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Design of New Heat Pump Dryer System: A Case Study in Drying Characteristics of Kitchen Waste

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Abstract

Existing kitchen waste treatment equipment primarily employs biological cultures for high-temperature fermentation of kitchen waste during the secondary decomposition stage. The temperature inside the fermentation chamber is mainly achieved by heating the air through electric heating tubes. However, this method of electric heating still possesses numerous shortcomings, such as high power consumption and significant energy loss. Given the aforementioned reasons, this article proposes a heat pump drying device specifically designed for the moisture removal process during the fermentation treatment of kitchen waste. This device effectively removes the moisture generated during the fermentation of kitchen waste and assists the electric heating unit in the biomass waste treatment equipment in heating the fermentation chamber, thereby reducing electricity consumption.The closed-loop heat pump drying system can continuously introduce hot, low-humidity air into the fermentation chamber through a circulating fan to remove moisture from kitchen waste.To investigate the dehumidification performance of this device, this article varies the airflow rate of the circulating fan in the heat pump drying system and the inlet water temperature of the plate heat exchanger, achieving changes in the airflow through the dehumidification evaporator and the condensation temperature of the system. Under experimental conditions, the range of the coefficient of performance (COP) achieved by the device is between 3.07 and 5.39; the specific moisture extraction rate (SMER) ranges from 0.62 to 1.81 Kg/(Kw·h), and the moisture removal rate (Mr) ranges from 1.9 Kg/h to 8.2 Kg/h.

Keywords

Heat Pump Drying System; Coefficient of Performance (COP); Compressor; Drying Chamber; Specific Moisture Extraction Rate (SMER).

1. Introduction

Drying technology is a crucial component in the production processes of numerous industries.In industrial production, the energy consumed by the drying process accounts for approximately 15% of the total industrial energy consumption[1].During the drying processes in various fields, there exist issues of low energy utilization efficiency and significant energy loss. The exhaust gas emitted during the drying process not only pollutes the environment but also carries away a significant portion of the energy[2].Traditional drying technologies also have many shortcomings, such as being heavily influenced by weather conditions and even causing issues with product quality and standards. In the field of drying, it is imperative to research and develop drying equipment that is both energy-efficient and environmentally friendly[3-4].

Depending on different heating methods, the common drying systems can be divided into fuel oil/gas heating drying system, electric heating drying system, vacuum drying system and heat pump drying system and so on[5-6].The research found that both the oil or gas-fired heating

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drying system and the electric heating drying system have the advantages of simple structure, flexible operation, convenient application, etc., but they still have some disadvantages such as high operation cost, low energy utilization rate, and greater safety risks[7].Due to the ability to achieve thorough drying, vacuum drying technology is particularly suitable for the drying of parts with complex shapes. However, it is difficult to be widely used in the industrial field because of high energy consumption, complex structure and large initial investment[8-9].Heat pump drying is a drying technology using the principle of heat pump (HP) and has many advantages such as high energy efficiency, wide temperature adjustment range, high drying efficiency, good drying quality and Variety in form and structure[10-12].

According to the system structure, the HP drying system can be divided into three types: open system, semi-open system and closed system.As is known, the closed loop heat pump drying (CLHPD) system can achieve environmentally friendly drying since exhaust gas is not emitted into the atmosphere, and its energy efficiency ranges from 5.3% to 91.95% depending on the temperature, operation parameters and material[13].This indicates that heat pump drying systems possess the characteristic of low energy consumption.Therefore, it can be inferred that in the field of green industrial drying, HP drying technology also has broad application prospects.

Appropriate state of circulating air in a heat pump drying system is an important means to achieve energy-efficient drying.REN Yan et al.and CHEN Zhongwei et al.studied the impact of circulating air volume on the performance of a closed heat pump drying system. The results showed that within a certain range, as the circulating air volume increases, the drying temperature decreases, and the COP (Coefficient of Performance) increases. However, the MER(Moisture extraction rate) and the SMER(Specific moisture extraction rate)of the system both increase initially and then decrease.[14]M. Ashok Kumar and his team conducted drying experiments on Moringa leaves in a closed heat pump drying system. Their research showed that reducing the pressure of circulating air and increasing the flow rate of circulating air can significantly shorten the drying time.[15].

Combining heat pump systems with other drying methods is also an important trend in the development of drying technology. QIU Yu et al.has developed a new type of solar-assisted heat pump drying system. Research shows that the maximum COP (Coefficient of Performance) of this system is 3.49, and it can save 40.53% of the system's energy consumption.[16]Zhang et al set up an experimental platform to conduct a comparative analysis of two different drying systems: the solar-heat pump combined drying system and the conventional hot air drying system. The research results found that the solar energy supply air duct provides energy to the heat pump due to the higher average value of the solar heating coefficient. This results in an increase in the COP (Coefficient of Performance) of the heat pump after heat supply by approximately 2.0, achieving energy savings of about 70%.[17]Liu Yunhong used an ultrasonic-combined heat pump system to dry slices of kiwi fruits, and the results showed that as the ultrasonic power increased, the drying rate also increased.[18].

Structural modifications to heat pump systems are also an important method to enhance system performance.ZHOU Pengfei et al.took into account the working principle of the two-stage compression system and used a low-temperature heat pump to provide supplementary heat for the drying heat pump to assist in drying wood. The research showed that compared to when the supplementary heating system was not activated, after turning on the low-temperature heat pump, the exhaust temperature of the drying heat pump decreased, the drying time was reduced, and both the heating capacity and the COP (Coefficient of Performance) were improved.[19]QIN designed a new type of normally closed heat pump drying system with dual evaporators, and carried out selection calculations for various components of the system. Experimental research on this heat pump system showed that within a certain range, the higher the temperature, the faster the drying rate.[20]Zhang et al.

