ORIGINAL ARTICLE

Dishwasher's closed drying process investigation based on heat pump system

Jie Yang · Zehua Miao · Jianghong Wu · Xianyi Yu · Chaopeng Liu · Shanshan Liu

Abstract A closed heat pump drying system using R134a refrigerant was designed to overcome the commonly used open dishwasher drying method's high power consumption and poor user comfort. To examine the effects of air flow rate and superheating on the system's performance, we analyzed its refrigerant-side performance and air-side (heat pump drying side) characteristics during the dynamic process. In the drying process of a dishwasher, there was a high demand for heating and dehumidification capacity in the early stage, which decreased later. An increase in air flow rate from 30 m^3/h to 45 m^3/h improved the average drying score, while excessive or low steady-state superheat degree affected the system's performance. The maximum heating coefficient of the system was 3.2, and the average heating power was 881 W, achieved at an airflow rate of 45 m^3/h and superheats of 6.2 °C with an average drying score of 0.92. The experimental results validate the numerical simulations performed using the MATLAB program. Compared to residual temperature drying, the closed heat pump drying system reduced the drying time by 50% and energy consumption by 0.131 kWh for a single operation, resulting in an energy-saving improvement of 17.3%. The experimental results showed that lowering the condensing temperature of the heat pump system in the later drying stages contributed to the system's energy savings.

Keywords Dishwasher · Heat pump drying · Economic analysis

Abbreviations

COP	Coefficient of heating performance
HP	Heat pump
HPD	Heat pump drying
SMER	Specific moisture extraction ratio
D_{total}	Total score for different types of dishes
$S_{average\ drying}$	Average drying score
Q_c	Average heating capacity (W)
m_{air}	Mass flow rate of air (kg/s)
h_{air}	Enthalpy of air (kJ/kg)
$h_{air,in}$	Enthalpy of air inlet the condenser (kJ/kg)
$h_{air,out}$	Enthalpy of air outlet the condenser (kJ/kg)
d_{air}	Moisture content of air (g/kg)
R_{air}	Relative humidity of air
T_{air}	Temperature of air (°C)
W_{all}	Average system power consumption (W)

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$W_{compress}$	Average power consumption of the compressor (W)
W_{fan}	Average power consumption of the fan (W)
P_{out}	Exhaust pressure of the compressor (MPa)
P_{in}	Intake pressure of the compressor (MPa)
ε	Compressibility

Introduction

With the development of technology and society, close to 80% (Porras et al., 2020) of American households and 44% (Brunzell & Renstrom, 2020) of European households are now using dishwashers. For dishwashers, it can be divided into open and closed depending on whether the gas is discharged to the outside (Bengtsson & Berghel, 2017). At this stage, the market products are mainly open-drying dishwashers.

The open-drying method has two drawbacks (Bengtsson & Eikevik, 2016; Jian & Zhao, 2017; Zhao et al., 2018). Firstly, it releases hot, high-relative humidity air directly into the kitchen, impairing user comfort and food freshness. Secondly, it consumes substantial electrical energy to heat tableware for drying after the rinsing stage. Therefore, current research and development are focused on developing a dishwasher that utilizes a closed-drying method and has energy-saving features.

In the twenty-first century, researchers began exploring energy-saving dishwasher technologies, focusing on residual heat recovery. De (Paepe et al., 2003) utilized the heat from wastewater to preheat the incoming cold water, reducing electricity consumption by 25%, but the 55 L water tank volume presented a challenge. Persson et al. 2007 developed a hot water circulation loop to heat dishwashers, achieving a 24% reduction in total power consumption. However, implementing this system requires a larger heat exchanger, significantly increasing the dishwasher's size. While these studies reduced power consumption, they neglected the impact on the dishwasher's volume. To optimize dishwashers comprehensively, reflections on their drying methods are essential.

Scholars have extensively researched methods to optimize dishwasher drying (Bengtsson et al., 2015) studied the dishwasher operation process and discovered that 80% of power consumption occurs during the heating phase. In response, (Bengtsson & Berghel, 2016) equipped dishwashers with refrigeration water tanks to condense hot and moist air, resulting in an energy-saving of 0.039 kWh per operation, but with an inferior drying effect compared to the traditional heating method. Researchers have developed adsorption drying dishwashers (Hauer et al., 2010; Erdogan et al., 2017; Santori et al., 2013; Ming, 2012; Longzhong et al., 2016), which utilized chemical adsorption agents to adsorb hot and moist air to achieve superior drying performance. This method reduced power consumption by 25% and increased the dish drying index by 20%, but it poses potential safety risks due to chemical agent usage. This paper presented the design and construction of a heat pump drying dishwasher that leverages the benefits of a heat pump system to reduce power consumption and improve drying effectiveness without the need for chemical adsorption agents.

Heat pump drying (HPD) technology offers several advantages, such as energy efficiency, environmental friendliness, high-quality drying, and closed circulation of the drying medium (Jeong & Dong, 2014). HPD systems have found applications in various fields, including the drying of agricultural products (Minea, 2015; Minea, 2013; Colak & Hepbasli, 2009; Jiubing et al., 2018; Pengfei et al., 2018; Xiaomei et al., 2005), lignite (Liu et al., 2019; Zlatanovic et al., 2017), and household appliances (Gataric et al., 2019; Lee et al., 2019; Jian et al., 2017). For instance, Tunckal & Doymaz, 2020 and Aktas et al., 2019 evaluated closed HPD systems for drying banana chips and grape pomace. They found that the best specific moisture extraction ratio (SMER) and coefficient of performance (COP) were obtained at a drying temperature of 50 °C. In household appliances, heat pump drying technology has been applied to clothes drying (Fil & Garimella, 2021; Tao et al., 2014) and integrated washer-dryer systems (Cranston et al., 2019), significantly improving energy efficiency and reducing power consumption. Although the closed HPD system was mainly used for clothes drying, this paper aimed to build a closed heat pump drying dishwasher based

on the same principle and investigate its operating characteristics.

