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Research on Testing Method of Refrigerant Direct Condensation Radiation Air Source Heat Pump

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Abstract

The refrigerant direct condensation radiation air source heat pump has the advantages of high heat transfer efficiency, good thermal comfort, no water circulation, easy maintenance of the system, and no need for antifreeze measures, which have high promotion value. In this article, three test methods are given for several types of refrigerant natural convection air source heat pumps, and their principles, measurement parameters and calculation evaluation methods are introduced in detail. Finally, specific examples are introduced to provide reference for the formulation of standards.

Keywords: Air source heat pump; Refrigerants; Natural convection; Testing; Standards ;

1. Introduction

In recent years, researchers have developed direct condensation natural convection air source heat pumps to address limitations of conventional heating. These systems feature three main terminal types: direct condensation heat dissipation, indirect condensation heat dissipation, and condensation heat storage dissipation. While multiple structural configurations have been developed and studied through theoretical and experimental work, China currently lacks specific performance test standards for such refrigerant-based natural convection terminals, and the standards that can be referred to are limited to GB/T 13754-2017 “Test methods of thermal output of heating radiators” [1], which applies to the determination of the standard heat dissipation of radiators with water as the heat medium; JGJ 142-2012 “Technical specification for radiant heating and cooling” [2] and JG/T 403-2013 “Test method for thermal performance of radiant cooling and heating unit” [3] apply to the thermal performance measurement of radiation cooling and heating terminals with water as the cold and hot medium or heating cables, and electric heating films as the heating unit. This article proposes targeted testing methods for different structural types of direct condensation natural convection heat pumps, providing crucial references for developing future performance testing standards.

2. Testing Methods

The testing methods for different types of refrigeration and air conditioning equipment are different, mainly due to different circulating media. For common systems, the testing method for air-cooled systems can refer to standard [4], and the testing method for water-cooled systems can refer to standard [5]. The core of the method is to measure the flow rate of the circulating medium, and then obtain the cooling capacity and heating capacity by multiplying it with the enthalpy difference before and after heat exchange.

For testing refrigerant direct condensation radiation air source heat pump system, the key is also to test the flow rate of the refrigerant, the development of testing standards should strive to balance high accuracy and ease of operation, and cover most end structures to avoid overly complex methods.

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2.1. Flow meter method

The test principle of flowmeter method is shown in Fig.1. The measured indoor unit is placed in the indoor environmental control room, while the outdoor unit, flow meter, temperature and pressure measuring points are placed in the outdoor environmental control room. The refrigerant mass flow is obtained by reading the value of the flowmeter in the pipeline, and the heating capacity of the system can be obtained by multiplying the enthalpy difference between the inlet and outlet of the heat dissipation end. Gas flowmeter can be added to the inlet pipe of the indoor unit, or liquid flowmeter can be added to the liquid pipe of the indoor unit.

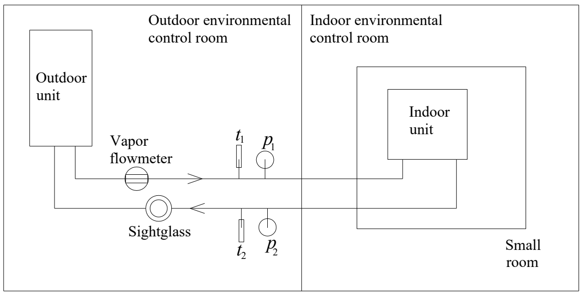


Fig. 1 Testing principle of flowmeter method

The flow meter method is used to calculate the heating capacity and coefficient of performance (COP) of the heat pump system. The calculation is as follows:

$$Q_h = G_m(h_1 - h_2) \tag{1}$$

$$\mathrm{COP} = \frac{Q_h}{W} = \frac{G_m(h_1 - h_2)}{W} \tag{2}$$

2.2. Air enthalpy difference method

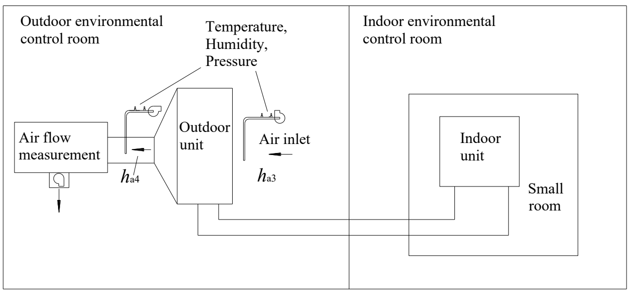


Fig. 2 Enthalpy difference method

The testing principle of the air enthalpy difference method is shown in Fig.2. The indoor unit is placed in the indoor environmental control room, and the outdoor unit and its temperature, pressure and other measuring points are placed in the outdoor environmental control room. The outdoor unit is equipped with an air flow measurement device and air parameter measurement points, which measure the mass flow rate of air and the enthalpy difference at the inlet and outlet of the outdoor unit. By calculating the cooling capacity of the system, the heating capacity of the system can be further determined. Heating capacity and COP:

$$Q_h = Q_l + W = G_a\left(h_{a1} - h_{a2}\right) + W \tag{3}$$

$$\mathrm{COP} = \frac{Q_h}{W} = \frac{G_a\left(h_{a1} - h_{a2}\right) + W}{W} \tag{4}$$

To measure the heating capacity more accurately, temperature and pressure measuring points need to be set up at the inlet of the expansion valve and the outlet of the evaporator inside the outdoor unit. The refrigerant mass flow rate is calculated by the ratio of the cooling capacity to the enthalpy difference between the two measuring points, and finally multiplied by the enthalpy difference at the inlet and outlet of the indoor unit to obtain the heating capacity of the system. Heating capacity and COP:

$$Q_l = G_a\left(h_{a1} - h_{a2}\right) \tag{5}$$

$$G_{\mathrm{m}} = \frac{Q_{\mathrm{l}}}{\left(h_4 - h_3\right)} = \frac{G_{\mathrm{a}}\left(h_{\mathrm{a1}} - h_{\mathrm{a2}}\right)}{\left(h_4 - h_3\right)} \tag{6}$$

$$Q_{\mathrm{h}} = G_{\mathrm{m}}\left(h_1 - h_2\right) = \frac{G_{\mathrm{a}}\left(h_{\mathrm{a1}} - h_{\mathrm{a2}}\right)\left(h_1 - h_2\right)}{\left(h_4 - h_3\right)} \tag{7}$$

$$\mathrm{COP} = \frac{Q_{\mathrm{h}}}{W} = \frac{G_{\mathrm{a}}\left(h_{\mathrm{a1}} - h_{\mathrm{a2}}\right)\left(h_1 - h_2\right)}{\left(h_4 - h_3\right)W} \tag{8}$$

It should be noted that using the air enthalpy difference method to calculate the heating capacity of a system also has some drawbacks. Firstly, when the ambient temperature is low and frost or condensation occurs, accurate measurement cannot be made; Secondly, the outdoor unit's fans, compressors, and other equipment inevitably release heat during operation, and this heat is not included in the calculation, which will affect the accuracy of the results.

2.3. Pipeline calorimeter method

The testing principle of the pipeline calorimeter method is shown in Fig. 3. The indoor unit is placed in the indoor environmental control room, and the outdoor unit, temperature and pressure measuring points are placed in the outdoor environmental control room. An electric heating calorimeter or heat exchange calorimeter is installed in the system pipeline. Electric heating elements are used for heating, and water or other solutions are used for heat exchange (heating/cooling). The electric heating power or the heat change of the working medium is equal to the heat change of the refrigerant in the system pipeline, and then the flow rate of the refrigerant is calculated to obtain the heating capacity of the heat pump system.