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proposed a combined heat pump drying device and conducted experimental research on it. The device is suitable for multiple circulation modes. The study found that changes in air bypass have a significant impact on the dewatering rate of the closed heat pump system. When the system's SMER reaches its maximum value, the air bypass ratio is 0.4 or 0.6, while the open heat pump drying system has a lower dewatering rate.[21].

In addition, the choice of refrigerant also has a certain impact on the performance of heat pump drying systems, and exploring suitable refrigerants is one of the current research hotspots.Dai Baomin et al. adopted a closed heat pump drying system using a CO_2/R32 refrigerant mixture, and found that compared to a heat pump system using pure CO_2 refrigerant, the new system using the refrigerant mixture had improved COP (Coefficient of Performance) and SMER (Specific Moisture Extraction Rate). Additionally, compared to traditional drying methods, the power consumption of this system was significantly reduced.[22].

In summary, in recent years, scholars have primarily adjusted the drying and dehumidifying capabilities of devices by changing relevant parameters of heat pump systems such as airflow, condensing temperature, or evaporating temperature. Meanwhile, some scholars have also modified the structures of traditional heat pump drying systems and designed various heat pump drying devices with different forms. For the kitchen waste heat pump drying system, the fermentation chamber requires a relatively high temperature. In this study, certain modifications were also made to the traditional heat pump drying device, such as installing a plate heat exchanger. The heat generated by the circulating water through the plate heat exchanger can increase the temperature of the fermentation chamber, partially replacing the role of electric heating, which has practical significance for energy saving.By adjusting the inlet water temperature of the plate heat exchanger to indirectly change the condensing pressure of the system, and adjusting the speed of the circulating fan to change the airflow through the dehumidifying evaporator,the dehumidification capacity and specific moisture extraction rate (SMER) of the heat pump drying device will be altered. This study aims to investigate the dehumidification performance of the heat pump drying device, providing reference for the research and optimization of closed heat pump drying systems.

Nomenclature

ρ	density of air kg/m3
v	circulating air velocity m/h
τ	drying time h
a	accuracy of measurement instrument
u	Uncertainty
d	moisture content (g/kg) of air
COP	coefficient of performance
Q_k	heating capacity kw
P_c	the power of the motor for the compressor
SMER	specific moisture extraction rate

Subscript

w	water
in	inlet
out	outlet

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2. System Composition and Principle

The CLHPD system designed in this paper is shown in Fig. 1. The system mainly consists of compressor, condenser, electronic expansion valve, evaporator,Plate heat exchanger, subcooler,material drying chamber, fans,Electronic Expansion Valve etc., which the main equipment and related parameters as Tab.1.This system uses R134a as refrigerant and air as drying medium.

The system contains two air ducts, inner and outer. The inner duct serves to dry the kitchen waste in the material room, while the outer duct can be used to cool the room and lower the room temperature. Fig.2.shows the composition of the inner and outer ducts. The cooling schematic of the system is shown in Fig.3.

