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Experimental Study on Performance of CO_2 Heat Pump Water Heater

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Abstract

In this paper, a CO_2 heat pump water heater is tested to study the effects of inlet water temperature, inlet water flow, ambient temperature and relative humidity on its performance. When the inlet water temperature increases from 9℃to 15℃, the outlet CO_2 temperature of the air cooler rises, and the evaporation temperature rises from -2.61℃to -1.60℃, reducing the heat absorption of the evaporator.As the inlet water flow increases from 80L/h to 140L/h, The CO_2 temperature at the outlet of the air cooler decreases due to the intensification of heat transfer in the air cooler, and the evaporation temperature decreases from -2.16℃ to -2.96℃. The increased heat absorption makes the frost more serious. The higher the ambient dry bulb temperature is, the greater the temperature difference between CO_2 and ambient heat transfer is.The heat absorbed by the evaporator becomes greater. The increase of the relative humidity of the inlet air leads to a significant reduction of the heat absorption of the evaporator, which results in deterioration such as the increase of the dryness of the CO_2 at the inlet of the evaporator and the decrease of the CO_2 mass flow.

Keywords:CO_2 *heat pump water heater,experimental study,COP*

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I. INTRODUCTION

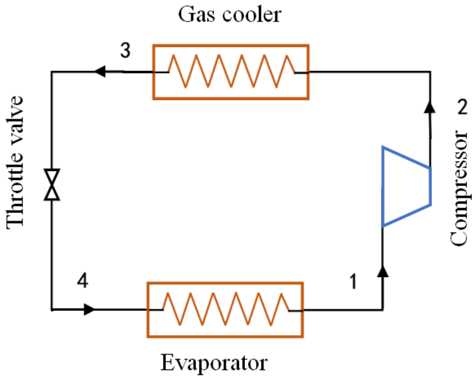
Nowadays, the global energy resource shortage, serious environmental pollution, tight power supply and other issues have become increasingly prominent. According to the statistical data of the World Energy Statistical Yearbook (70th Edition) released by BP, the total global energy consumption decreased by 4.5% year on year in 2020, and the total carbon emissions decreased by 6.3% year on year [1]. China's carbon emissions continued to grow from 2017 to 2020, including 9.899 billion tons in 2020, up 0.7% year on year, accounting for 30.7% of the global total. Therefore, China must assume the responsibility of a big country in terms of environmental protection. Some researchers predict that China will reach a peak of 6.259 billion tons of carbon in 2029 under the low carbon scenario [2].

Among the carbon emissions of various industries in China in 2020, thermal power generation still was the main carbon emission industry [3]. The carbon emissions caused by combustion in electric power production, industrial production, process emissions (metallurgy, cement, chemical industry), direct emissions from the transportation industry, buildings and indirect emissions from northern central heating accounted for 42.6%, 26.6%, 10.6%, 8.5%, 6.4% and 5.3% respectively. A large number of environmental pollution led to the development and utilization of renewable energy has been widely concerned. The comprehensive application of heat pumps in various related fields can reduce the emission of about 1.5 billion tons of CO_2. Under the goal of carbon neutralization and carbon peaking, the vigorous application of heat pumps is of great significance.

As its ODP(Ozone Depletion Potential) equals zero and GWP(Global Warming Potential) equals 1,CO_2 has excellent thermodynamic performance. Ithas no damage to the ozone layer of the atmosphere and can significantly reduce the global greenhouse effect, thus fundamentally solving the problem of environmental pollution.At the same time it has a wide range of sources and does not need to be recycled, which can greatly reduce costs. CO_2 is safe, non-toxic, non-flammable and has good thermal stability and large refrigeration capacity. The unit refrigeration capacity at 0℃ is 5 to 8 times higher than that of conventional refrigerants[4]. Lorentzen proposed the trans-critical CO_2 cycle according to the special physical properties of CO_2[5]. The CO_2 heat release in the air cooler is variable temperature heat release, and there is a large temperature slip in the process, which matches with the water heating process. This greatly reduces the irreversible loss of heat transfer caused by temperature difference, which is incomparable to other working medium air source heat pumps.The advantage promoted the development of CO_2 systems in the field of refrigeration and air conditioning.