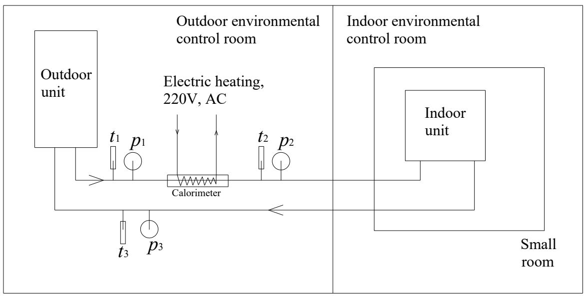


Fig. 3 Testing principle of pipeline calorimeter method (electric heating)

Heating capacity and COP are:

$$G_{\mathrm{m}} = \frac{E}{h_2 - h_1} \tag{9}$$

$$Q_{\mathrm{h}} = G_{\mathrm{m}}\left(h_2 - h_3\right) = \frac{E\left(h_2 - h_3\right)}{h_2 - h_1} \tag{10}$$

$$\mathrm{COP} = \frac{Q_{\mathrm{h}}}{W} = \frac{E\left(h_2 - h_3\right)}{\left(h_2 - h_1\right)W} \tag{11}$$

When the heat exchange calorimeter is used, it can be installed on the inlet pipe of the indoor unit, or installed on the outlet pipe of the indoor unit to cool the refrigerant, so as to avoid the phase change of the refrigerant and ensure the accuracy of the calculation.

When the refrigerant is cooled by water, the testing principle is shown in Fig. 4. the heating capacity and COP of the heat pump system are calculated:

$$G_{\mathrm{m}} = \frac{G_{\mathrm{w}}\left(t_{\mathrm{w2}} - t_{\mathrm{w1}}\right)C_{\mathrm{p}} - K\left(t_{\mathrm{c}} - t_{\mathrm{a}}\right)}{h_2 - h_3} \tag{12}$$

$$Q_{\mathrm{h}} = G_{\mathrm{m}}\left(h_1 - h_2\right) = \frac{G_{\mathrm{w}}\left(t_{\mathrm{w2}} - t_{\mathrm{w1}}\right)C_{\mathrm{p}} - K\left(t_{\mathrm{c}} - t_{\mathrm{a}}\right)}{h_2 - h_3}\left(h_1 - h_2\right) \tag{13}$$

$$\mathrm{COP} = \frac{Q_{\mathrm{h}}}{W} = \frac{G_{\mathrm{w}}\left(t_{\mathrm{w2}} - t_{\mathrm{w1}}\right)C_{\mathrm{p}} - K\left(t_{\mathrm{c}} - t_{\mathrm{a}}\right)}{W\left(h_2 - h_3\right)}\left(h_1 - h_2\right) \tag{14}$$

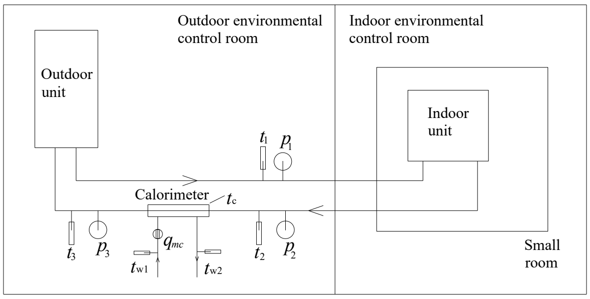


Fig. 4 Testing principle of pipeline calorimeter method (water cooling)

It should be noted that the heat transfer from the surface of the calorimeter to the air may have some errors when calculated using simple methods. Therefore, the calorimeter should be insulated during testing; Secondly, the calorimeter calculates the flow rate by heating and cooling the refrigerant in the pipeline, which changes the temperature of the refrigerant and affects the operation of the heat pump system.

2.4. Comparison and Combination of Testing Methods

There exist four typical configurations and various novel variants for refrigerant natural convection terminals, and distinct terminals exhibit significant discrepancies in heat transfer characteristics and installation modes. The combined application of three testing methods (primary measurement plus auxiliary measurement, with a deviation of ≤ 5%) can satisfy the testing requirements of all types of terminals: the flowmeter method ensures measurement accuracy, the air enthalpy difference method guarantees operational convenience, and the pipe calorimeter method provides adaptability to special scenarios, thereby serving as a comprehensive performance verification tool for technological iteration. A detailed comparison of the three distinct testing methods is presented in Table 1.