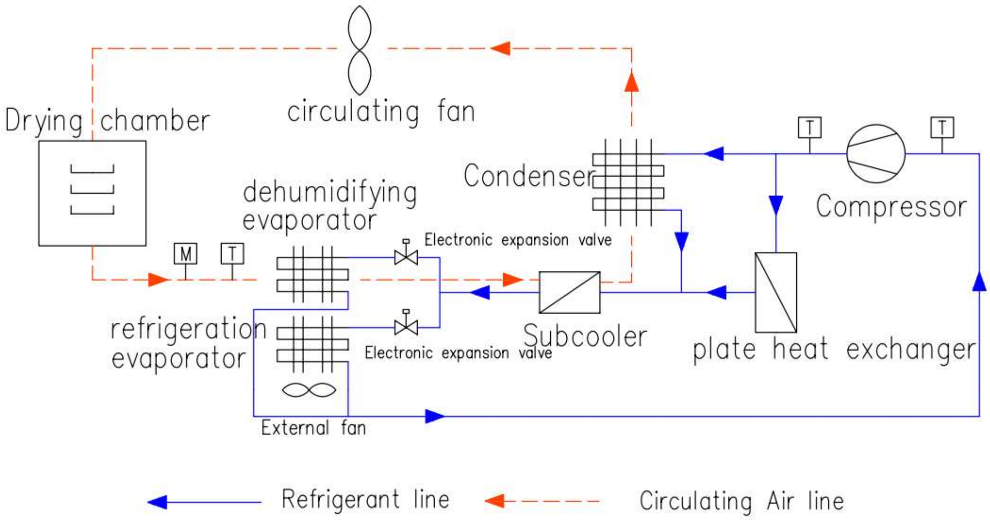

Fig. 1 Schematic Diagram of System Principles

Table 1. Main equipments and related parameters of the system

Equipment Name	Model	parameter
compressor	ZB38KQE-TFD	Power:1.315kw;Rated Heating Capacity:4.81kw;Exhaust Volume:34.77m^3/h
condenser	Finned Copper Tube Heat Exchanger	Copper Tube Specification:ф9.52mm×0.3mm;Fin Thickness:δ=0.115mm;Effective Length:23.76m
Dehumidifying evaporator	Finned Copper Tube Heat Exchanger	Copper Tube Specification:ф9.52mm×0.3mm;Fin Thickness:δ=0.115mm;Effective Length:31.68m
Refrigeration evaporator	Finned Copper Tube Heat Exchanger	Copper Tube Specification:ф9.52mm×0.3mm;Fin Thickness:δ=0.115mm;Effective Length:69.72m
subcooler	Finned Copper Tube Heat Exchanger	Copper Tube Specification:ф9.52mm×0.3mm;Fin Thickness:δ=0.115mm;Effective Length:7.92m
Electronic Expansion Valve	DPF(TS1)3.2C-01	Step Range:0~500;Nominal Capacity:10.7kw;Tube Diameter:3.2mm
circulating fan	Axial Flow Circulating Fan	air volume:0~0.3m^3/s
External Fan	Axial Flow Circulating Fan	air volume:0~0.8m^3/s
Plate heat exchanger	Finned Copper Tube Heat Exchanger	Copper Tube Specification:ф9.52mm×0.3mm;Fin Thickness:δ=0.115mm;Effective Length:37.1m
Storage Tank	JHC-1HP	2L
Temperature Sensor	NTC Thermistor	Measurement Range: -50~100℃; Accuracy: ±0.1℃

Anemometer	EE70-VT62B5	Measurement Range: 0~10m/s; Accuracy: ±(0.1m/s+2.0%Measured Value)