II. THEORETICAL CYCLE OF CO_2 HEAT PUMP

CO_2 heat pump cycle is mainly composed of evaporator, compressor, gas cooler and throttling device. The schematic diagram and temperature entropy diagram of the CO_2 heat pump system are shown in Figures 1 and 2. The low temperature and low pressure gas phase CO_2 is compressed by the compressor into high temperature and high pressure gas (process 1-2). After that, CO_2 flows through the gas cooler to transfer heat to the cold water to make its temperature rise, and CO_2 changes to the medium temperature and high pressure state (process 2-3). CO_2 flows through the throttling valve and becomes low temperature and low pressure (process 3-4). The low temperature and low pressure CO_2 absorbs heat at the evaporator, and the liquid refrigerant absorbs heat and evaporates (process 4-1). Different from the traditional subcritical cycle, CO_2 releases heat in the area close to or beyond the critical point. The heat release process is variable temperature heat release with large temperature slip, which can reduce the energy loss caused by heat transfer temperature difference. Compared with 55℃ outlet temperature of traditional heat pump water heater, CO_2 heat pump water heater can produce 65℃ or even 90℃ hot water due to trans-critical cycle. Therefore, CO_2 trans-critical cycle is very suitable for heat pump systems.



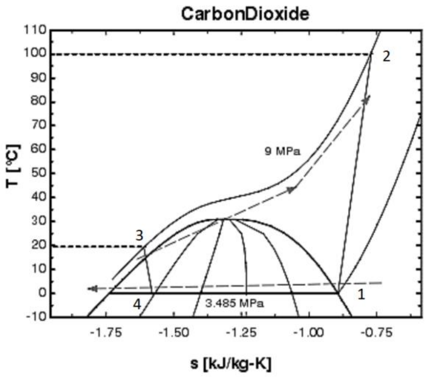


Figure1: Schematic diagram of CO_2heat pumpFigure 2: Working principle of CO_2 heat pump circulation inT-S diagram

III. EXPERIMENTAL SYSTEM

3.1 Flow chart of the experimental system

This research was carried out in the enthalpy difference measurement laboratory. Two refrigeration units of the indoor air system in the laboratory simulated the outdoor environment, and the refrigeration unit of the water system provided constant low temperature cold water. Related experimental research was carried out on a trans-critical CO_2 heat pump water heater. The flow chart of the experimental system is shown in Figure 3.

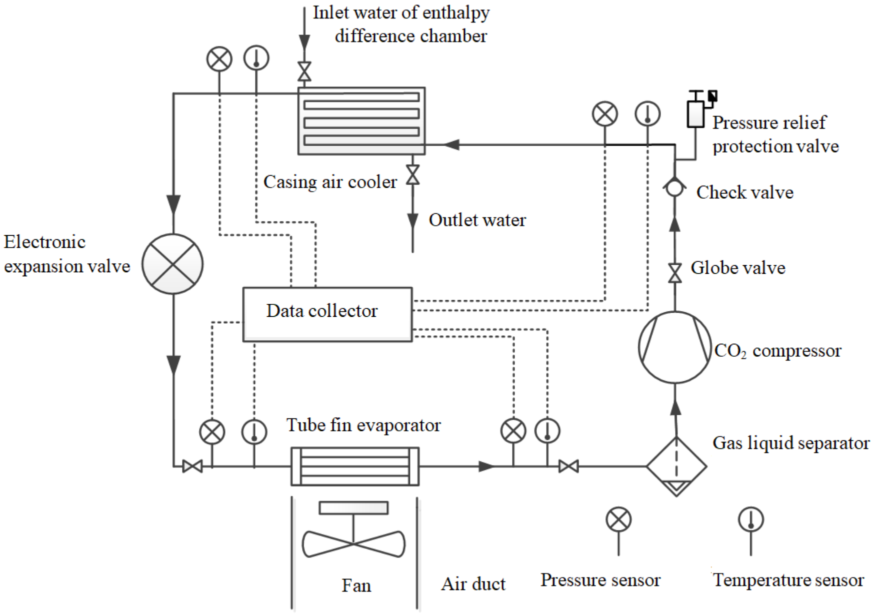


Figure 3: Flow Chart of Experimental System

3.2 Components

The heat pump water heater is composed of piston compressor, casing air cooler, tube fin evaporator, electronic expansion valve and other components.

The heat pump water heater adopts Turin (CD-180-HCO$_2$) semi enclosed piston compressor, with rated heat of 4.61kW, rated input power of 1.4kW, rated air displacement of 1.12m^3/h, and rated speed of 1450 rpm (50 Hz).