Table 1 Comparison of Three Distinct Testing Methods

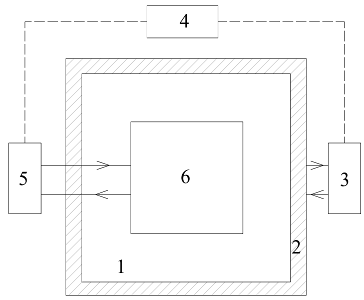
Testing Methods	Flow Meter Method	Air Enthalpy Difference Method	Pipeline Calorimeter Method
Core Principle	Measure refrigerant mass flow rate + enthalpy difference at terminal inlet/outlet, and calculate the heating capacity	Measure outdoor-side air flow rate + enthalpy difference, and back-calculate the heating capacity	Measure the power of the calorimeter + enthalpy difference, and back-calculate the heating capacity
Accuracy	High (directly measures core refrigerant parameters)	Medium (susceptible to environmental interference)	Medium (affected by thermal insulation and phase change)
Error Sources	Flowmeter accuracy; deviation in refrigerant thermophysical property parameter query	Condensation/frosting; heat dissipation leakage of the outdoor unit; enthalpy difference calculation error	Calorimeter heat dissipation; refrigerant phase change; temperature measurement deviation
Core Advantages	Accurate data; compatible with all terminals; low modification cost	No pipeline modification required; rapid testing; user-friendly for on-site sampling inspection	Adaptable to embedded terminals; capable of controlling refrigerant states
Main Disadvantages	Relies on flowmeter accuracy; high cost; requires precise selection for small-diameter terminals	Interference from outdoor unit heat dissipation; ineffective under low-temperature operating conditions	Calorimeter heat dissipation error; affects the system operating state
Applicability	All terminal types; preferred for laboratory calibration and factory inspection	Wire-tube/heat-pipe types (exposed terminals); normal-temperature, frost-free operating conditions; preferred for routine performance testing	Plate-tube/capillary types (concealed terminals); phase-change operating conditions requiring control; mainly used for auxiliary verification

To ensure measurement accuracy, two methods are used for measurement: main measurement and auxiliary measurement. The difference between the two measurement results is controlled within a certain range, and the average of the two is taken as the heating capacity of the heat pump system.

3. Small Room Requirements

There are also strict requirements for the specific structure of the chamber. Here, only a brief introduction is given. The specific content can refer to GB/T 13754-2017 "Test methods of thermal output of heating radiators" and JG/T 403-2013 "Test method for thermal performance of radiant cooling and heating unit".

The schematic diagram of the small chamber testing device is shown in Fig. 5. The net size inside the chamber is: length (4.00±0.02) m; width (4.00±0.02) m; the height is 2.80 m ~ 3.00 m. A circulating air layer or a water inter-layer is laid outside the six walls of the chamber, and a special treatment device is provided to adjust the temperature of the chamber under different working conditions. When the chamber is cooled by air, the average velocity of the air in the inter-layer should be 0.1~0.5 m/s; When the chamber is cooled by water, the total flow rate of cooling water should not be less than 6000 kg/h, and the water flow rate in each wall inter-layer should be controllable separately.



1---Cell
2---Cooling(heating) wall
3---Cooling(heating) wall temperature control device
4---Instrument and equipment for detection and control
5---Outdoor unit of heat pump
6---Radiation end

Fig. 5 Schematic diagram of chamber testing device

In addition to the standard regulations for the structure of the small chamber, there are also strict requirements for the installation position of the tested radiation end. For the radiation end of a structure similar to a conventional radiator, it should be parallel to the wall where it is installed and symmetrical to the center-line of the wall, with a spacing of (0.050±0.005) m, and the bottom should be parallel to the floor of the small room, with a spacing of (0.11±0.01) m. For the end attached to the wall or floor, the projection area of the test product should not be less than 20% of the installation surface area. The size of the product installed on the ground or the top surface should be 1.0 m ~ 3.4 m long and 1.0 m ~ 3.4 m wide, while the wall installation test product should be 1.0 m ~ 2.2 m high and 1.0 m ~ 3.4 m wide.