Based on the existing research, this paper utilized heat pump drying technology in the dishwasher drying system. A closed heat pump drying system was designed and constructed for closed dishwashers. Performance experiments were conducted to evaluate the system. The system provided continuous heat in an enclosed environment, resulting in enhanced energy efficiency, reduced energy consumption and
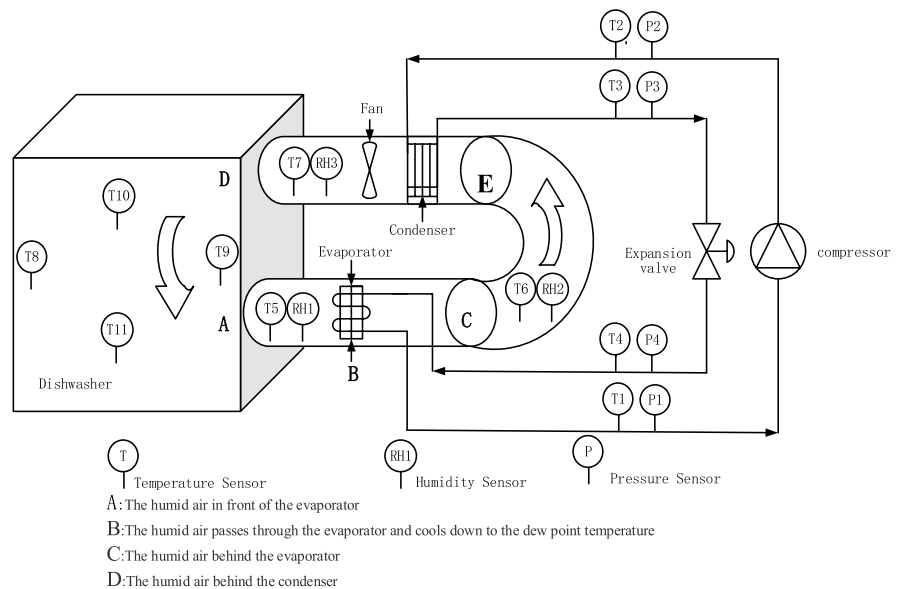
drying time, minimized environmental impact, and valuable insights for engineering applications.

Experimental system

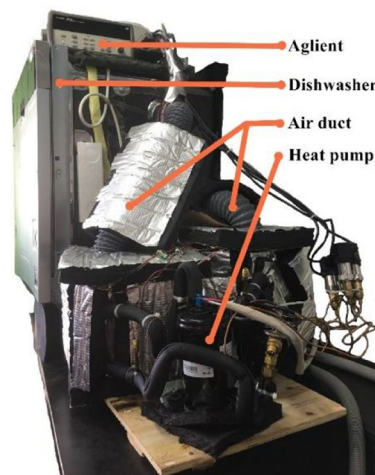### Experimental device

The experimental setup and measurement points for the heat pump drying dishwasher are depicted in Fig. 1(a) and (b). The system comprises a dishwasher,

Fig. 1 Heat pump drying dishwasher test device diagram

A:The humid air in front of the evaporator
B:The humid air passes through the evaporator and cools down to the dew point temperature
C:The humid air behind the evaporator
D:The humid air behind the condenser

(a) Schematic diagram of heat pump drying dishwasher test device

(b) Physical drawing of heat pump drying dishwasher test device

air duct, fan, expansion valve, and piping. Circular holes of 55-mm diameter are cut on the upper (at D) and lower (at A) parts of the dishwasher, which are linked to a rigid PVC air duct (D to condenser and A to evaporator). A flexible nylon cloth air duct connects the evaporator and condenser in series (sections E to C). The evaporator, condenser, and pipes are in an enclosed air processing room with a 10-mm-thick chevron board and 40-mm-thick insulation cotton. The remaining components of the heat pump system (compressor and thermal expansion valve) are associated with 6.5-mm-inner-diameter copper tubes and placed outside the air handling chamber. A variable frequency fan with a maximum air flow rate of 45 m^3/h is installed at the air handling chamber's outlet, facing the condenser. The system uses R134a refrigerant, and the primary parameters are presented in Table 1.

Operation mode

The study examines the operation process of dishwashers, which consists of four steps: pre-washing, washing, rinsing, and drying. During pre-washing, impurities on the tableware's surface are removed. In the washing step, high-temperature hot water, detergent, and a sterilization function are used to remove oil stains. Residual detergent is then washed away in the rinsing step, which includes adding a dish agent to improve the drying effect and reduce drying time. Finally, the drying step removes moisture from the tableware's surface. The paper investigates the duration and temperature of each stage during the normal operation of two dishwashers: residual temperature drying and heat pump drying systems.

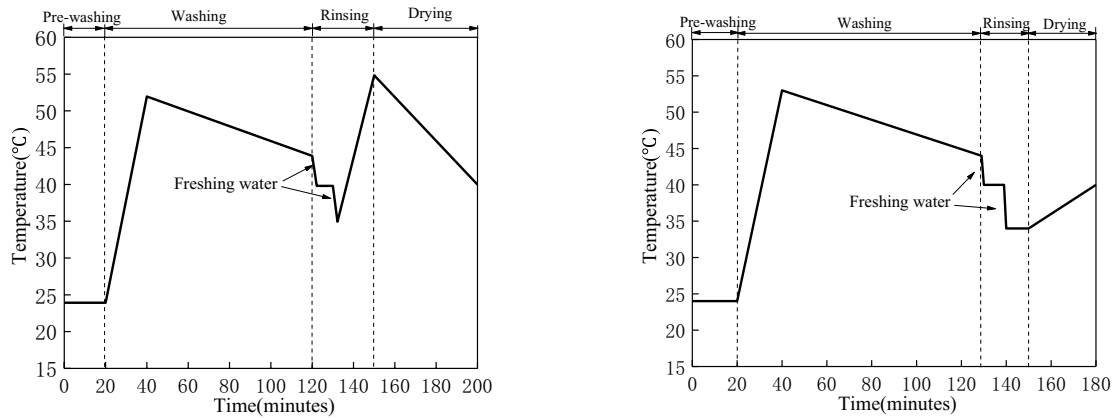The residual temperature drying dishwasher dries dishes using its residual heat to evaporate surface water. This dishwasher uses high-temperature hot water during the main washing and rinsing stages. The operational process typically involves 20 min of pre-washing with cold water, followed by 100 min of hot water washing and 30 min of hot rinsing. After the standing water is drained, the dishwasher door automatically opens, and the dishes dry for 60 min. This process takes a total of 210 min. Figure 2(a) shows the internal temperature changes of the dishwasher.

The heat pump drying dishwasher differs from the residual temperature drying dishwasher in two ways: cold water is used instead of hot water during rinsing, and the drying time is reduced from 60 min to 30 min. The operational process consists of a 20-min pre-wash with cold water and 100 min of washing, followed by a 30-min cold water rinse. After draining standing water, the dishes are dried for 30 min using a heat pump. This process takes a total of 180 min. Figure 2(b) illustrates the internal temperature variations of the dishwasher.

The research built a closed heat pump drying dishwasher system. During operation, dry air entered the dishwasher and removed moisture from the tableware or inner wall. The dry air mixed with the wet air inside the dishwasher, becoming damp air carried to the air treatment room through the air duct. There, the air was cooled on the surface of the evaporator, reached the dew point temperature, and precipitated moisture. The resulting low-temperature saturated air was heated on the surface of the condenser to become high-temperature dry air. A fan inside the dishwasher circulated the high-temperature dry air repeatedly until the end of the drying process without releasing gas into the environment. The air's relative humidity inside the dishwasher varied, with higher humidity in the lower part, which reduced the need for cooling and increased the drying efficiency.