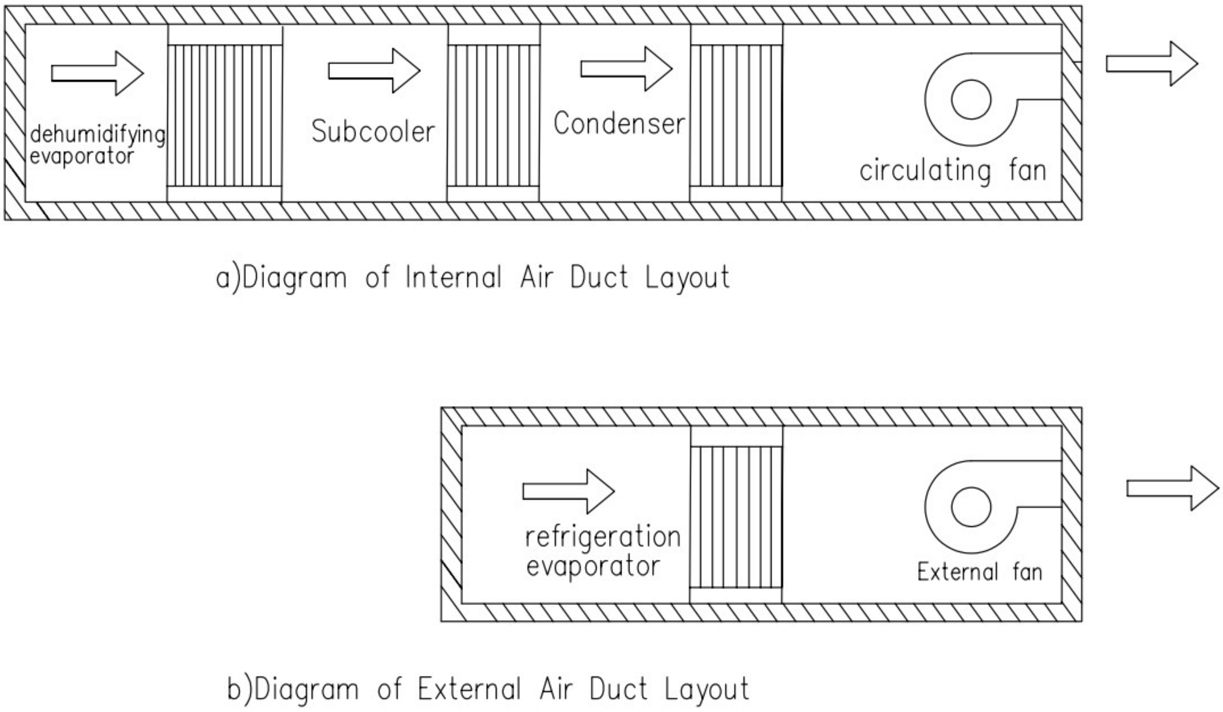

Fig. 2 Internal and External Air Duct System Diagram

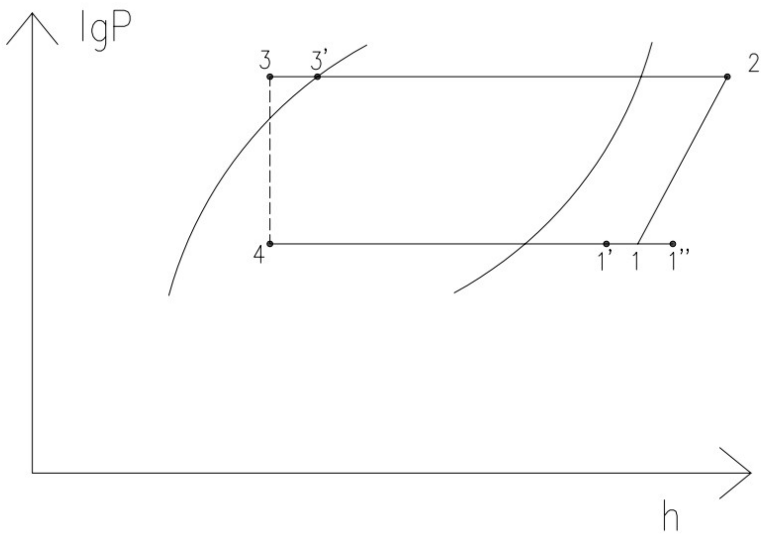

Fig. 3 Schematic Diagram of System Refrigeration

The high temperature and high pressure refrigerant discharged from the compressor (state point 2) is divided into two parts, one of which flows through the condenser and exchanges heat with the circulating air in the inner duct in the condenser, and the other part flows through the plate heat exchanger and exchanges heat with the test water in the water tank, and finally the two parts of the refrigerant are mixed to become the saturated refrigerant (state point 3').At this time, the saturated refrigerant flows into the subcooling device and exchanges heat with the circulating wind in the inner duct and then flows out in the subcooling state (state point

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3).A portion of the refrigerant flows through the electronic expansion valve 1, after throttling and pressure reduction into a low-temperature, low-pressure refrigerant (state point 4), and then flows through the dehumidification evaporator and from the material room out of the humid air heat exchange, the wet air cooling and dehumidification, into a gaseous refrigerant (state point 1"). Another part of the refrigerant flows through the electronic expansion valve 2, after throttling and pressure reduction and then flow through the refrigeration evaporator and air heat exchange, reduce the temperature of the indoor air into a gaseous refrigerant (state point 1') The two parts of the refrigerant after mixing (state point 1) and then into the compressor for compression to complete a refrigeration cycle

3. Experimental Research

3.1. Measurement Method

To determine the dehumidification performance of the heat pump drying device performance test bench, parameters such as the dehumidification capacity, heating capacity, and power of the test bench need to be acquired. Fig. 4 shows the layout of the measurement points in the internal air duct. Temperature and humidity meters 1 and 2 are used to measure the temperature and humidity of the air entering and exiting the drying chamber in the internal air duct. Temperature and humidity sensors 1 and 2 are used to measure the temperature and humidity of the air after flowing through the dehumidification evaporator and the subcooling device. An anemometer is used to measure the air velocity entering the material chamber.

Once the device operation stabilizes, it can be considered that the air temperature and humidity inside the material chamber are equivalent to the temperature and humidity of the air entering the dehumidifying evaporator.

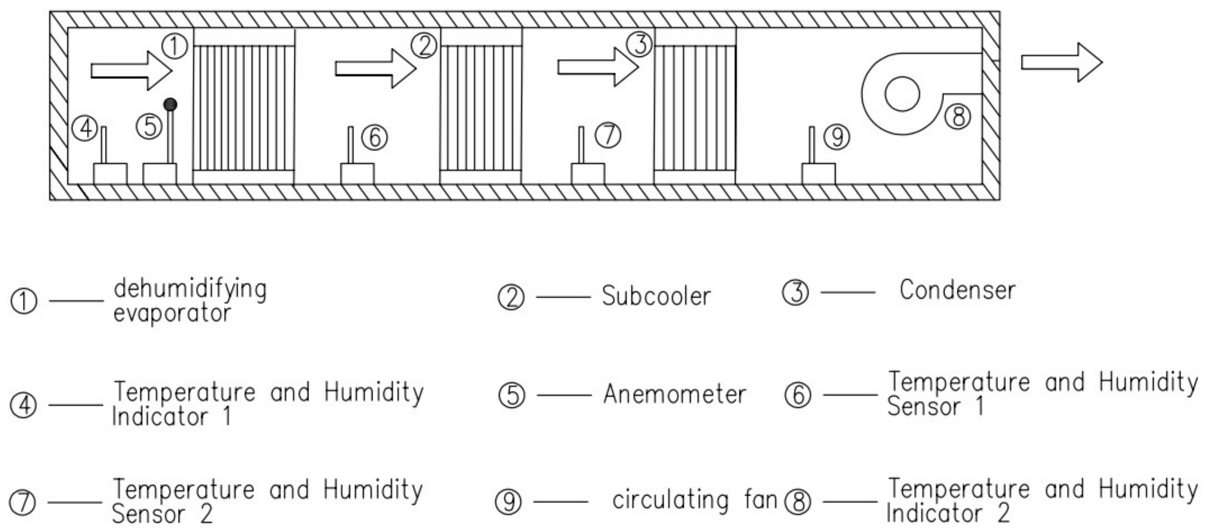

Fig. 4 Schematic Diagram of Measurement Points within the Internal Air Duct

The measurement and control system of the whole test bench mainly includes two parts, namely, software and hardware, in which the software part can realize the control of the test bench, the acquisition of measurement point data and the calculation and processing of data. The hardware part includes computers, switches, serial servers, industrial touch screen, engineering control boards, communication lines and a variety of sensors and so on.

Through the collection of compressor suction and discharge temperature, pressure and other refrigerant status parameters can determine whether the test bench is stable operation. The engineering control board has an interface to communicate directly with personal computer through RS485 to USB communication line to monitor the system operation or debugging. Software developed with the help of labview platform, running the software can adjust the system electronic expansion valve opening, fan speed, etc..

3.2. Experimental Method

Wait until the system operation is stabilized, respectively, by changing the size of the air volume of the inner air duct and the size of the inlet water temperature flowing through the plate heat exchanger inlet to explore the changes in the dehumidification performance of the test bench.