4. Test Examples

The flowmeter method is introduced as an example. The performance testing principle of an air source heat pump with a heat pipe natural convection end is shown in Fig. 6.

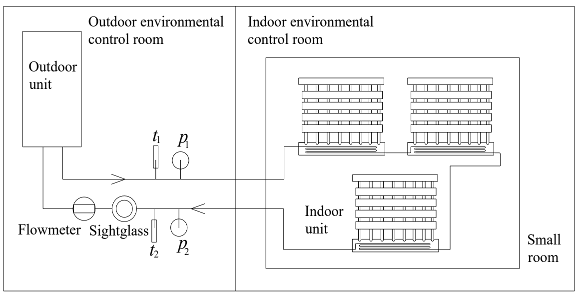


Fig. 6 Schematic diagram of the testing principle of an air source heat pump with heat pipe radiators

The heat pump adopts a compressor with a rated power of 3 HP, and the evaporator uses a finned tube evaporator. The condenser, which is the indoor heating end, is a sleeve heat exchanger/heat pipe radiator. The working fluid of the heat pump is R410A, and the working fluid of the heat pipe is R134a. During experimental testing, an outdoor unit consisting of a compressor, evaporator, throttle valve, and reservoir is installed on the outside of the room, while a heating end composed of a composite structure of heat pipe radiators and condensing coils is installed on the indoor side. According to the test requirements, the temperature, humidity, pressure, power, flow and other data are collected. Through the calculation and analysis of the data, the start-up characteristics, temperature distribution law, frosting/defrosting law of the heat pump system, as well as the heating capacity and heating COP of the unit under different operating frequencies are obtained.

According to the formulas (1) and (2):

$$Q = f(G_m, p_1, t_1, p_2, t_2) \tag{15}$$

$$COP = f(G_m, p_1, t_1, p_2, t_2, W) \tag{16}$$

$$u_Q = \sqrt{\left(\frac{\partial f}{\partial G_m} u_{G_m}\right)^2 + \left(\frac{\partial f}{\partial t_1} u_{t_1}\right)^2 + \left(\frac{\partial f}{\partial t_2} u_{t_2}\right)^2 + \left(\frac{\partial f}{\partial p_1} u_{p_1}\right)^2 + \left(\frac{\partial f}{\partial p_2} u_{p_2}\right)^2} \tag{17}$$

$$u_{COP} = \sqrt{\left(\frac{\partial f}{\partial G_m} u_{G_m}\right)^2 + \left(\frac{\partial f}{\partial t_1} u_{t_1}\right)^2 + \left(\frac{\partial f}{\partial t_2} u_{t_2}\right)^2 + \left(\frac{\partial f}{\partial p_1} u_{p_1}\right)^2 + \left(\frac{\partial f}{\partial p_2} u_{p_2}\right)^2 + \left(\frac{\partial f}{\partial W} u_W\right)^2} \tag{18}$$

$$u_{rel,Q} = \frac{u_Q}{Q} \tag{19}$$

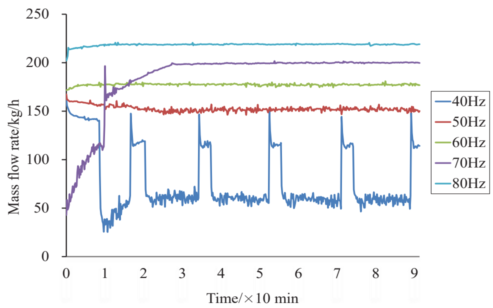
$$u_{rel,COP} = \frac{u_{COP}}{COP} \tag{20}$$

Table 2 shows the performance parameters of the main instruments and meters used in the experiment. During the experiment, the Agilent 34970A data collector was used to convert data information into digital signals. The results were updated every 10 seconds and displayed in real-time in computer software, stored in Excel format for further analysis and processing.