Table 1 Model and parameters of test equipment and equipment

Devices and equipment	Model/type	Specifications
Evaporator	Microchannel	Heat exchange capacity 900 W
Condenser	Microchannel	Heat exchange capacity 1200 W
Compressor	WHP00680BSX-Y1DN	Rated power 232 W
Expansion valve	DanFoss-TN2	Spool 01
Fan	DELTA-THB1212B	120*120*25 mm
Dishwasher	—	Internal dimensions 500*540*620 mm

(a) The internal temperature change of the residual temperature drying dishwasher

(b) The internal temperature change of the heat pump drying dishwasher

Fig. 2 The internal temperature change for the residual temperature drying vs. heat pump drying

Main performance indexes of the closed drying of heat pump dishwasher

To evaluate the performance of the heat pump drying dishwasher system, proposed measurement standards include average drying score, average heating capacity, average energy consumption, heat pump heating coefficient, and compressor operating pressure ratio. The calculation method is outlined below:

a) Average drying score

To measure the drying performance of heat pump drying dishwashers, this paper combined GB/T 20290-2016 (GB/T 20290-2016, n.d.) and IEC60436-2019 (IEC 60436-2019, n.d.) standards and proposed the average drying score ($S_{average\ drying}$). The average drying score was defined as the ratio of the sum of the drying scores of each load of cutlery to the total

number of load cutlery within this operation. The $S_{average\ drying}$ is calculated as follows:

To acquire a drying score, the dishwasher is allowed to stand for 30 min after the drying cycle is complete. Tableware in the bottom, middle, and upper baskets are then sequentially measured to prevent water droplets from the top from affecting the results. Each tableware item is evaluated for no more than 8 s, and the observation time is limited to 3 s. The scoring criteria are specified in Table 2. To ensure objectivity, the same individual performs all evaluations.

Total scores for different types of dishes are calculated.

$$D_{total} = \sum_{c=0}^{2} a_c \times c \qquad (1)$$

where D_{total} is the total score for different types of dishes; c is the score; a_c is the number of dishes with a score of c on each cutlery.

Table 2 Drying score evaluation index (IEC 60436-2019, n.d.)

Amount of water residue	Points
The item is completely free from water residue.	2
The item has up to two drops of water, or one wet streak, or a total wet area not more than 50 mm^2	1
The item has more than two drops of water, or one drop and one streak, or two streaks, or a total wet area of more than 50 mm^2	0

In this paper, we use 6 sets of cutlery, a total of 67 pieces. To verify the heat pump dishwasher more drying effect, 3 extra soup spoons are added.

Therefore, the total number of cutlery is $N=70$. Refer to IEC60436-2019 for a detailed classification of each cutlery set.

The average drying score is calculated.

$$S_{average\ drying} = \frac{D_{total}}{N} \qquad (2)$$

b)   Average heating capacity

The average heat capacity represents the heating capacity of the heat pump system. From the air side, the formula is as follows:

$$Q_c = \int \dot{m}_{air}\left(h_{air,out} - h_{air,in}\right)dt \qquad (3)$$

where Q_c is the average heating capacity. $h_{air,\ in}$ is the enthalpy of air entering the condenser; $h_{air,\ out}$ is the enthalpy of air exiting the condenser; and $\dot{m}_{air}$ is the mass flow rate of air.

c)   Average system power consumption

The average system power consumption comprises the compressor's and fan's average power consumption. The specific formula is as follows:

$$W_{all} = W_{compressor} + W_{fan} \qquad (4)$$

where W_{all} is the average system power consumption; $W_{compressor}$ is the r consumption of the compressor; W_{fan} is the average power consumption of the fan.

d)   Coefficient of performance

The coefficient of performance is a parameter used to evaluate the heat pump's performance. It is defined as the ratio of the heat obtained by air through the condenser to the compressor's energy consumption. Its formula is as follows:

$$COP = \frac{Q_c}{W_{compressor}} \qquad (5)$$

where COP is the coefficient of performance.

e)   Compressibility

Compressibility represents the degree of gas compression, defined as the volume ratio before gas compression to the volume after gas compression. Its specific formula is as follows:

$$\varepsilon = \frac{P_{out}}{P_{in}} \qquad (6)$$

where ε is the compressibility; P_{out} is the exhaust pressure of the compressor. P_{out} is the intake pressure of the compressor.

Experimental process and data collection

Experimental conditions

The total cutlery used in this experiment was 70, including 6 sets totaling 67 pieces, and then 3 other soup spoons were added. According to GB/T 20290-2016 (GB/T 20290-2016, n.d.) standard is recommended by the top basket, bottom basket, and cutlery on the knife and fork rack into the arrangement.

This paper investigated the performance of a heat pump drying dishwasher by varying the fan flow rate and the superheat degree of the heat pump system. Other components were kept constant. The experiment was conducted by adjusting the fan flow rate. To vary the superheat degree of the heat pump system, the air flow rate of the fan was kept constant at 45 m³/h, and the experiment was conducted by changing the expansion valve opening size while other components remained constant. In addition, regarding the practical application of heat pump drying dishwashers, the kitchen had a wide range of ambient temperature variations. To ensure practical application, the performance of the heat pump drying dishwasher was tested at a range of ambient temperatures typically experienced in a kitchen, from −5 to 45 °C. All parameters were held constant except the ambient temperature, as detailed in Table 3.

Heat pump dishwasher drying experiments must be conducted in a stable and adjustable ambient temperature laboratory to ensure accurate experimental results. In this paper, all experiments were conducted in the enthalpy difference laboratory, which had controlled conditions as outlined in Table 4.

Experimental data acquisition

This experiment measured temperature, humidity, and pressure at various locations to analyze the properties of wet air and refrigerant during dishwasher drying and evaluate heat pump performance. The temperature sensors were positioned at the inlet/outlet of the air handling chamber, the evaporator inlet/outlet, the condenser inlet/outlet, the dishwasher interior, and the surface of the dishes. The humidity sensors were located at the inlet/outlet of the air handling chamber and the outlet of the evaporator inside the chamber. The pressure sensors were arranged at the heat pump system's evaporator inlet/outlet and condenser inlet/outlet. Figure 1(a) shows the specific measurement points. The type, accuracy, and range of measurement sensors and acquisition devices are shown in Table 5.

