Modeling and Analysis of a Heat Pump Clothes Dryer

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Abstract

In comparison with conventional electric clothes dryers consuming huge energy, heat pump clothes dryers have remarkable energy savings. A model of air-source heat pump clothes dryer system was developed in this paper, which included the steady-state heat pump system model and the dynamic fabric drying process model. Simulation results were validated with the test data of a household heat pump clothes dryer and reached a good agreement. The drying time error is within 3 minutes and the relative error of electricity consumption is 2.3%. Based on the validated model, system parameters including circulation air flow rate and ratio of fresh air were changed and calculated for system optimization, of which the impact on SMER (Specific Moisture Extraction Rate) and drying time of were analyzed. Simulation results indicated that optimum circulation air flow rate (180m^3/h) and optimum ratio of fresh air (9.8%) existed for maximum SMER. The results are meaningful for the system design of heat pump clothes dryers.

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Keywords: heat pump; clothes dryer; drying; model; optimization

1. Introduction

Drying is a complex and energy-intensive process. Conventional drying methods of fire coal and electric heating have low efficiency of energy use and will discharge hot humid air containing a lot of sensible and latent heat as well as material impurities, which would cause environmental pollution.

Heat pump absorbs heat from low-temperature heat sources and changes low-grade thermal energy into high-grade heat energy. It could also absorb heat from natural environment or residual heat resources, so as to obtain more thermal energy output than energy input [1]. The first drying patent of heat pump, issued in 1973 [2], has been widely used in many fields such as wood dehydration, food preservation, biological medicine and chemical processing [3-7]. Heat pump drying has the feature of energy efficient [8]. Compared with coal, it can reduce 40% to 70% of energy consumption, and can decrease above 90% of PM2.5 and PM10 particulate pollutant emissions [9].

The energy consumption of household tumbler dryer is quite considerable [10]. According to the statistics of International Energy Agency, the energy consumption of dryers in 22 member countries exceeds 3% of average annual household electricity consumption [11]. Thus, with people pursuing environmental protection, heat pump technology is also applied to household tumble dryer. The schematic of heat pump dryer (HPD) is shown in Fig. 1. In the HPD system, there are two closed circulations, namely refrigerant loop and air loop. Both loops exchange heat from each other through evaporator and condenser. When the heat pump is in cycle operation, the system acts through the compressor and drives the refrigerant to cycle, so that the refrigerant absorbs exhaust

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waste heat from drying cylinder and latent heat of condensate in the evaporator, and transfer the heat with high temperature in the condenser to the air entering into the drying cylinder. In the air circulation, under the impetus of fan, the temperature of warm and humid air discharged from drying cylinder is decreased in the evaporator, and it condenses moisture in the air; and then the air with low temperature and low moisture content increases temperature through condenser, but the moisture content keeps the same, the relative humidity decreases, and the moisture absorbing capacity of air becomes quite strong at this time; finally, the air with high temperature and low moisture content blows through the surface of clothing, the clothing has heat and humidity exchange, gives off heat and takes away moisture. As the system inputs power continuously, in order to maintain the energy balance of circulating air, the system need to set auxiliary cooler, auxiliary condenser or add fresh air to maintain system stability.

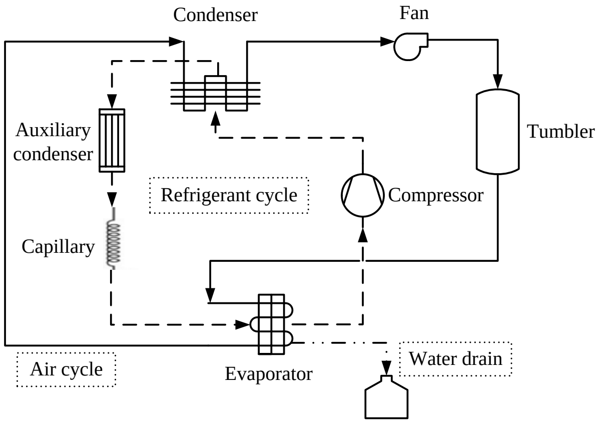

Fig. 1. Schematic of heat pump clothes dryer

As a complex coupling system, the simulation research of HPD is relatively challenging. So far the study of HPD is mainly experiment [12-15] and theory analysis [4, 16-20]. For involved simulation study method, it builds traditional simulation model in steady state for heat pump system, while simplifies the clothing model [16]. For example, assuming that the drying process is an isenthalpic process and gives the relative humidity of outlet air to avoid building complicated dynamic model of heat and mass transfer; or assuming that the drying rate is constant, the clothing drying process carries out along with wet-bulb temperature line, and the relation of inlet and outlet dry-bulb temperature and moisture content of drying cylinder is defined as drying rate of clothing, as shown in equation (1).