The inner tube of the casing air cooler is spiral grooved tube with a diameter of 9.52mm and a wall thickness of 1.5mm. The outer tube made of steel is smooth and straight, with an outer diameter of 16mm and a wall thickness of 1.5mm.Its heat exchange area per unit length is3.73× 10^{-2}m^2, and the design pipe length is 12m. When the heat pump is running, water flows in the pipe and carbon dioxide flows between the inner and outer pipes.

The tube fin evaporator adopts a copper tube with an outer diameter of 7mm and a thickness of 0.41mm. The length of the single hole is 0.86m, the center distance of the copper tube is 18.2mm, and the vertical distance of the tube is 21mm. The fins are flat and straight, 630mm high, 55mm wide and 0.3mm thick. The spacing between adjacent fins is 1.9mm. A fan with rated power of 280w is equipped at the back.

Electronic expansion valve of Japanese Lugong (JKV-24D27) is selected. The maximum allowable differential pressure is 10MPa, the maximum working pressure is 15MPa, and the operating temperature range of environment and fluid is -30℃~70℃.

3.3 Thermal calculation

(1) Heat exchange of air cooler:

$$Q_1 = c_{p,w} \cdot m_w \cdot \Delta t_w \quad (1)$$

(2) System performance coefficient:

$$COP = Q_1 / W \quad (2)$$

(3) CO_2 mass flow:

$$m_r = Q_s / (h_{r,o} - h_{r,i}) \quad (3)$$

IV. RESULT AND DISCUSSION

4.1 Effect of inlet water temperature

The experiment was conducted under the conditions that the dry bulb temperature was 2℃, the wet bulb temperature was 1℃, the expansion valve opening was 15%, and the inlet water flow was 80L/h.According to the requirements of GB/T 23137-2020 Heat Pump Water Heaters for Household and Similar Purposes, the inlet water temperatures were set at 9, 11, 13, and 15℃, and the actual data within 160 minutes of operation were selected for analysis.

Figure 4 and Figure 5 showed the changes of outlet water temperature and COP under different inlet water temperatures. The higher the inlet water temperature, the higher the outlet water temperature, but the smaller COP. When the inlet water temperature was 9, 11, 13 and 15 ℃, the outlet water temperature was 54.8, 56.5, 58.5 and 60.1℃ respectively, and the COP was 2.46, 2.41, 2.37 and 2.34 respectively. The outlet water temperature began to drop significantly (down to below 98% of the maximum outlet water temperature) after 96, 100, 116 and 138 minutes of operation respectively. After 160 minutes of operation, the outlet water temperature dropped to 52.1, 54.3, 57, 58.8℃, meaning the temperature decrease of 2.7, 2.2, 1.5, 1.3℃ respectively. COP dropped to 2.38, 2.36, 2.34 and 2.30 respectively,representing the drop of 3.25%, 2.07%, 1.27% and 0.84%. The lower the inlet water temperature is, the lower the CO_2 temperature at the outlet of the air cooler. This led to the lower the evaporation temperature and frosting,causing the earlier and more severe operation deterioration. At the same time, the higher the inlet water temperature, the greater the system power consumption. In order to delay frost formation, the inlet water temperature can be increased. However, considering the increase of compressor power consumption, the increase range of inlet water temperature needs to be limited.