Table 3 Scheme of experiments

Variables	Ambient room temperature °C	Ambient Humidity %	Expansion valve opening	Fan flow rate m³/h
Fan flow rate experiment	23±2	55±5	O	30
	23±2	55±5	O	35
	23±2	55±5	O	40
	23±2	55±5	O	45
Superheat degree experiment	23±2	55±5	O+1	45
	23±2	55±5	O+1/2	45
	23±2	55±5	O	45
	23±2	55±5	O-1/2	45
Ambient temperature experiment	-5±2	55±5	O	45
	5±2	55±5	O	45
	15±2	55±5	O	45
	23±2	55±5	O	45
	35±2	55±5	O	45
	45±2	55±5	O	45

Note: O is the expansion valve opening measured when the drying capacity of the heat pump system is optimal

Table 4 Enthalpy laboratory test conditions

Reference: IEC60436-2012			
Voltage	Frequency	Room temperature	Humidity
230V±1%	50Hz±1%	(−10~50)±0.5 °C	55±5%
Water supply temperature	Water supply hardness	Water supply pressure	Dishwashing powder/dish polish
15±2 °C	2.5±0.5 mmol/l	2.4±0.2 bar	Detergent B/Formula III

Table 5 Experimental system parameters

Temperature sensor	J-type thermocouple	Accuracy±0.5 °C
Humidity sensor	AM2001	Range 0–99.9%, accuracy±3%
Pressure sensor	PCM300	Accuracy±12.5kPa
Acquisition instrument	Agilent-34972A	60 channel /s
Anemometer	AM-4214SD	Range 0.2–5.00 m/s, accuracy±0.01 m/s
		Range 5.1–25.00 m/s, accuracy±0.1 m/s
Power meter	HP-9800	Range 0.5–4400 W, error level 0.5

Results and analysis

Heat pump drying dynamic change process

The dishwasher's heat pump drying system used moist air as a medium to transfer heat from the heat pump supply to the inside. Further investigation was necessary to thoroughly analyze the dynamic process of wet air and heat pump systems.

Figure 3 shows the changes in the dehumidification process of moist air in the heat pump drying system with time using the Euler method on the enthalpy-humidity diagram. For example, in the state at 1800 s of operation in Fig. 3, points A, C, and D corresponded to the T5, T6, and T7 temperature measurement points in Fig. 1(a). Point B was the position of the wet air passing through the evaporator, which was cooled to the temperature of the dot, and this was the calculated point, not the actual measurement point. Figure 3 shows the enthalpy and humidity changes to visualize the dehumidification process. Point A was the inlet of the dishwasher's moist air, and the temperature difference between the AB section was 0 in the early stage of operation and gradually increased as the operation time became longer. The moist air inside the dishwasher was initially saturated but gradually became unsaturated as the heat pump system functions. As a result, the BC and AD sections' lengths increased and then decreased. Initially, the dehumidification effect improved gradually but slowly diminished as the heat pump system continued

running. Even after the heat pump system stopped running at 1800 s, moist air passing through the evaporator underwent dehumidification. As a result, the length of the CD section increased before eventually stabilizing. This indicated that the enthalpy of moisture at point D decreased gradually, along with the latent heat of moist air inside the section.

Figure 4 illustrates the variation of humidity with air temperature inside the dishwasher. The return air temperature was lower than the average temperature of the dishwasher walls, resulting in energy loss. The relative humidity of the return air started at 99.6% and gradually dropped to 78% over 975 s. The relative humidity of the supply air decreased continuously during the heat pump drying process, leading to a gradual improvement in the drying effect. Initially, the supply of air relative humidity fluctuated due to the gradual increase in the condenser capacity, which caused a rapid decrease in the air's relative humidity around it. As the saturated moist air from the evaporator mixed, the air's relative humidity rose again. As the drying process continued, the condensate precipitated, the potential heat of moist air decreased, and the need for dehumidification capacity increased while heat production by the heat pump system decreased.

Figure 5 illustrates the temperature changes at various measurement points within the heat pump system. The supply air temperature exhibited a similar trend to the condenser refrigerant outlet temperature, albeit with a 10 °C difference. Ultimately, the supply

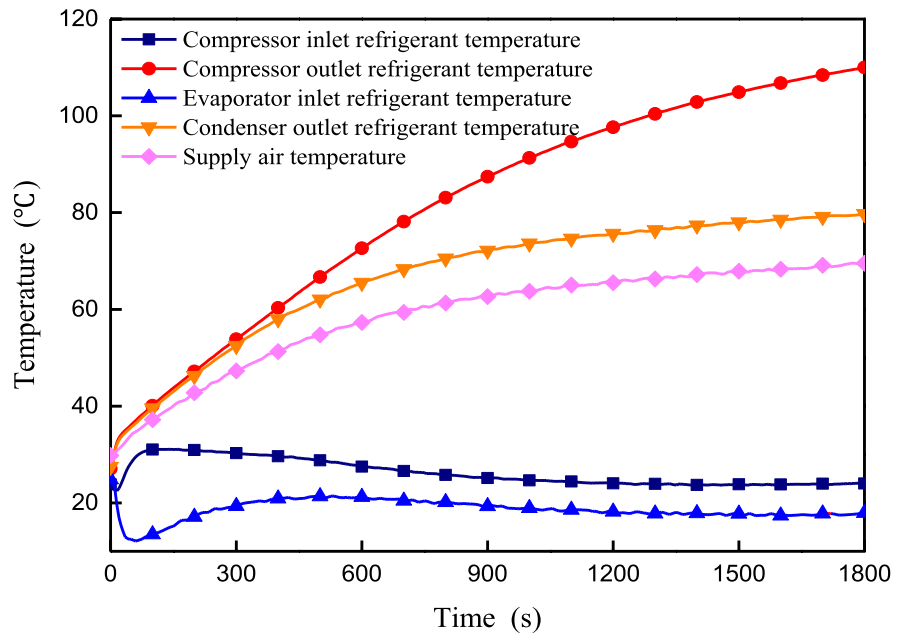**Fig. 3** Enthalpy-humidity chart of internal air in the dishwasher at different times
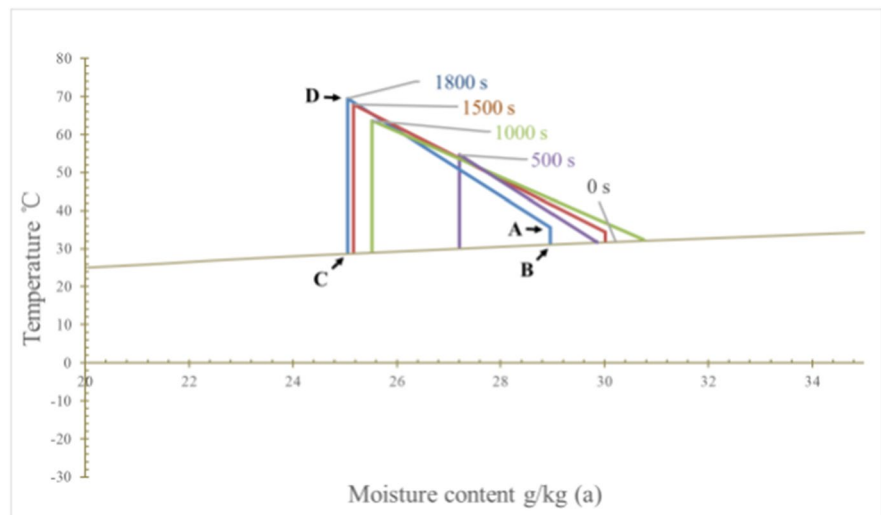
Fig. 4 Dishwasher internal air temperature and humidity curve
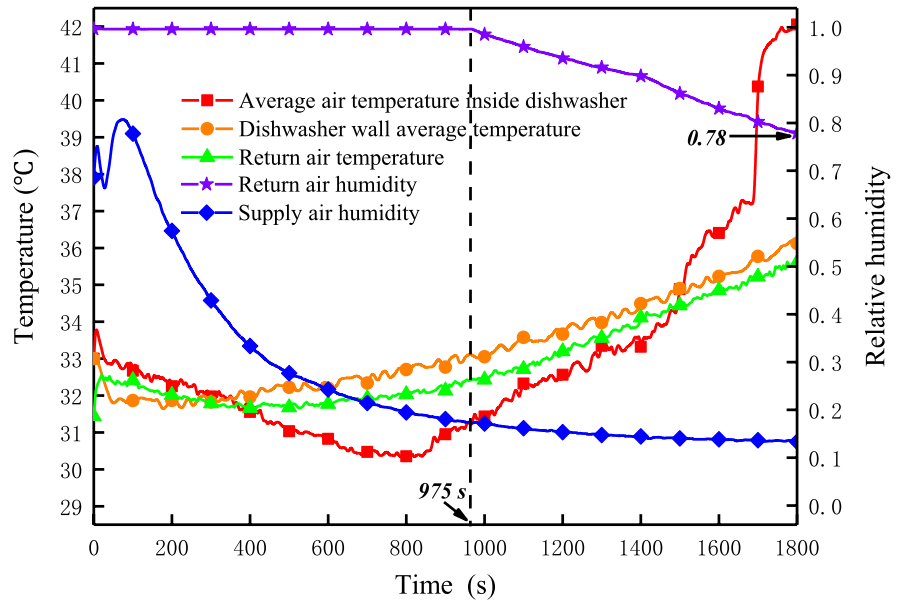