$$\eta_{\mathrm{dry}} = \frac{T_{\mathrm{in}} - T_{\mathrm{out}}}{T_{\mathrm{in}} - T_{\mathrm{sat}}} = \frac{W_{\mathrm{out}} - W_{\mathrm{in}}}{W_{\mathrm{sat}} - W_{\mathrm{in}}} \tag{1}$$

where η_{dry} denotes the drying rate of clothing and often takes 0.75. T_{in} and T_{out} are inlet and outlet air temperature (°C) of drying cylinder, respectively. T_{sat} is the air temperature of intersection point of constant wet-bulb line and saturation line, and W_{in} and W_{out} represent moisture content of inlet and outlet air of drying cylinder, respectively.

In addition, the drying process of clothing could be analyzed in three stages below[21, 22]:

1. The heating process of clothing and drying drum including the wall of the cylinder;
2. The stable drying process of clothing, at this point the outlet air is basically saturated, and the temperature of clothing is basically constant;
3. The drying process in reduction speed, at this time the relative humidity of outlet air decreases, while the temperature of clothing will increase continuously till the end of the drying process.

Therefore, the actual drying process is not an isenthalpic process, and the drying rate is not constant, either. Previous analysis and system design of HPD mostly aim at stable drying process, and the heating process of clothing and drying process in reduction speed are ignored. In fact the time needed for the two processes accounts for 40% ~ 50% of the drying process. If we don't build dynamic model of heat and mass transfer for clothing and combine with the heat pump model, major economic indicators such as clothing drying time and energy consumption of the system cannot be well predicted.

In this work, setting up the HPD model, system analysis and optimization as main targets, the heat pump model in steady state and the dynamic model of heat and mass transfer for clothing were combined to simulate the whole process of clothing drying and to verify with experiment. Matching study of components size and optimization of important parameters were carried out with verified model for the clothing drying system of heat pump, which provided reference for design and optimization of clothes dryer.

2. HPD system Model

2.1 Heat pump dryer system model

An quasi-steady state HPD model, which consists of the heat pump system model and the heat and mass transfer model of clothing, is designed with the refrigeration and heat pump simulation software GRAEATLAB [23], which is used for component sizing and selection.

The schematic of the model established in this paper is shown in Fig. 2. The HPD system model consists of AHRI compressor performance model [24], 3D finned-tube condenser model, evaporator model, auxiliary condenser model, capillary model, fan models and other connections such as refrigerant pipes and air duct. Detailed simulation algorithm of the finned-tube heat exchanger model can refer to our previous work [25].

