; \( T_{\text{suc}} \) is the suction temperature of compressor, K.

Input power of compressor:

\[ P_{\text{com}} = \frac{1}{\eta} m_{\text{com}} V_{\text{suc}} \frac{k}{k-1} \left( \frac{P_{\text{dis}}}{P_{\text{suc}}} \right)^{\frac{k-1}{k}} \]  \[ (2) \]

Where \( \eta \) is the electrical efficiency; \( k \) is the adiabatic index of the CO₂ refrigerant, 1.1; where: \( m_{\text{com}} \) is the mass flow rate of the CO₂ refrigerant, kg s\(^{-1}\); \( V_{\text{suc}} \) is the suction specific volume, m\(^3\)kg\(^{-1}\).

3.2. Mathematical model of gas cooler

Energy equation on the refrigerant side:

\[ Q_{\text{g},r} = m_{\text{com}} \times (h_{gr,\text{in}} - h_{gr,\text{out}}) \]  \[ (3) \]

Where \( Q_{\text{g},r} \) is the amount of heat absorbed by the refrigerant, kW; \( h_{gr,\text{in}} \) is enthalpy of the refrigerant inlet, and \( h_{gr,\text{out}} \) is the enthalpy of the refrigerant outlet, kJ kg\(^{-1}\).

3.3. Mathematical model of evaporator

Heat exchange on the air side:

\[ Q_{\text{e},w} = m_{\text{w2}} \times C_{\text{pe},\text{w2}} \left( T_{\text{ew2,in}} - T_{\text{ew2,out}} \right) \]  \[ (4) \]

Where \( Q_{\text{e},w} \) is the amount of heat released on the air side, kW; \( m_{\text{w2}} \) is the mass flow rate of air, kg s\(^{-1}\); \( C_{\text{pe},\text{w2}} \) is the given hot power of air, kJ (kg / °C)\(^{-1}\); \( T_{\text{ew2,in}} \), the inlet temperature of air ,and \( T_{\text{ew2,out}} \) is the outlet temperature of air, K;  

3.4. Mathematical model of storage water tank

The overall energy balance equation of the hot water storage tank:

\[ m C_p \frac{dT_s}{dt} = m C_p (T_{co} - T_s) \cdot UA \cdot (T_a - T_s) \]  \[ (5) \]

Where: \( m \) is the mass of heated water, kg; \( C_p \) is the constant pressure given hot power of water, 1.167 kJ.(kg.K)\(^{-1}\); \( T_s \), the average temperature of the water tank, K; \( T_{co} \), exit temperature of condenser, K; \( U \),water tank Heat transfer factor with the environment; \( T_a \) is the temperature of the surrounding environment, K.

3.5. Simulation modeling

Simulink is a tool for system modeling and simulation in MATLAB software. This study is based on the simulink tool and the mathematical model of the transcritical hot water unit heater system. The boundary condition of the hot water unit is installed: the ambient temperature is 15 °C. As shown in figure 2, the simulink calculation simulation block chart of the heat pump system is established.
Figure 2. Simulink simulation block diagram of cross-critical heat pump water heater

4. Test apparatus and methods

4.1. Test device of transcritical carbon CO₂ hot water unit

According to heat pump standard of GB21362-2008 "Hot Water Unit Heaters for Commercial or Industrial Use and Similar Uses", a test bench of transcritical carbon dioxide hot water unit was built.

The specifications and components of the transcritical carbon dioxide heat pump are displayed in Table 1. The test device of the transcritical carbon dioxide hot water unit is displayed in Figure 3. The flow chart of the water heater system and the temperature, stress, and fluxion test status are expressed at Figure 4.

Table 1. Specifications and models of the ingredients of the trans-critical carbon dioxide hot water unit

| Structural components       | Specification model          | Parameter                                        |
|-----------------------------|------------------------------|--------------------------------------------------|
| Compressor                  | CD750H (CH SALL&DORIN)       | Power: 5.5 kW; Rated speed: 1450 r.min⁻¹;         |
| Gas cooler                  | B17H*49/3P-SC-U&SWEP          | Number of fins: 49; Number of channels: 3        |
| Electronic expansion valve  | CCMT4 & Danfoss              | Velocity: 0.45 m.s⁻¹;                            |
| Evaporator                  | UEN-380-D/03_.H.SS.P-3C(S)   | Number of tube rows: 4 rows; Fin spacing: 3 mm;  |
|                             |                              | Heat exchange area: 3.2 m²;                      |