Under the experimental conditions, the temperature of the material chamber was controlled at 40°C and 90% relative humidity. The circulating air volume of the inner duct is set to 5 groups, which are 200m^3/h, 300m^3/h, 400m^3/h, 500m^3/h and 600m^3/h respectively. Plate heat exchanger inlet water temperature is also set 5 groups, respectively 45 ℃, 50 ℃, 55 ℃, 60 ℃, 65 ℃.the experimental working conditions could be seen in Tab.2.

For the above settings, 25 groups of different working conditions can be formed, and the dehumidification performance of the system under each working condition is calculated separately. By adjusting the opening of the electronic expansion valve, the suction port superheat of the compressor of the heat pump system is stabilized at 5℃.The measurement and control system collects test information every 20 seconds, and the collection period is 15 minutes. The collected data are saved and averaged for error reduction.

Table 2. List of experimental working conditions.

Name	Chamber Drying Temperature	Chamber Drying Humidity	Superheat at Evaporator Outlet	Water Tank Temperature	Airflow Volume in Internal Air Duct
Unit	℃	%	℃	℃	m^3/h
Series 1	30~50	85~92	5	45	200
Series 2	30~50	85~92	5	45	300
Series 3	30~50	85~92	5	45	400
Series 4	30~50	85~92	5	45	500
Series 5	30~50	85~92	5	45	600
Series 6	30~50	85~92	5	50	200
Series 7	30~50	85~92	5	50	300
Series 8	30~50	85~92	5	50	400
Series 9	30~50	85~92	5	50	500
Series 10	30~50	85~92	5	50	600
Series 11	30~50	85~92	5	55	200
Series 12	30~50	85~92	5	55	300
Series 13	30~50	85~92	5	55	400
Series 14	30~50	85~92	5	55	500
Series 15	30~50	85~92	5	55	600
Series 16	30~50	85~92	5	60	200
Series 17	30~50	85~92	5	60	300
Series 18	30~50	85~92	5	60	400
Series 19	30~50	85~92	5	60	500
Series 20	30~50	85~92	5	60	600
Series 21	30~50	85~92	5	65	200
Series 22	30~50	85~92	5	65	300

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Series 23	30~50	85~92	5	65	400
Series 24	30~50	85~92	5	65	500
Series 25	30~50	85~92	5	65	600

3.3. Performance Evaluation Index

The performance indexes used to evaluate the CLHPD system in this paper include: COP, SMER and Mr. COP is used to evaluate the heating performance of heat pump systems.

The calculation method of COP is shown as follows:

$$COP = \frac{Q_k}{P_c} \tag{1}$$

Where, Q_k and P_c respectively denote the heating capacity(kw) of the heat pump drying device and the power of the motor for the compressor.Mr is the ratio of the moisture extracted during the drying process to the drying time(τ/h). The calculation method of Mr is detailed in Eq. (2),where, v and A are the circulating air velocity (m/h) and the air channel cross-sectional area (m^2) at the measurement point; ρ and d respectively denote the density (kg/m^3) and moisture content (g/kg) of air;subscript w, in and out respectively represent drying chamber, inlet and outlet.

$$M_r = \rho v \times A \times \left(d_{w,out} - d_{w,in}\right) \tag{2}$$

The above Mr is a crucial parameter to reflect the drying rate, while, in order to reflect the system comprehensive performance from the aspect of energy consumption, SMER is needed. SMER is the dehumidification capacity of the system when unit energy is consumed and can be obtained by Eq. (3), where the meanings of symbols are the same as that mentioned before.

$$SMER = \frac{Mr}{P_c \tau} \tag{3}$$

3.4. Uncertainty Analysis

The uncertainty of the performance evaluation index is mostly caused by the inherent errors of the measuring instruments. According to the uncertainty calculation and analysis method promoted by R.J.Moffat [23,24], the relative uncertainty of the system performance evaluation index can be calculated by Eqs. (4) to (6).

$$u = \frac{a}{\sqrt{3}} \tag{4}$$

$$R = f\left(x_1, x_2, \ldots, x_N\right) \tag{5}$$

$$u_R = \left[\sum_{i=0}^{N}\left(\frac{\partial R}{\partial x_i}\right)^2 u^2\left(x_i\right)\right]^{0.5} \tag{6}$$

where, a and u respectively denote the accuracy of measurement instrument and the uncertainty; R and x_i respectively are the performance evaluation index and the i^{th} uncertainty component. According to the above equations, the relative uncertainties of the COP, Mr and SMER of this paper were 2.27%, 0.31% and 0.77%, respectively.

4. Results and Discussion

Perform experiments according to the experimental arrangement designed in Tab. 2. Once the equipment operation stabilizes, record 25 sets of experimental data and calculate the values of COP, Mr, and SMER under different operating conditions.

4.1. The Impact of Different Hot Water Temperatures and Air Supply Volumes on the Amount of Dehumidification

The results of the 25 sets of experimental data, after being calculated and organized, are plotted in Fig. 5.From the content shown in the figure, it can be observed that when the air volume remains unchanged and only the hot water temperature is varied, the dehumidification capacity of the heat pump unit increases as the hot water temperature rises. Similarly, when the hot water temperature is kept constant and the circulating air volume is varied, the dehumidification capacity of the heat pump unit also increases as the air volume increases. The minimum dehumidification capacity of the entire system occurs when the hot water temperature is 45°C and the circulating air volume is 200 m^3/h, with a minimum dehumidification capacity of 1.9 kg/h.The maximum dehumidification capacity of the system occurs when the circulating air volume is 600 m^3/h and the hot water temperature is 65°C, with a maximum dehumidification capacity of 8.2 kg/h.