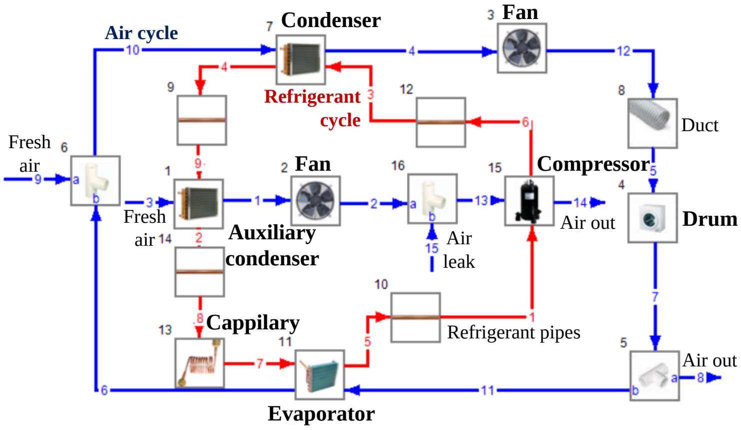

Fig. 2. System model of a heat pump clothes dryer in GREATLAB

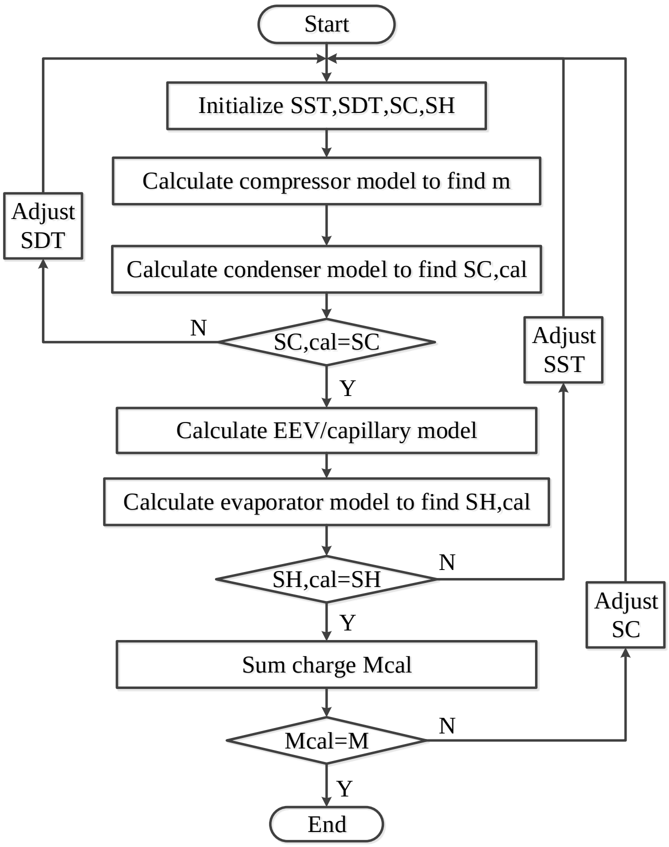

Fig. 3. Flowchart of heat pump simulation

The simulation algorithm of the heat pump system is shown in Fig. 3, where the parameters SST, SDT, SC, SH, m, M denote the suction saturated temperature, discharging saturated temperature, subcooling, superheating, mass flow rate, and system refrigerant charge, respectively. The subscript, cal, represents model calculation.

It can be known from the law of energy conservation: The heat of air emitted by the condenser is greater than that the evaporator absorbed from the air, and the closed air circulation in the system cannot be in steady state, or the temperature of clothing will rise continuously till that the discharge pressure of the system is too high to operate. There are usually several system arrangements to maintain the stability of air circulation [26]: introducing certain percentage of RAR, installing auxiliary condenser behind the main condenser in series, adding the auxiliary condenser of air and indoor air before the evaporator, and bypassing air without passing through the evaporator, or several ways are combined to use [27].

The difference of heat pump system built in the work and conventional heat pump air conditioning system is that, when the outlet temperature of the condenser is greater than a certain set value as the discharge pressure is too high, it will start auxiliary fan in order to reduce the discharge pressure; when the outlet temperature of the condenser is lower than another set value, the auxiliary fan will be shut down.

2.2 Heat and mass transfer model of clothing

For the clothing drying drum and air cycle, the dynamic heat and mass transfer model of clothing and wet air was built in the research. The model assumptions are as follows:

1. In the drying process, the textile garments rotate continuously with the drum, and assume that the temperature, moisture content and specific heat of clothing distribute uniformly in space;
2. Assume that within time step Δt of drying process, the temperature of drum, clothing and the moisture of clothing are uniform, and the moisture content in saturated air layer of clothing surface is also uniform;
3. During drying process, the convective heat transfer coefficient of air on the clothing surface and mass transfer coefficient are constants;

4. The saturation degree of vapor in air layer on the surface of clothing is represented by activity coefficient.

The details of mathematical model during drying process can be found from paper [27]. During the drying process, the temperature of air outlet decreases and the moisture content increases. The schematic of energy balance of clothing during clothes drying process is shown as Fig. 4. During the drying process, the air exchanges heat with clothing and part heat Q_{load} is absorbed by the clothing and drum to heat them; part heat Q_{loss} disperses in the environment; meanwhile, the air and clothing have mass transfer, part moisture m_{evap} in the clothing enters into the air, the temperature of evaporative water in the clothing and on the surface of clothing are the same of T_{clo}.