Fig. 5 Heat pump system temperature curve

air temperature reached 80 °C, whereas the condenser refrigerant outlet temperature peaked at 69.5 °C. The refrigerant temperature at the evaporator inlet initially decreased, then increased, and gradually declined during the system's operation. This was due to the refrigerant in the evaporator continually decreasing after system initiation. However, the discharged gas from the condenser lacked sufficient cooling capacity to lower the outlet air temperature of the evaporator, which led to a temperature rising (Li et al., 2018). Over time, the evaporator inlet temperature experienced a slight decrease.

Figure 6 shows the curve of instantaneous power and instantaneous COP with time. The immediate

**Fig. 6** Instantaneous power
and instantaneous COP
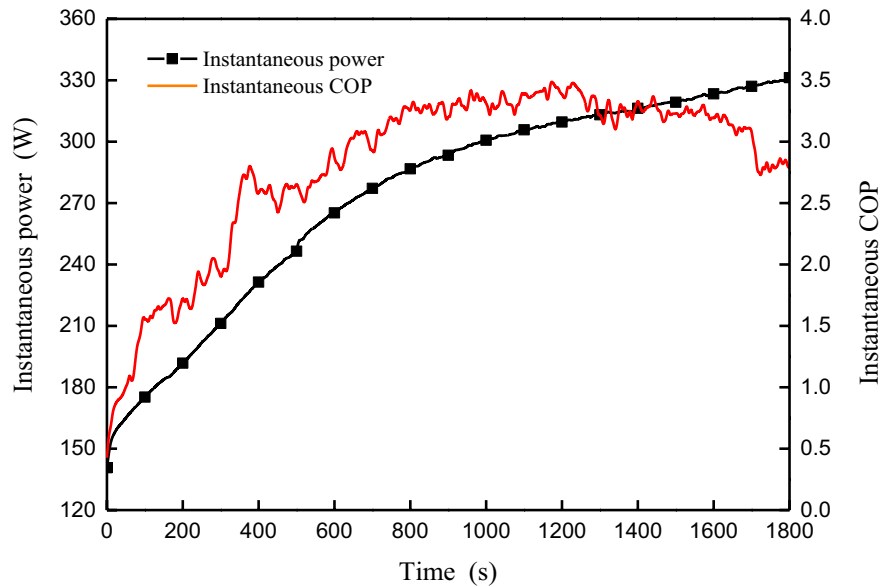
power continued to increase, while the quick COP
rose first and then decreased. In the experiment,
when the condensation temperature was 74.3 °C,
and the evaporation temperature was 19 °C, the
short COP was the highest, reaching 3.47. The
analysis of the heat pump system showed that the
system's heat supply and dehumidification capacity
was gradually enhanced.

Effect of air flow rate on the closed drying of heat
pump dishwasher

To optimize the heat pump drying dishwasher, it was
essential to understand the relationship between air
flow rate, drying performance, and heat pump perfor-
mance. As shown in Fig. 7, higher air flow rates led
to lower return air relative humidity. Increasing the

Fig. 7 Different fan flow
rates, relative humidity
change of the return air
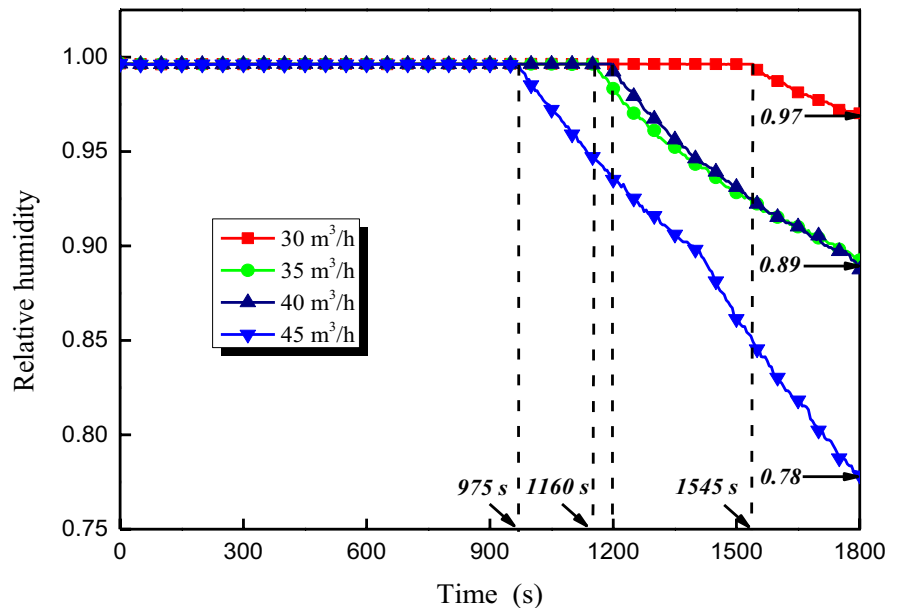
return air flow rate from 30 to 45 m³/h caused a gradual decrease in the absolute return air relative humidity to a minimum of 78%. As the return air flow rate improved, it increased the contact speed between the wet air and the dishes, which could better remove the moisture inside the dishwasher, and thus, the humidity of the return air was reduced.