Figure 3. Cross-critical carbon dioxide heat pump hot water test unit
Figure 4. Test system diagram of transcritical carbon dioxide heat pump water heater

Q—Flowmeter  T—Thermocouple  P—Pressure gauge  W—Power meter

4.2. Experimental method

Calculation and simulation experiment 1: in this experiment, inlet temperature of the gas cooler is changed by controlling the electric heating device, and the control accuracy of the electric heating device is ± 0.5 ℃, to study the influence of different inlet temperature of water on coefficient of hot water unit, heating capacity, exhaust temperature of the hot water unit. Test conditions of the carbon dioxide hot water unit are demonstrated in Table 2. The experiment is carried out in a constant temperature laboratory. The Control parameters is the inlet temperature of the condenser. The variables measured are the entrance temperature, entrance pressure and exit pressure of the compressor, the vast flow rate of the refrigerant, the outlet temperature of the gas cooler, and the volume flow of tap water on trial. Measurement accuracy of measuring tools are shown in Table 3. Inlet fluxion rate of the gas cooler is 30cm³.s⁻¹ on trial. For the sake of ensuring dependability of the measurement information, under the same working condition, starting to record data after 30 minutes of stable operation [19-21]. Through the touch screen of the heat pump, the suction temperature of compressor, entrance pressure and exit pressure of compressor, vast fluxion velocity of refrigerant, and outlet temperature of gas condenser are respectively recorded.

The data are inputted into simulation platform after calculation and measurement. Through the calculation simulation platform, calculating the relationship among the coefficient of heat pump, heating capacity and exhaust temperature of the simulated hot water unit with ingress temperature of gas condenser.

Table 2. Operating conditions of carbon dioxide hot water unit.

| Working conditions | Inlet water temperature (℃) | Ambient temperature (℃) |
|--------------------|-----------------------------|-------------------------|
| 1                  | 15                          | 15                      |
| 2                  | 20                          | 15                      |
| 3                  | 25                          | 15                      |
| 4                  | 30                          | 15                      |
| 5                  | 35                          | 15                      |
| 6                  | 40                          | 15                      |
Table 3. Measurement accuracy of measuring tools.

| Measuring tools                  | Measurement accuracy |
|----------------------------------|-----------------------|
| Piezoresistive pressure sensor   | ±0.5%FS               |
| Glass rotameter                  | ±0.25%                |
| Copper constantan t-type thermocouple | ±0.5℃               |

5. Results and discussion

It is observed from figure 5 that entrance water temperature of gas condenser increases from 15 °C to 40 °C, and the exhaust temperature results of the CO₂ compressor simulation and test show an increasing trend. In actual operation, for preventing the exhaust temperature of compressor from being too high to cause carbonization of lubricating oil, it is necessary to control water entrance temperature of gas condenser, and install a switch of pressure protection in the system if necessary [22]. In experiments and simulations, the temperature of inlet water is increased by 25 °C, and in experiments and simulations, the discharge temperature of compressor is respectively increased by 18.7 °C and 25 °C. As the inlet temperature of the cooling water increases, the temperature difference between the cooling water and the refrigerant decreases, and the enthalpy of the refrigerant outlet increases, so the exhaust temperature increases. The mimetic consequences are contrasted with laboratorial consequences. The experimental consequences of the discharge temperature of compressor are higher than the simulation results. This is because in the actual carbon dioxide heat pump operation, the gas cooler leaks heat to the external surroundings, bring about heat loss. The gas temperature is lower than the calculation simulation result. As the water temperature increases of gas condenser, both the test results and the simulated exhaust temperature add. As is shown in formula (6) and figure 6, and the function relevance between inlet water temperature and exhaust temperature (taking the average value of simulated and experimental exhaust gas temperature) are fitted by MATLAB.

![Graph](image_url)

**Figure 5.** Impacting of different inlet water temperature of gas cooler on exhaust temperature of CO₂ compressor

\[ T_{\text{dis}} = 0.004071T_w^2 + 0.4015T_w + 107.8 \]  