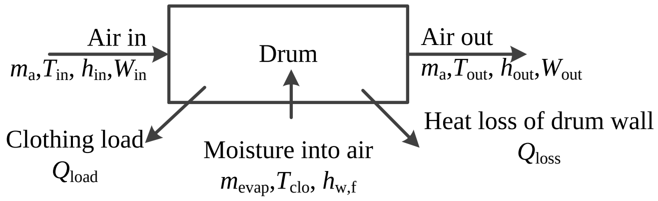

Fig. 4. Energy balance within the drum over a time interval

3. Model validation

The specifications of household HPD heat exchangers used in the test are shown in Table 1. In the heat pump system, capillary is adopted as restricting element (1.4mm × 500mm), the refrigerant charge is 360 g, the air flow rate of circulating fan is 170m^3/h, and the air flow rate of auxiliary fan is 80 m^3/h. The environmental parameters in test of the HPD is 23°C dry-bulb temperature, 55% relative humidity. The initial load temperature is 20°C, the dry weight of clothing is 8.027kg, the initial moisture content is 0.7, and the weight of clothing after drying is 8.275kg. The total drying time is 160min.

Table 1 Heat exchanger specifications of the HPD

Dimension	Condenser	Evaporator	Auxiliary condenser
Inside diameter (mm)	9.52	9.52	9.52
Row number	8	4	1
Tube number per row	6	6	4
Row pitch (mm)	25.4	25.4	25.4
Tube pitch (mm)	22	22	22
Tube length (mm)	230	230	120
Fin pitch (mm)	2.2	2.2	2.2
Fin thickness(mm)	0.12	0.12	0.12
Fin type	Waves	Hydrophilic waves	Waves
Tube type	Smooth	Smooth	Smooth

In order to monitor operating parameters of HPD, two pressure measuring points are set on the circulating pipeline of the heat pump to continuously monitor the discharge pressure and suction pressure of the system (the uncertainty of pressure measurement is 0.25%); eight temperature measurements are set to continuously monitor the temperature of the exhaust and suction of compressor, the outlet of condenser, before restriction, the inlet of evaporator, the inlet and outlet air and the environmental temperature of compressor (the uncertainty of temperature measurement is 0.5K).

In addition, measured results of HPD contain boot process (establishing process of high and low pressure of cooling system), but the model built in the paper is quasi-steady-state model: i.e. The heat pump model in steady state combines with clothing model in dynamic state and it cannot simulate the start-up and shutdown processes of heat pump system. Therefore, the data in start-up and shutdown stage is removed by the comparison of measured and simulated results, the total drying time is shortened to 151min finally, and power consumption is 1.95 kWh. The drying time of simulated results is 148min and power consumption is 1.905kWh. Overall results are in good agreement, the error of drying time is less than 3 minutes, and that of power consumption is -2.3%. In addition to the overall economic indicators of the dryer, the model can also predict the process parameters of the system. In order to validate the model fully and accurately, the measured and simulated results of important parameters of the system changing with time are compared.

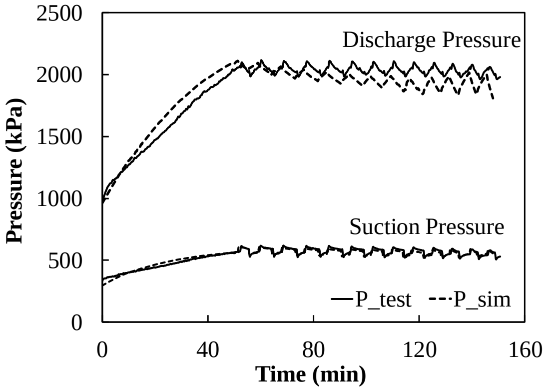

Fig. 5. Comparison of system pressures between measured and simulated results

Fig. 5 is the comparison of measured and simulated results of discharge pressure and suction pressure of the heat pump system. Seen from the trend, the first 50min of the entire drying process is the initial heating process of clothing, and the suction pressure and discharge pressure are all increasing with the temperature rising of the clothing. Since outlet wet-bulb temperature changes little, the rising range of suction pressure is much lower than discharge pressure. When the discharge pressure rises to 2100kPa, the auxiliary condenser fan is turned on, the discharge pressure drops, and the suction pressure rises; when the outlet temperature of condenser is below the set value, the auxiliary fan is shutdown, the discharge pressure rises, and the suction pressure drops. The results of Fig. 5 also show that, after the temperature rising process of the initial clothing finishes, the discharge pressure and suction pressure begin to oscillate periodically, and enters into a relatively stable drying stage. Seen from accuracy, since the working condition of evaporator is relatively stable in the whole drying process, the simulated and measured results of suction pressure are in high goodness of fit; as the working condition of condenser changes a lot, the simulated and measures results of discharge pressure have great difference, especially in the stages of initial temperature rising and drying with reducing speed. Since the activity coefficient of textiles will change with clothing temperature and moisture content, and only its changes with moisture content X is considered in the model, which has great difference with actual condition and results in the deviation of the model.