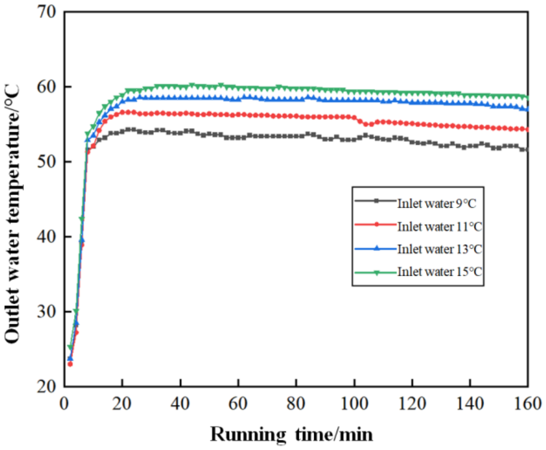


Figure 4: Effect of inlet water temperature on outlet water temperature

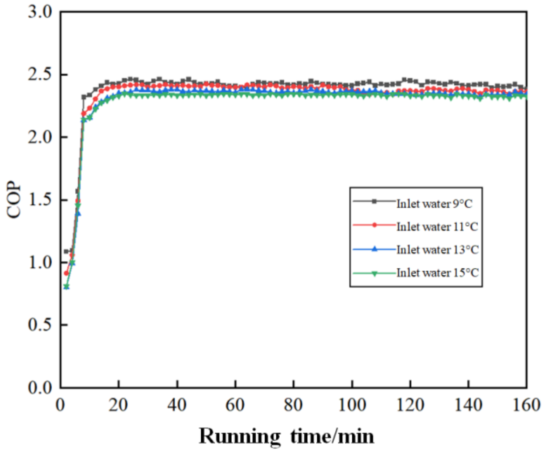


Figure 5: Effect of inlet water temperature on COP

4.2 Effect of inlet flow

When the dry bulb temperature was 2℃, the wet bulb temperature was 1℃, the opening of the electronic expansion valve was 15%, and the inlet water temperature was 9℃, the inlet water flow was set to 80, 100, 120, and 140 L/h . As the inlet water flow was 80 L/h, the outlet water temperature of the heat pump water heater could reach 55℃ under the low temperature environment, which is required by the national standard in China).The effect of the inlet water flow on the operating performance of the tube fin evaporator was studied. Considering that when the water flow was large (such as 120, 140L/h), the outlet water temperature was too low, and the system would automatically shut down after 30 minutes of operation, so only the data within 30 minutes of operation were analyzed.

Figure 6 showed the effect of inlet water flow on outlet water temperature. With the increase of inlet water flow, the heat supply is larger, but the heat obtained by the unit mass flow of cold water decreased, which reduced the outlet water temperature. When the inlet flow was 80, 100, 120 and 140 L/h respectively, the outlet water temperature was 54.8, 49.3, 43.8 and 38.6 ℃.

In Figure 7, it was shown that the larger the inflow, the higher the COP. When the inlet water flow was 80, 100, 120 and 140L/h respectively, the CO_2 mass flow and heating capacity increased accordingly.However the compressor power and the total heat pump power decreased due to the decrease of the exhaust pressure. COP was 2.46, 2.86, 3.08 and 3.19 respectively.

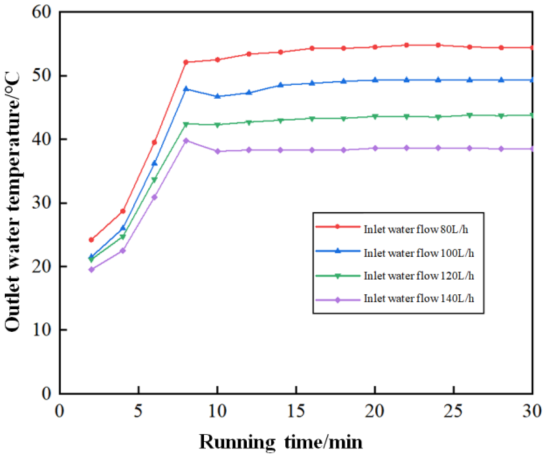


Figure 6:Effect of water flow on outlet water temperature

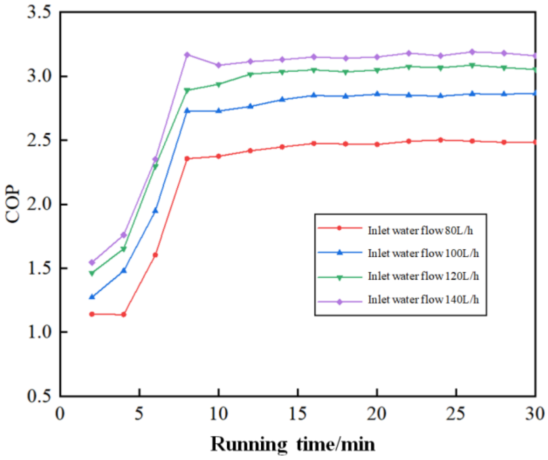


Figure7:Effect of water flow on COP

4.3 Effect of ambient temperature

When the inlet water temperature was 9℃, the inlet water flow was 80L/h, the expansion valve opening was 15%, and the ambient relative humidity was 85%, the experimental data with ambient dry bulb temperatures of -4, -2, 0, 2, and 4℃ were selected for analysis. Since the outlet water temperature of the system in a low temperature environment (such as -4℃) was lower than the set minimum outlet water temperature of

45℃, the system would automatically stop after 30 minutes of operation, only 30 minutes of data were available for the experiment with a dry bulb temperature of -4℃.