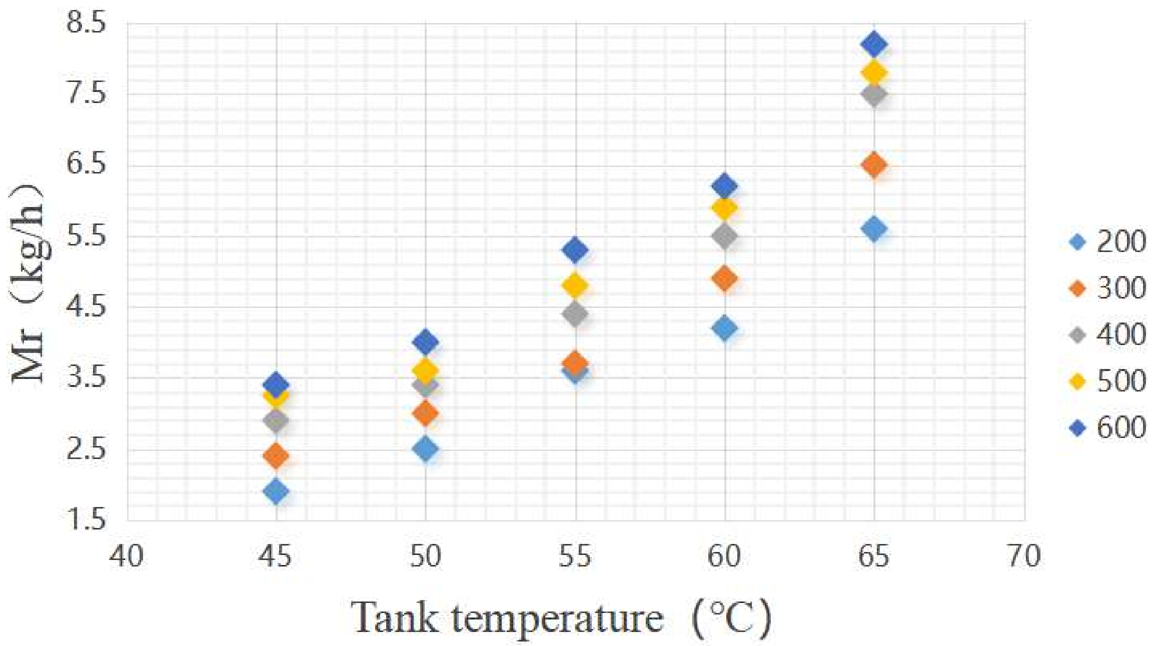

Fig. 5 Schematic Diagram Illustrating the Impact of Different Hot Water Temperatures and Airflow Rates on the Mr

Analyzing the reason behind the situation where the dehumidification capacity of a system with constant hot water temperature increases as the circulating air volume rises, it is easy to

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understand that as the circulating air volume increases, a large amount of hot air with low humidity passes through the dehumidifying evaporator, which subsequently enhances its dehumidification capacity accordingly. When the hot water temperature increases, the condensing temperature of the system also rises, resulting in an elevated compressor discharge pressure and a corresponding increase in evaporation temperature. This causes an increase in the refrigerant flow rate within the system. As the refrigerant mass flow rate of the system increases, the refrigerant flow through the dehumidifying evaporator will also increase accordingly. A higher refrigerant mass flow rate through the evaporator will lead to a gradual increase in the enthalpy value at the outlet of the evaporator. Consequently, the heat exchange capacity of the refrigerant in the dehumidifying evaporator will increase, resulting in a greater cooling capacity of the dehumidifying evaporator and subsequently an increased dehumidification amount.

Fig. 6 illustrates the change in refrigerant mass flow rate with the alteration of hot water temperature, while the air volume remains constant at 500m^3/h. Fig.7 shows the variation of the compressor's suction and discharge pressures as the water temperature changes.