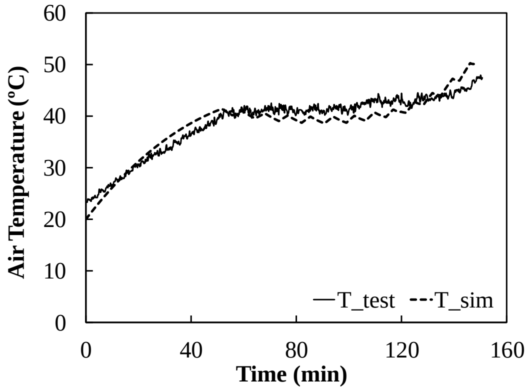

Fig. 6. Comparison of air temperature leaving drum

Typically, the temperature of outlet air is very close to clothing temperature (in general the difference is less than 1K), which can be approximately treated as clothing temperature. Therefore, the temperature of outlet air is one of the important parameters of HPD, and Fig. 6 is the comparison of measured and simulated results of outlet temperature. It can be seen from the figure that measured and simulated results fit well, and the clothing temperature has gone through three stages of initial temperature rising stage, intermediate stationary stage and final heating stage. Since the change of temperature is not considered in the calculation of activity coefficient of clothing, the predicted activity coefficient in drying stage with reduction speed is lower than the actual value. Therefore, the simulated results of clothing temperature in final stage rises faster than actual results, but the error is less than 4K, and the accuracy is acceptable.

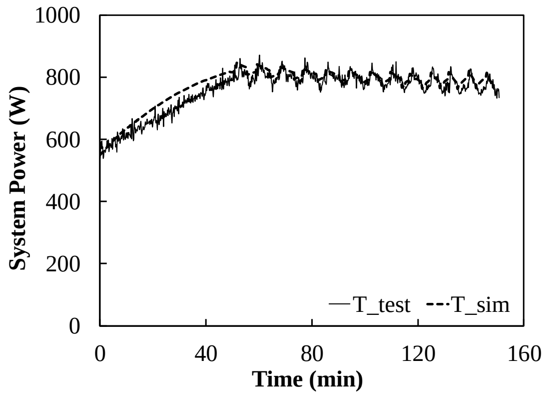

Fig. 7. Comparison of system power consumption

Fig. 7 indicates the comparison of measured and simulated results of system power consumption. It can be seen that not only the total power consumption of the error is small and the real-time simulated and measured results of power consumption are also in good agreement. Thus, the simulation model has been comprehensively validated with high accuracy, which can be used to guide the subsequent design and product optimization.

4. Parametric study

Previous literatures about study on HPD mainly focused on the impact of its load and surrounding environment on economic performance during drying process. In order to have deeper understanding on the performance of heat pump dryer, commonly SMER (Specific Moisture Extraction Rate) is used to comprehensively evaluate the heat pump drying system. The impact of some important parameters such as the air flow rate of circulating fan and the proportion of fresh air on SMER and drying time were studied and optimized with simulation method.

4.1 Impact of circulation air flow rate

Baines and Carrington [28] indicated that the matching relation of circulating fan and heat exchanger had a great impact on the energy consumption of drying, and improper matching could cause energy waste. Fig. 8 is the impact of the air flow rate of circulating fan on SMER and drying time. When study the change of air flow rate, maintain certain fan efficiency. It can be seen that the drying time is shortened with the increase of air flow rate, but for SMER, there is an optimal value for circular air flow, i.e. about 180 m^3/h. As the evaporating temperature rises and condensing temperature decreases, the increase of air flow rate is favorable to improve heat pump system COP; however, if the air flow rate is too big, it will result in temperature rising on surface of evaporator, which is not conducive to dehumidification. The main function of HPD is dehumidification, and high heat pump system COP does not mean that the amount of unit energy consumption SMER is also maximized. Therefore, it is quit essential to choose the best circulation air flow rate for HPD design.