Figure 8 and Figure 9 respectively showed the effect of dry bulb temperature on outlet water temperature and COP. The higher the inlet air dry bulb temperature was, the higher the system outlet water temperature and COP were. When the inlet air dry bulb temperature was -4, -2, 0, 2, 4℃, the outlet water temperature was 44.5℃, 47.4, 50.8, 54.8, 56.3℃ respectively, and the COP was 2.15, 2.28, 2.40, 2.46, 2.54respectively. When the dry bulb temperature was 0℃, the outlet water temperature dropped to 49.3℃, meaning the decrease of 1.5℃, and COP dropped from 2.40 to 2.35. When the dry bulb temperature was 2℃, the outlet water temperature and COP decreased from 54.8℃ and 2.46 to 53.1℃ and 2.41 respectively. At 4℃, a large amount of condensation occurs, and the outlet water temperature and COP are stable at 56.3℃ and 2.54℃.

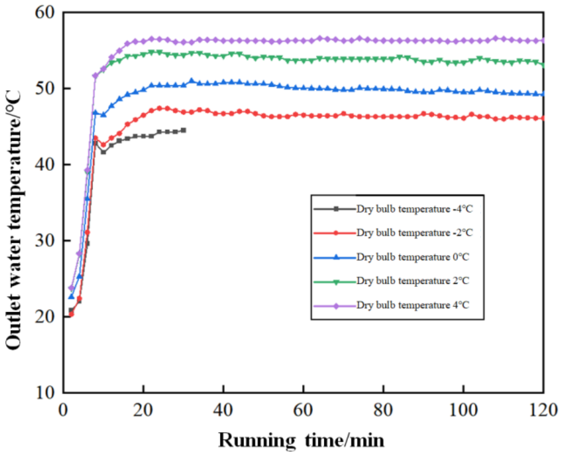


Figure 8:Effect of dry bulb temperature on outlet water temperature

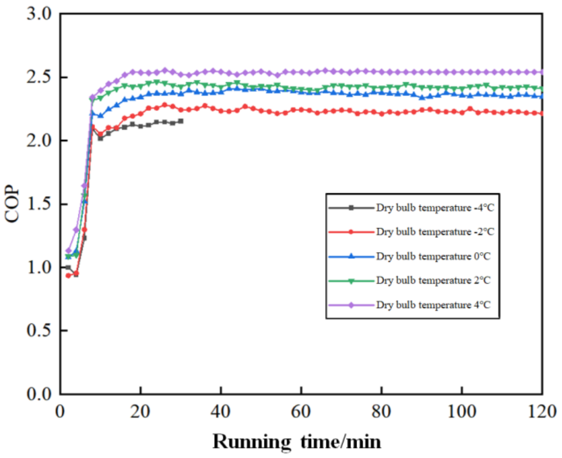


Figure9:Effect of dry bulb temperature on COP

4.4 Effect of environmental humidity

Under the conditions of inlet water temperature of 9℃, inlet water flow of 80L/h, expansion valve opening of 15%, and ambient dry bulb temperature of 0℃, the relative humidity was set to 55%, 70%, 85%, and 100% respectively to study the influence of the change of relative humidity on the operating parameters. The experimental data within 120 minutes of operation were analyzed.

As shown in Figure 10 and Figure 11, when the ambient temperature was 0℃, the outlet water temperature was 50.4℃ and COP was 2.39. When the relative humidity was 55%, there was no condensation or frost. With the increase of relative humidity, the outlet temperature and COP had a downward trend, and the greater the relative humidity was, the greater the decline of effluent temperature and COP. When the relative humidity was 70%, the outlet water temperature and COP began to decline in the 90th minute; After 120 minutes, the outlet water temperature decreased from 50.5℃ to 50.1℃, and COP decreased from 2.392 to 2.386, meaning the drop of 0.79% and 0.25% respectively. When the relative humidity was 85%, the change starts at 56th minute; At 120 minutes, the outlet water temperature decreased from 50.5℃ to 49.4℃, and COP decreased from 2.388 to 2.343, representing the decrease of 2.18% and 1.88% respectively.