Figure 8(a) depicts the air flow rate and average drying score correlation. Increasing the air flow rate from 30 m³/h to 45 m³/h improved the average drying score from 0.64 to 0.92. Moreover, it could be inferred from Fig. 8(a) that a higher air flow rate led to a more effective drying process. A higher air flow rate reduced the final air supply temperature, as

Fig. 8(b) depicts. This decrease in temperature was attributed to the enhanced removal of moisture from the dishwasher by the increased air flow rate.

Figure 8(c) to (f) demonstrate the relationship between the return air flow rate and the performance of the heat pump system. It could be observed from these figures that higher return air flow rates correspond to improved heating capacity and COP. The maximum heating capacity and COP achieved were 881 W and 3.2, respectively. This phenomenon was due to the increased heat dissipation required to dry the dishes resulting from higher air flow rates. Figure 8(d) shows a gradual increase in the system's average power consumption as the air flow rate increased from 30 m³/h to 45 m³/h.

Fig. 8 Average drying score and heat pump system performance with the different air flow rates

(a) Average drying score

(b) Air supply temperature

(c) Average heating capacity

(d) Average system power consumption

(e) COP
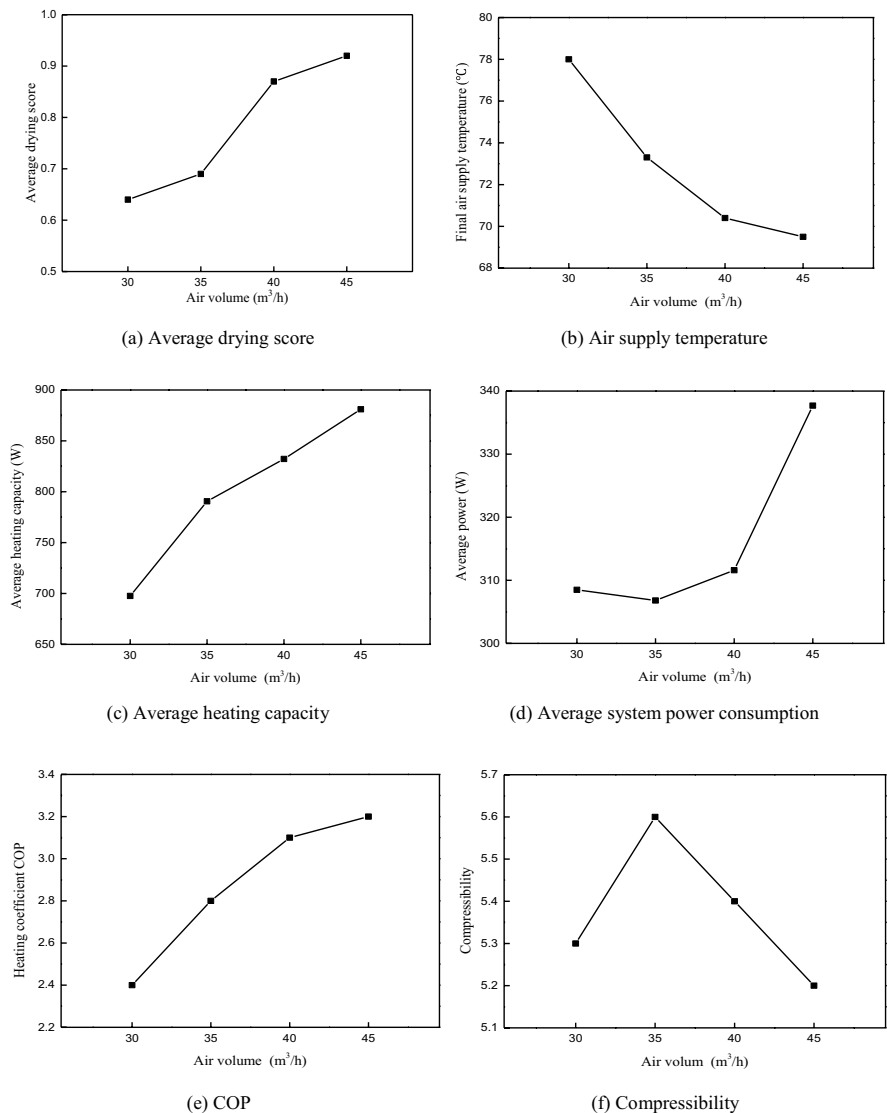
(f) Compressibility

Additionally, Fig. 8(f) indicates that a higher air flow rate reduced compressor compressibility due to the decreased supply of air temperature. This led to increased energy consumption, despite rising heating capacity and COP. The optimal return air flow rate was 35 m³/h, resulting in the highest compressor compressibility and the lowest average system power consumption.

Effect of superheat on the closed drying of heat pump dishwasher

In addition to the air flow rate, the superheat degree affected the heat pump dishwasher status. The change in return air relative humidity with time for different superheat degrees is shown in Fig. 9. As seen from the figure, the superheat degree gradually increased from 3.5 °C to 6.2 °C. The starting time of the dropped and final value of its return air relative humidity has decreased. When the superheat degree was 6.2 °C, the system had the best drying performance, at which time the relative humidity was 0.78, and the starting drop time was 975 s. As the superheat degree increased, the starting time dropped, and the final value of the return air relative humidity increased. When the superheat degree was 9.1 °C, the starting time declined, and the absolute value of the return air relative humidity was similar to when

the superheat degree was 4.8 °C. It was a result of the superheat degree of the heat pump system, which affected the system's heating capacity, involving the inlet temperature of the evaporator and, in turn, the return air relative humidity.

Figure 10(a) depicts the relationship between the superheat degree and the average drying score. There was an optimal superheat that allowed the highest average drying score. This trend was similar to the final relative humidity value in the return air. The lower the superheat degree, the larger the absolute air supply temperature, leading to higher return air humidity and a lower average drying score. The optimum superheat degree reduced the return air humidity in the shortest possible time, resulting in the smallest final return air humidity value and maximum moisture removal from the dishwasher interior.