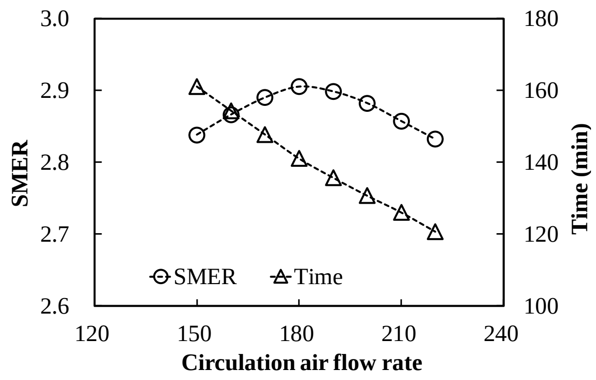

Fig. 8. Impact of circulation air flow rate on SMER and drying time

4.2 Impact of fresh air ratio

In the heat pump cycle, as the heat absorbed by the evaporator is less than the heat emitted by the condenser, in order to maintain the energy balance of circulating air, part of fresh air is introduced into the air circulation, as shown in Fig. 1. Parametric analysis is required for how much fresh air shall be introduced. Fig. 9 shows the impact of fresh air proportion on SMER, drying time and the opening time of auxiliary condensate fan. The auxiliary condenser has taken away part of heat in the heat pump drying system studied in the paper, thus the proportion of fresh air is lower than conventional systems. The proportion of fresh air in prototype is 8%, and the ratio range of fresh air in simulating calculation is 6 to 12%. There is also optimum value of fresh air proportion for impact on SMER. The simulation results show that in present system, when the proportion of fresh air is 9 to 10%, SMER is the highest. When the proportion of fresh air rises from 6% to 9%, SMER increases by 2.9%. When the proportion of fresh air increases continuously, the running time of auxiliary condensate fan decreases gradually; when the proportion of fresh air exceeds 10%, it is found that the auxiliary condensate fan does not need to open and the fresh air has taken away all excessive heat. That's also the reason when the proportion of fresh air exceeds 10%, the proportion of fresh air almost has no impact on SMER and the curve becomes gentle. Instead, due to the increase of the proportion of fresh air, the drying time rises rapidly. Therefore, HPD system needs to choose appropriate proportion of fresh air and the proportion of fresh air is also related to the size of auxiliary condenser. If the proportion of fresh air is too small, it can't maintain the stability of the system, the operation time of auxiliary condenser is too long, and the power consumption of auxiliary fan increases; If the proportion of fresh air is too big, though it is no need to open the auxiliary fan, but the moisture in fresh air is brought in the system, which would result in longer drying time and it is not economical for the system.

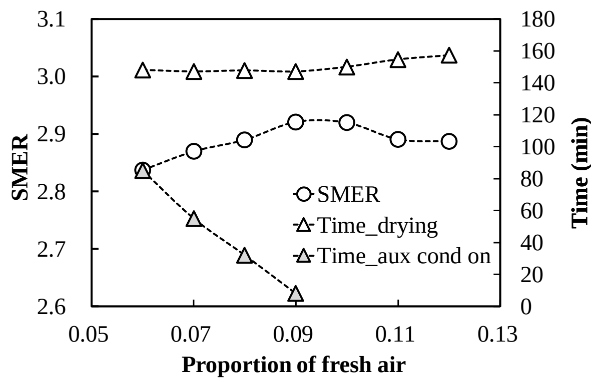

Fig. 9. Impact of fresh air rate on SMER, drying time and operation time of auxiliary condenser fan

5. Conclusions

In this work, the mathematical model of HPD was built in GREATLAB to simulate the whole process of clothing drying in the HPD system. Compared with the experimental data of a small household dryer, the drying process of simulation had good accuracy, little drying time error of less than 3 minutes and power consumption error of -2.3%.

The verified simulation model was adopted to study and optimize some key operating parameters on the system performance (SMER and drying time). Simulation results indicated that optimum circulation air flow rate (180m^3/h) and optimum ratio of fresh air (9.8%) existed for maximum SMER. The results are meaningful for the system design of heat pump clothes dryers.

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