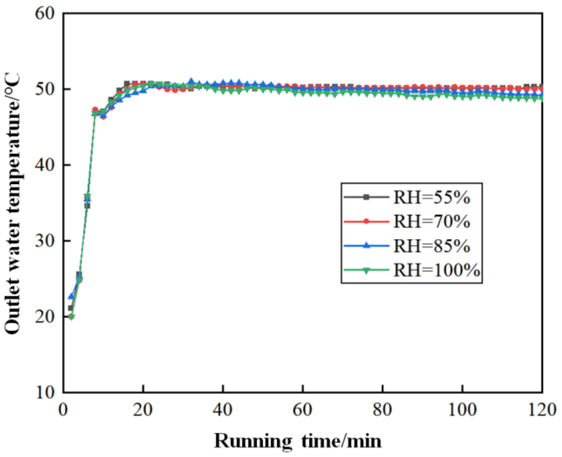


Figure 10: Effect of RH on Outlet Water Temperature

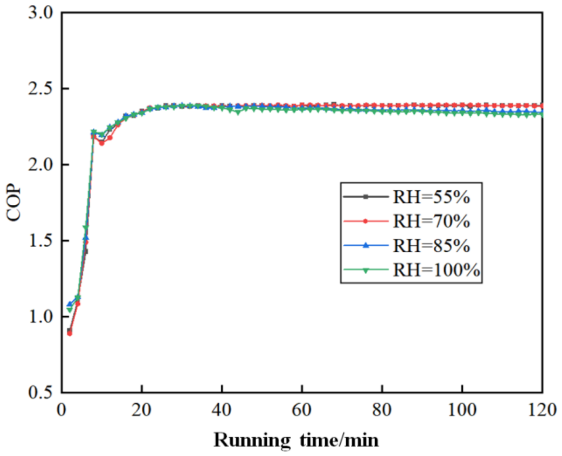


Figure 11: Effect of RH on COP

V. CONCLUSION

In the enthalpy difference measurement laboratory, the CO_2 heat pump water heater was tested and the effects of inlet water temperature, inlet water flow, ambient temperature and relative humidity on its performance were obtained.The conclusions are:

(1) The higher the inlet water temperature, the higher the CO_2 temperature at the outlet of the air cooler, the higher the evaporation temperature, and the lower the heat transfer temperature difference, which will reduce the heat absorption of the evaporator. During the 160 minute continuous operation, when the water inlet temperature rises from 9℃ to 15℃, the frost on the evaporator surface decreases by 57.27%.

(2) The increase of inlet water flow intensifies the heat transfer of the air cooler, and the decrease of CO_2 temperature and evaporation temperature at the outlet of the air cooler leads to the increase of heat absorption of the evaporator. When the inlet water flow increases from 80L/h to 140L/h, the evaporation temperature drops from -2.16℃ to -2.96℃. The greater the heat supply, the less heat the unit mass flow of cold water gets, which reduces the outlet water temperature.

(3) The higher ambient temperature, the higher evaporation temperature. The larger temperature difference of heat transfer leads to the greater the heat absorption of the evaporator. When the ambient dry bulb temperature rises from -4℃ to 4℃, the heat transfer temperature difference increases from 2.2℃ to 5.6℃, the CO_2 dryness at the evaporator inlet decreases from 0.282 to 0.196, and the CO_2 mass flow rate increases from 15.42g/s to 19.77g/s. When the ambient dry bulb temperature is lower than 4℃ and the relative humidity is not lower than 70%, Frost will form on the evaporator surface. When the ambient dry bulb temperature is 2℃ and the wet bulb temperature is 1℃, the tube fin evaporator has the most severe surface frosting and the most obvious performance degradation.

(4) With the increase of relative humidity, the outlet temperature and COP are downward.The greater the relative humidity, the greater the decline of outlet temperature and COP.

REFERENCES

[1]. Liu Lingling Last year, global energy consumption fell by a record 4.5% year on year [N] China Coal News, 2021,7

[2]. Zhang Yang. Research on the prediction of China's energy consumption carbon emissions based on IPSO-LSTM model [D]. North China Electric Power University (Beijing), 2021

[3]. Zhang Junyu, Song Meng, Liu Bowen. Current situation of China's carbon dioxide emissions and emission reduction suggestions [J/OL]. China's land and resource economy: 1-14

[4]. LorentzenG.The use of natural refrigerants: a complete solution to the CFC/HCFC predicament[J]. Int. J. Refrig, 1995,18(3), 190-197.

[5]. Yan Qisen. Refrigeration technology for air conditioning [M] Beijing: China Architecture Press, 2010