Figure 10(b) to (f) illustrate the relationship between the superheat degree and the performance of the heat pump system. The results showed that as the superheat degree increased, the system's average heating capacity, coefficient of performance (COP), and compressibility initially increased, peaking at the superheat degree of 6.2 °C, then decreased. Specifically, at the superheat degrees of 3.5 °C, 4.8 °C, 6.2 °C, and 9.1 °C, the average heating capacities were 830.1 W, 863.3 W, 881 W, and 729 W, respectively. The COP values were 2.97, 3.14, 3.21, and 2.83, and

Fig. 9 Air relative humidity change in the evaporator with different superheat degrees
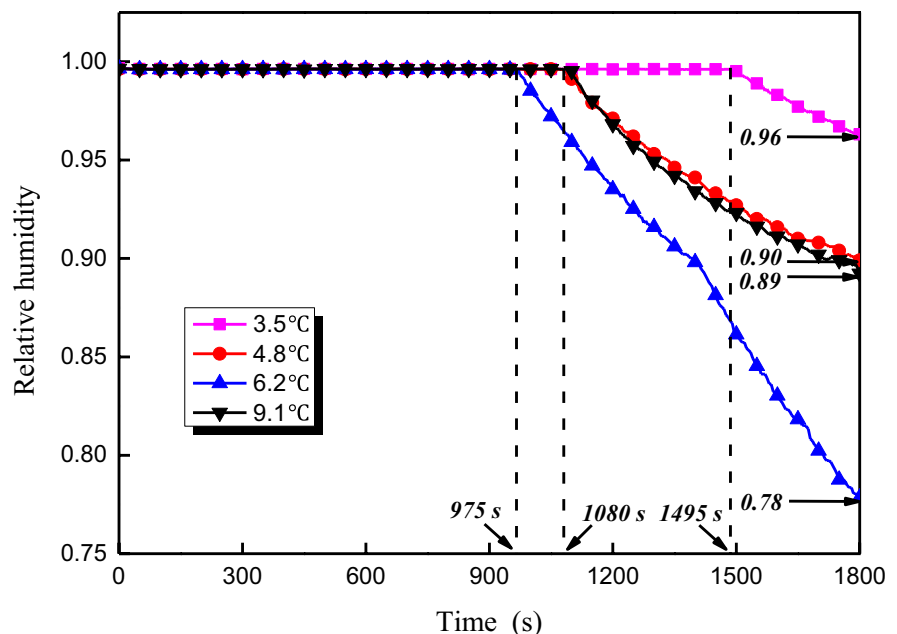
Fig. 10 Average drying score and heat pump system performance with the different superheat degrees

(a) Average drying score

(b) Air supply temperature

(c) Average heating capacity

(d) Average system power consumption

(e) COP
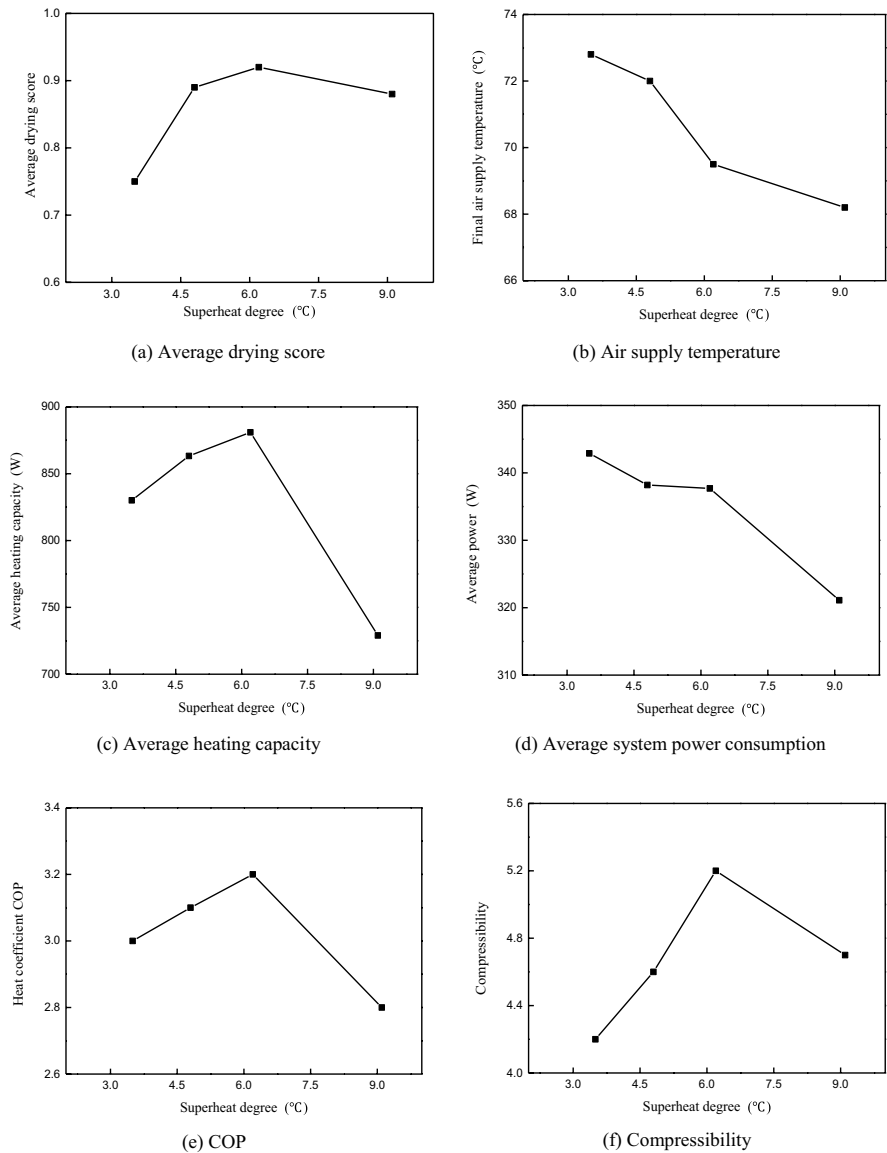
(f) Compressibility

the compressibility values were 4.2, 4.6, 5.2, and 4.7, respectively. The system's power consumption decreased as the superheat degree increased due to the minor difference between the dew point temperature of the return air and the evaporating temperature, reducing the compressor's power consumption.

When the superheat degree was too large, the flow rate of refrigerants was low, the system's heating capacity was small, and the drying effect was poor. When the superheat degree was overheated, the flow rate of refrigerants was significant, and the evaporation pressure was high. The difference between the

dew point temperature and evaporation temperature of return air was slight. The heat transfer capacity and dehumidification effect of the heat pump system were poor, which made the impact of drying and heat pump performance poor. In addition, the greater the superheat degree was, the lower the average system power consumption, which was because the increase in the superheat degree led to a minor difference between the dew point temperature of the return air and the evaporating temperature, which led to a decrease in the power consumption of the compressor. With the same power consumption of the fan, the

system power consumption decreased, and the change is shown in Fig. 10(d).