(6)
Figure 6. Fitting image of inlet temperature and exhaust temperature

Available from the figure 7 that the entrance temperature of the gas condenser increases from 15 °C to 40 °C, and the consequences of the carbon dioxide heat pump system simulation and experimental heating show a declining trend. The simulated heating capacity is respectively reduced by 4.31 kW and 4.69 kW. Because the inlet temperature of the cooling water rises, the temperature disparate between cooling water and refrigerant decreases, resulting in a reduction in the heat exchange production of the energy swapper and decrease in the amount of heat produced. In the calculation simulation, the heating production of the carbon dioxide heat pump is always greater than the heating capacity of the test process. This is because during the actual handling of the carbon dioxide heat pump, the gas cooler exchanges heat with the external environment, and there is a certain amount of heat loss. As is shown in formula (7) and figure 8, the function contact between the inlet temperature and the heating capacity (taking the average value of simulated and experimental heating capacity) is fitted by the curve fitting tool of MATLAB.

\[
Q_{g, w} = 0.0003357T_0^2 - 0.2003T_0 + 28.38
\]

(7)
Available from figure 9 that the inlet temperature of the gas cooler increases from 15 ℃ to 40 ℃, and the heat pump coefficient of the experimental and simulation results show a decreasing trend. In the experiment and simulation, the inlet temperature increases by 25 ℃, the experimental and simulated coefficient of heat pump respectively fell by 0.63 and 0.66. In the process of increasing the entrance temperature of the gas condenser tube, the simulation results are always greater than the experimental results, because in the actual handling of the CO₂ heat pump, the CO₂ refrigerant, pipelines and valves will produce resistance and have a certain pressure drop loss. Insufficient heat preservation measures result in a certain amount of heat interchange between the CO₂ refrigerant and the external environment, resulting in heat loss. As is shown in Figure 10, the curve fitting tool is used to fit the function touching between the inlet water temperature and the heat pump coefficient (taking the average value of the simulated and experimental heat pump coefficients) in MATLAB software.

\[ \text{COP} = -0.0001786T_0^2 - 0.01612T_0 + 3.928 \]  

**Figure 8.** Fitting image of inlet temperature and heat production

**Figure 9.** Impacting of different inlet temperature of gas condenser on heat pump coefficient
Figure 10. Fitting image of inlet temperature and heating coefficient

![Graph showing the relationship between COP and T0](image)

Figure 11. Error rate of system performance due to gas cooler of inlet water temperature

We can see this in Figure 11, the error rate between the measure consequences and the simulation results of exhaust temperature is within 10 %, and the they have a good agreement. Available from the figure 11 that error proportion between test value and the simulation value of heat production is within 10 %, and the measure consequences matching well with the computing simulation results. it is observed that from figure 11 that the coefficients of heat pump obtained from the experimental and simulation results show a downward trend, and the error rate of the experimental and simulation results is within 10%. The established mathematical model of the carbon dioxide heat pump is in good agreement with the experimental device.

6. Conclusions and future research orientations

The test bench of transcritical carbon dioxide heat source device built in this experiment can meet the demand for making hot water, and has the advantages of green, environmental protection and reliability. Using a carbon dioxide heat pump can also reduce greenhouse gases and suppress the greenhouse effect. Through calculation simulation and experimental research, the following conclusions are obtained:
(1) Through a combination of calculation simulation and test verification, after comparison, the simulation and test error rate of the discharge temperature of compressor, heating capacity, and heat pump coefficient is within 10 %, and the simulation and test have a high degree of agreement, which proves the mathematical model and calculation method of the CO₂ heat source device components used in this study are feasible, and through the fitted curve, the performance change of the CO₂ heat source device can be predicted.

(2) Through computational simulation and experimental research, at an ambient temperature of 15 °C, the coefficient of heat pump decreases with the increase of the access temperature of gas condenser, energy produced decreases with the increase of the inlet temperature. For the sake of boosting energy efficiency of architecture, inlet water temperature of the gas condenser should be reduced under the condition of satisfying the hot water temperature. At this time, the heat pump coefficient of the CO₂ hot water unit will increase, and discharge temperature of the CO₂ compressor will decrease.

(3) In the process of using the carbon dioxide heat pump, the entrance temperature is closely related to the heating expression of heat source device. The entrance temperature is not as high as possible. The increase of the entrance water temperature will augment the exhaust temperature, which is easy to carbonize the lubricating oil, and the heat exchange efficiency will decrease, resulting in a decrease in the heating capacity. Only so the system will run efficiently and stably.

(4) In this paper, the influence of entrance water temperature of air condenser on heat pump construction was studied. Besides water entrance temperature of air cooler, the influence of entrance water flow change on the system is also very important. In addition, the exhaust stress of the compressor and the evaporation temperature of the evaporator are also key factors affecting the performance of the heat pump. These can be studied through the establishment of simulation models under different working conditions, which are also the direction of future research.

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