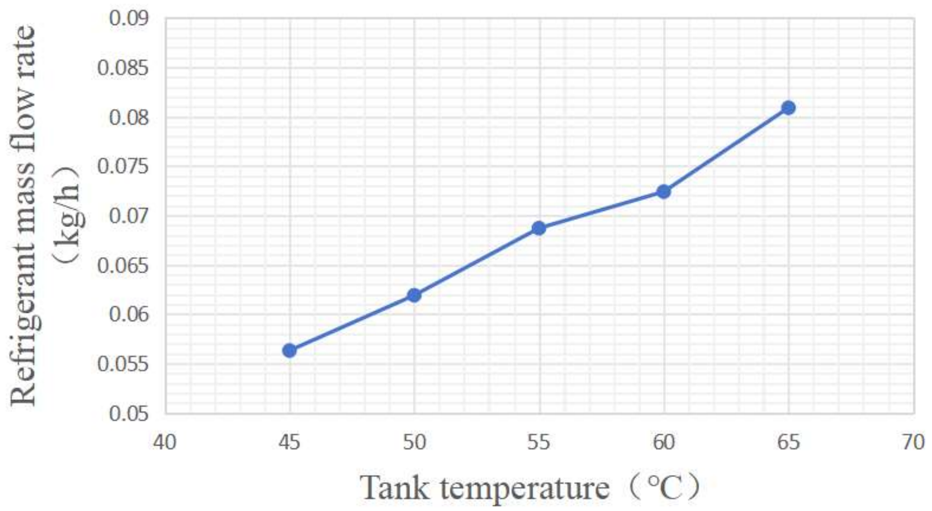

Fig. 6 Graph of Refrigerant Flow Rate Changing with Hot Water Temperature

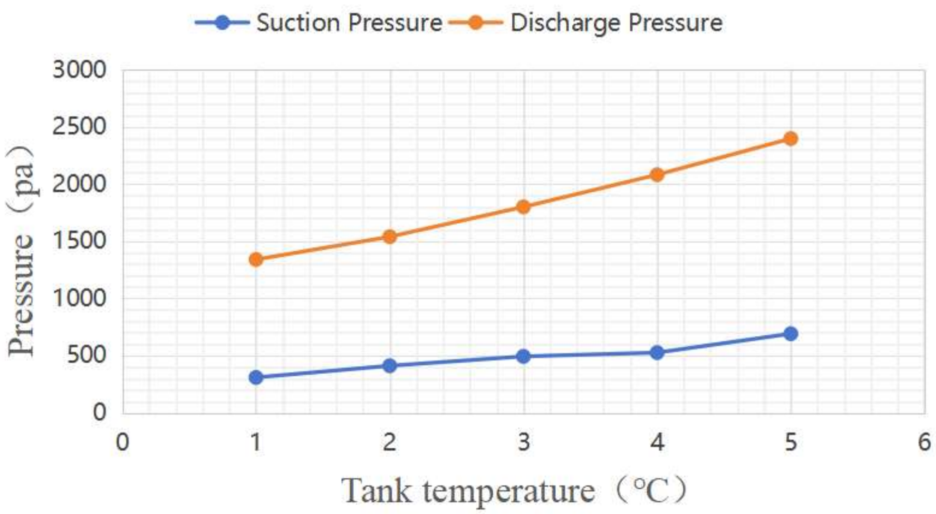

Fig. 7 Graph of Compressor Suction and Discharge Pressures Changing with Hot Water Temperature

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By calculating 25 sets of experimental data, we can obtain the dehumidification capacity and the specific moisture extraction rate (SMER) for each set. Plotting these two sets of data as the horizontal and vertical axes respectively, we can obtain the dehumidification characteristics of the heat pump drying test rig, as shown in Fig. 8. The figure depicts a roughly quadrilateral region formed by the air volume ranging from $200m^3/h$ to $600m^3/h$, with four points labeled A, B, C, and D. This region can be regarded as the operating range of our heat pump unit. By adjusting the hot water temperature and the volume of circulating air, the heat pump drying test rig can achieve the desired dehumidification requirements at any point within the ABCD region.

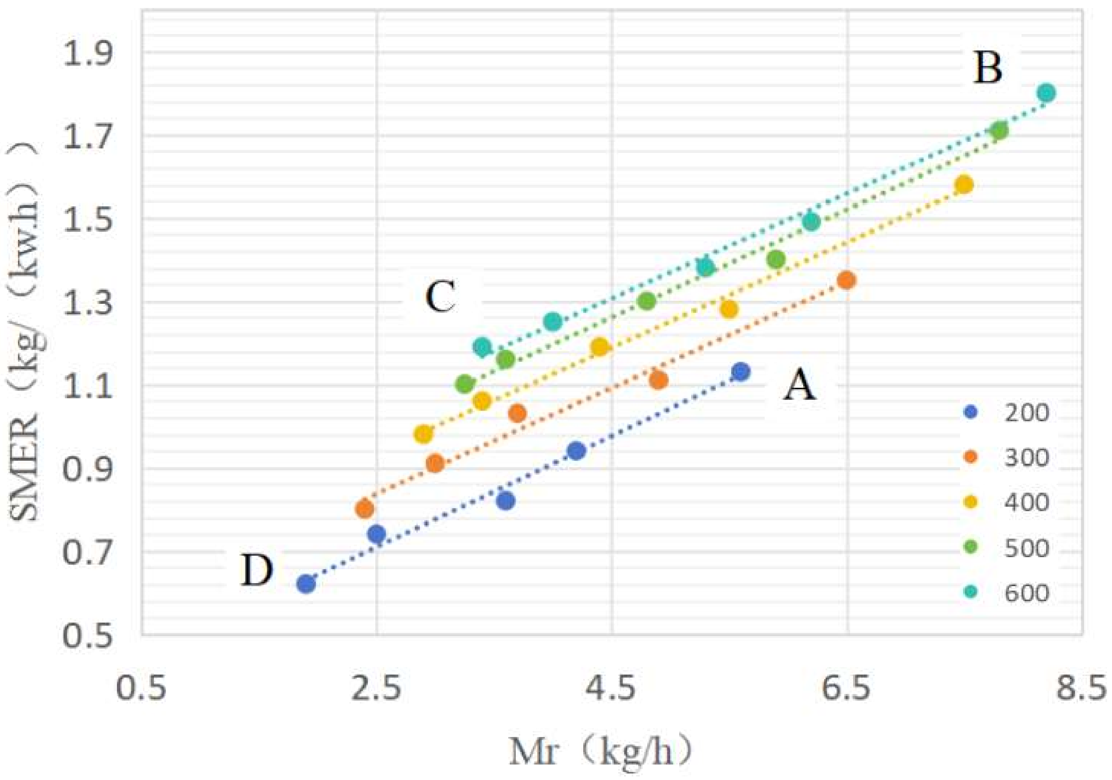

Fig. 8 Schematic Diagram of the Dehumidification Performance Range of the Heat Pump Unit