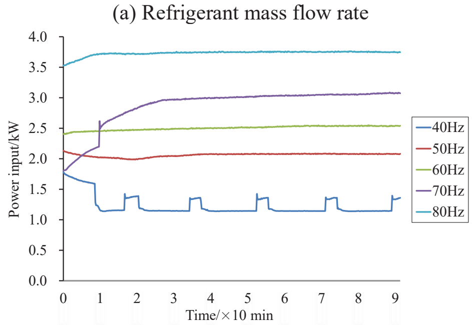
Table 2 Parameters of measurement instruments

Instruments	Parameters	Range	Accuracy
PT100	temperature /℃	-150~150	±0.15℃
Pressure sensor	pressure /MPa	-0.1~4.5	±0.2%
Flow meter	refrigerant flow rate（kg/h）	0~150	±0.2%
Power meter	compressor power input /kW	----	±0.5
Data collector	----	0~100mA	±0.2%

The performance of the heat pump system when the compressor is running at different frequencies is tested. In the experiment, the indoor temperature is set to 20 ℃, the outdoor temperature is-10 ℃, and the compressor is operated at a fixed frequency of 40 /50/60/70/ 80 Hz, respectively. The flow meter data is read from the start of the system as shown in Fig. 7 (a), and then the system power input changes with time as shown in Fig. 7 (b).



(a) Refrigerant mass flow rate



(b) Power input

Fig. 7 Performance of heat pump system under different compressor frequency

The heating capacity and COP of the system can be further calculated, and their changes are shown in Table 3. By analyzing the data diagram and data table, it can be seen that the heating capacity and power input of the system increase with the increase of compressor frequency, while the COP of the system decreases with the increase of compressor frequency. When the compressor is running at 50 Hz, the performance of the system is the best, but the heating capacity is the smallest. At 80 Hz, the heating capacity of the system is the largest, but the heating performance of the system is the worst.

Table 3 System performance at different frequencies

Frequency (Hz)	Heating capacity (kW)	Absolute uncertainty of heating capacity(W)	Relative uncertainty of heating capacity(%)	Power input (kW)	COP	Absolute uncertainty of COP	Relative uncertainty of COP(%)
50	8.42	270.1	3.21%	1.81	4.65	0.158	3.40%
60	9.44	286.8	3.04%	2.29	4.12	0.132	3.20%
70	10.57	303.5	2.87%	2.82	3.74	0.112	3.00%
80	11.58	320.2	2.76%	3.37	3.44	0.098	2.85%

Shao et al. experimentally measured that, for a novel direct condensation heating terminal applied in the air-source heat pump system, the uncertainties of its heating capacity and COP fall within the ranges of 1.51%–3.10% and 1.68%–3.79%, respectively [6]. The uncertainty of the test results obtained in this study is consistent with the above-mentioned range.

5. Conclusion

At present, there is a lack of performance testing standards for air source heat pumps with natural convection refrigerants. This article refers to the existing performance testing standards for household heat pump terminals driven by hot water, summarizes and generalizes the relevant testing methods, and the measurement of refrigerant flow rate is the key to performance testing. All three testing methods are based on commonly used testing schemes, so it is only necessary to make appropriate modifications to existing equipment without adding too many devices. Based on the heat transfer characteristics of the main structural types at the end, a combination of different testing methods has been developed to provide reference for the performance testing methods and related standards of refrigerant direct radiation heating air source heat pumps.

Nomenclature

Symbol	Meaning	Unit	Symbol	Meaning	Unit
Q	Heat exchange capacity	W	W	Measured heat pump power	W
G	Mass flow rate	kg/s	t	Temperature	K
E	Electric heating power of the electric heater	W	p	Pressure	Pa
h	Specific enthalpy	J/kg	u	Parameter uncertainty	/

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