Performance of all-climate closed drying of heat pump system dishwasher

Table 6 displays the performance of the closed heat pump dishwasher at different ambient temperatures. At 45 °C, due to the high ambient temperature, the heat pump system triggered compressor shutdown protection which could not measure the key parameters. This indicated that the experimental system was unsuitable for high ambient temperatures. The optimal drying performance was achieved at 23 °C, and the average drying score decreased at temperatures higher or lower than this. The average system power consumption increased with higher ambient temperatures as the system superheat degree and compressor power consumption varied with ambient temperature. Hence, heat pump dishwashers were more energy-efficient in winter than in summer.

The heating capacity of the heat pump system increased with rising ambient temperatures, with the highest heating capacity reaching 968 W. For heating capacities below 900 W, a higher heating capacity resulted in a better drying effect. During the initial 800 s of operation, the wet air inside the dishwasher became saturated, making it difficult to evaporate moisture from the dishes. Increasing the heating capacity reduced the relative humidity of the supply air and increased the power available for moisture evaporation. Production heat exceeding 900 W did not enhance the drying effect nor shorten the time for the supply temperature to reach its maximum. When the production heat was between 600 and 900 W, experimental results indicate that lowering the evaporation temperature was more effective than increasing

the production heat in improving the average drying score.

Numerical simulation comparison

A calculation program was written for simulation comparison based on the mathematical model of the dishwasher. It used a MATLAB program for numerical simulation. Figure 11 compares the experimental and simulated values of the supply air temperature over time. The average supply air temperature was 57.0 °C in the simulated value and 55.5 °C in the observed value, with a difference of 2.63% between them. The experimental and simulated values trends were consistent; both grew first and stabilized, especially after 400 s, with a good match. The reason was that the speed gradually increased to the set value during the compressor start-up process. The refrigerant mass flow and heat production rates simultaneously increased to the set value. In the mathematical
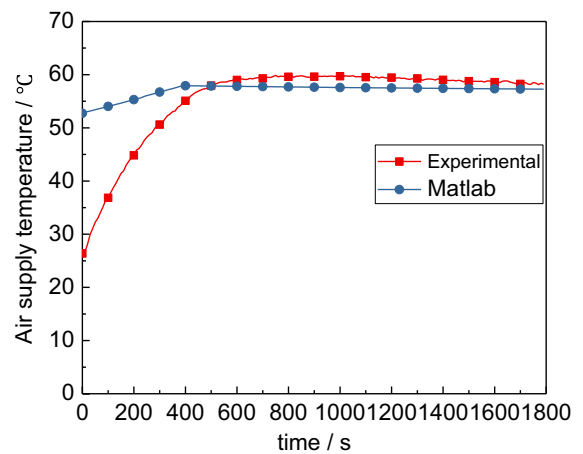
Fig. 11 Supply air temperature over time Experimental vs. Matlab code

Table 6 System performance at different ambient temperatures

Ambient temperature /°C	−5	5	15	23	35	45
Average drying score	0.79	0.78	0.88	0.92	0.79	0.60
Heating capacity /W	530	591	640	881	968	-
Final humidity of return air	0.99	0.44	0.48	0.45	0.51	0.99
Average power /W	245	263	293	337.5	370	-
COP	2.16	2.25	2.18	3.21	2.62	-
System power consumption /kWh	0.123	0.131	0.147	0.169	0.185	0.158
Superheat degree /°C	16.5	12.3	9.5	6.2	6.1	-

model, the compressor speed was a constant value, i.e., the heat production was the set value at the beginning of drying. Hence, the experimental value lagged in the early stage. As the drying proceeds, this gap decreased significantly. The model calculation results and the experimental results were consistent in trend. The model average difference was slight with high accuracy, which could be used to predict the law of the drying process of a closed heat pump dishwasher.

Economic analysis of the closed drying of heat pump dishwasher and residual temperature drying dishwasher

Table 7 compares the economic performance of fast drying with a heat pump dishwasher versus residual temperature drying. The former involved drying with hot air after rinsing with cold water. In contrast, the latter consisted in rinsing with hot water to achieve a temperature of 55 °C before opening the door to discharge hot and humid air, using residual temperature for drying. This paper conducted experiments on these two dishwashers under the same conditions and tableware load (6 sets of cutlery and 3 other soup spoons, additionally, a total of 70 pieces). The closed drying of the heat pump dishwasher took only 30 min, with the system power consumption mainly concentrated in the main wash heating stage, accounting for 70.5%. Drying energy consumption accounted for 25.4%, and the total energy consumption for a single operation was 0.61 kWh. By contrast, the residual temperature drying dishwasher took 60 min, with primary power consumption concentrated in the main wash heating and rinse heating stages, accounting

for 98.3% of the total energy consumption of 0.755 kWh for a single operation. Compared with residual temperature drying, the heat pump drying time was reduced by 50%, the power consumption of a single process was reduced by 0.145 kWh, saving 17.3%, and the cost of a single operation was reduced by 0.093 RMB.

Conclusions

A closed heat pump drying system using R134a was designed and built to address common dishwasher issues, such as long drying time, customer discomfort, and high energy consumption. The system's performance was evaluated through experimental studies, yielding the following conclusions:

In the drying process of a dishwasher, there was a high demand for heating and dehumidification capacity in the early stage, which decreased later. However, the energy consumption of the heat pump system was low, with a high coefficient of performance (COP) in the early stage, and this was reversed in the last step. Therefore, reducing the condensation temperature of the heat pump system during the late drying stage could improve the system's energy efficiency.

When the air flow rate was within the range from 30 to 45 m^3/h, the greater the air flow rate was, the higher the average drying score and the higher the system's average heating capacity and the system heating coefficient were. The final relative humidity decreased with increasing air flow rate. When the air flow rate was increased from 40 m^3/h to 45 m^3/h, the average energy consumption of the system surged.

Table 7 The economics of the closed drying of the heat pump dishwasher vs. the residual temperature drying dishwasher

Drying method	Heat pump drying	Residual temperature drying
Drying time /minute	30	60
Power consumption during pre-washing/kWh	0.013	0.013
Power consumption during washing /kWh	0.43	0.43
Power consumption during rinsing /kWh	0.012	0.312
Power consumption during drying /kWh	0.169	0
Power consumption per run /kWh	0.624	0.755
Household electricity price /(RMB/kWh)	0.647	0.647
Total cost per run /RMB	0.404	0.488

If the superheat degree in a stable state was too large or too small, it affected the average drying score. Superheat directly affected the evaporation temperature. When the superheat degree was too small, the difference between the evaporation and dew point temperatures would decrease, and the heat transfer effect would worsen. When the superheat degree was too large, the system's heating capacity would decrease, thus affecting the impact of the average drying score. The experimental results reveal that when the air flow rate was 45 m^3/h, the superheat degree was 6.2 °C. The average drying score was 0.92.

Compared with automatic opening drying, the time that the heat pump drying uses was reduced to 30 min from 60 min, and the energy consumption of a single operation was reduced by 17.3%. Furthermore, no hot or wet air was discharged into the environment.

Declarations

Conflict of interest The authors declare no competing interests.

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