4.2. The Impact of Different Hot Water Temperatures and Air Supply Volumes on the COP

Fig. 9 shows the variation of the system's Coefficient of Performance (COP) with changes in the circulating airflow rate and the hot water temperature. As can be seen from the figure, there is a certain regularity in the change of COP. By adjusting the inlet hot water temperature of the plate heat exchanger and the airflow rate, the achievable range of COP for the unit is between 3.07 and 5.39. From the figure, it can be observed that an increase in hot water temperature leads to a gradual decrease in COP. This is because as the hot water temperature rises, the condensing temperature also increases. With the evaporating temperature remaining unchanged, the compressor's power consumption also increases, resulting in a decrease in COP. On the other hand, as the airflow rate increases, the COP gradually increases. Among the conditions tested, the maximum COP was achieved at a hot water temperature of 45°C and an airflow rate of $600m^3/h$, while the minimum COP was achieved at a hot water temperature of 65°C and an airflow rate of $200m^3/h$.

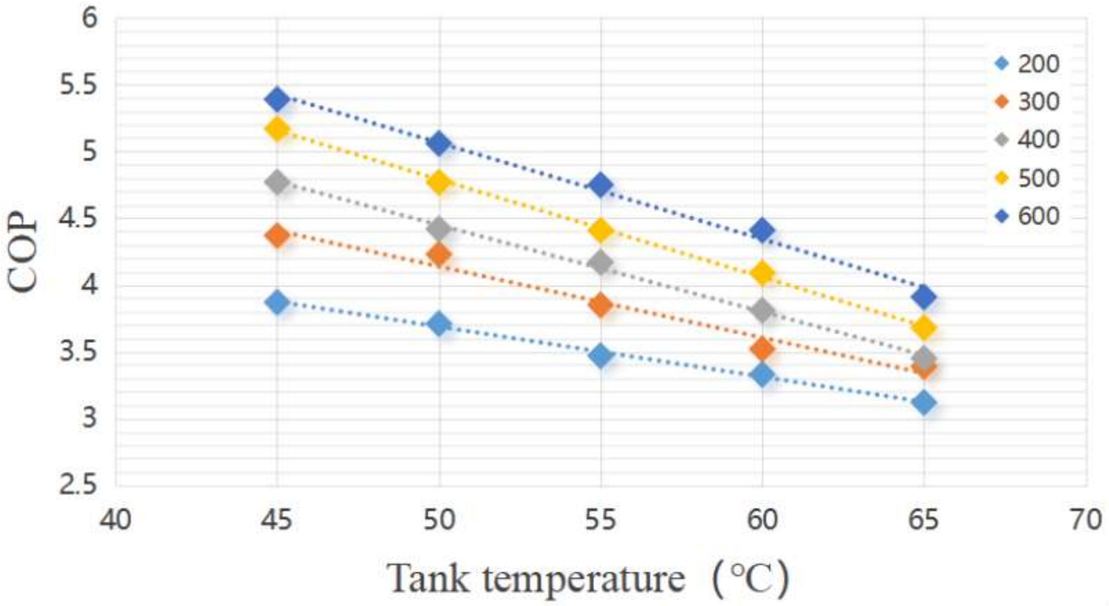

Fig. 9 Schematic Diagram Illustrating the Impact of Different Hot Water Temperatures and Airflow Rates on the COP

5. Conclusion

This article designs a closed heat pump drying system for the traditional kitchen waste treatment equipment that uses electric heating for fermentation and dehumidification. This system can effectively warm and dehumidify the material compartment, and at the same time, compared to electric heating, the heat pump drying system is more energy-efficient. This article also makes some modifications to the traditional heat pump drying device by installing a plate heat exchanger. The heat generated by the circulating water in the plate heat exchanger can be used to increase the temperature of the drying chamber, which is greatly helpful for high-temperature drying. Additionally, the heat generated by the plate heat exchanger can serve to replace part of the electric heating. From this perspective, the heat pump drying device designed in this article has significant energy-saving potential.

This article mainly studies the impact of water tank temperatures of 45°C, 50°C, 55°C, 60°C, and 65°C, as well as air supply rates of 200m^3/h, 300m^3/h, 400m^3/h, 500m^3/h, and 600m^3/h, on the dehumidification capacity (Mr) and specific moisture extraction rate (SMER) of the heat pump drying system. It explores the dehumidification performance of the device under these operating conditions and draws the following conclusions.

(1) Under the experimental conditions, the dehumidification range achievable by this heat pump drying device is 1.9-8.2 kg/h. Increasing the circulating air volume and the hot water temperature entering the plate heat exchanger can both enhance the dehumidification performance of the device. The range of specific moisture extraction rate (SMER) achievable by this device is 0.62-1.81 kg/(kw.h).

(2) The coefficient of performance (COP) of the heating system will increase as the airflow in the internal air duct rises. However, increasing the inlet water temperature of the plate heat exchanger will lead to a gradual decline in the system's COP. This is because as the hot water temperature rises, the condensing temperature will also increase accordingly. With the evaporation temperature remaining unchanged, the compressor's power consumption will also increase, leading to a reduction in the system's COP. Under experimental conditions, the achievable range for the system's COP is 3.07-5.39.

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