

Performance Analysis of Heat-pump Dryer to Dry Mushroom

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Abstract: This study investigates the performance of a heat pump dryer. Taking the mushroom as the research object, a Heat-Pump Dryer (HPD) was designed and manufactured. Through the measure of air temperature and air humidity in the drying chamber, it shows that air distribution is more uniform in the lower part, drying process lasted 670 min, 90 kg of fresh mushroom ware load in the drying chamber, finally 75.2 kg of water was evaporated and same time 33.2 kW·h of electricity was consumed. The average value of Specific Moisture Extraction Rate (SMER) is 2.3 kg/kW·h for the whole heat pump dryer, if only calculated the power consumption of compressor, the SMER was 3.5 kg/kW·h.

Keywords: Drying, heat pump dryer, mushroom, performance

INTRODUCTION

Fresh mushroom are dehydrated to conserve them for future use. The optimum moisture content of dried mushroom is less than 13%, because the putrefying bacteria cannot reproduce under the level. Presently, both air-curing drying and hot air drying are still mostly applied in drying mushroom because of simple structure and low running cost (Pan, 1998; Chua *et al.*, 2002). Heat pump consume a little of mechanical energy or electricity and output lots of heat energy and based on the remarkable energy-saving effect, it is of great significance to rationally utilize of energy and reduce the pollution of the environment. Preliminary studies found that the color and aroma qualities of dried agricultural products using heat pumps were better than those products using conventional hot air dryers (Prasertsan and Saen-saby, 1998; Soponronnarit *et al.*, 1998; Strommen, 1994). Heat-hump drying technology has the advantage of high efficient, low cost and no pollution and same time can easily control the drying medium temperature, relative humidity and flow rate, so heat pump has been using in wood drying and agricultural products (Chen and Xie, 2006).

The research of heat pump drying mushroom is scanty, Li *et al.* (1998) introduce a close-loop heat pump drying system, its experimental result show the system is a better way to dry mushroom, but its structure is complex and difficult to operate.

The study is to introduce a new semi-open heat pump dryer with simple structure and automatic control system.

DRYING MATERIALS

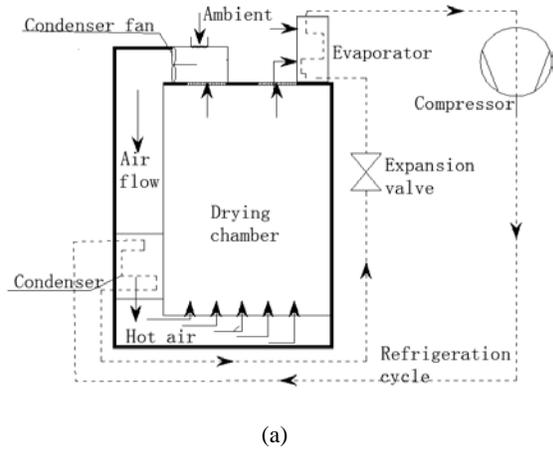
In the experiments, the drying materials are fresh mushrooms that are cultivated on basswood in Lushan county of Henan province and gathered on April 6, 2012. The moisture content of the fresh mushroom is about 85%. The umbrella are 30~50 mm in diameter and 5~10 mm thick and the stem is about 20~30 mm long and its diameters is about 3~10 mm.

Dry process: The drying process adopted in the experiment is according to local coal-fired drying process and it has following three stages:

First-stage is primary dehydration. The air inlet and outlet of the drying chamber open fully to discharge moisture as soon as possible (Zhou and Pan, 2009). The average air temperature which is the average value of the upper air temperature, middle air temperature and the bottom air temperature gradually rise to 45°C in 4~5 h.

Second-stage is drying stage. The air inlet and outlet adjust to half opening, the average air temperature slowly rise to 50°C and maintain 5~6 h. The moisture of fruiting body continues to evaporate, mushroom's bodies harden gradually and their shapes tend to be fixed. The moisture contents of mushroom are less than 20%.

Third-stage is called finalizing stage. The air inlet and outlet are closed, the average air temperature in the drying chamber is 55°C and maintain 1~2 h. At the end



(a)



(b)

Fig. 1: Schematic diagram of heat pump dryer, (a) A schematic illustration of heat pump drying system, (b) Image of heat pump dryer

of the stage, the most of mushrooms are dried to less than equilibrium moisture content of 13%.

EXPERIMENT SETUP AND METHODS

The experiment setup was designed and constructed for drying mushroom only and it is composed of a heat pump system and drying system, Fig. 1 illustrates a schematic diagram of the experiment setup.

System descriptions: The heat pump system consists of a scroll compressor, a fin and tube condenser, an expansion valve, a fin and tube evaporator, a condenser fan, an evaporator fan and a set of process control equipment. The working fluid of the heat pump is R-22. The input power of compressor is 2.6 kW. The heat pump system is designed and manufactured in a way that evaporator enables to recover the energy of the exhausting air discharged from drying chamber. There are air cycle and refrigeration cycle. Air is heated by



Fig. 2: Schematic diagram of drying chamber inside

Table 1: System operating parameters and reference values

Variables	Values
Fresh mushroom M_1 /kg	90
Moisture content of dried mushroom ω_2 /%	12
Air flow rate leaving condenser G_c /(kg/h)	1700
Air flow rate leaving evaporator G_e /(kg/h)	1000
Ambient temperature t_{1a} /°C	25
Ambient relative humidity r_{1a} /%	78
Latent heat of vaporization of water γ /(kJ/kg)	2500
Evaporating temperature of refrigeration t_e /°C	15
Superheat of refrigeration Δt /°C	5
Displacement of compressor V /(m ³ /h)	8.00
Input power of evaporator fan W_1 /kW	0.02
Input power of condenser fan W_2 /kW	1.00

refrigerant in condenser, then the hot air enter drying chamber from the bottom and do heat and humidity's exchange with mushrooms, finally leave the drying chamber through the two outlets located on the top of drying chamber. A part of hot humid air can be extracted by evaporator or directly discharge to ambient, another part mixed with fresh air pass condenser and go to next cycle.

Figure 2 shows the internal structure of the drying chamber, it can load thirteen baboon curtains with 0.8 m wide \times 1.0 m dimension of deep and pore size of 10 \times 10 mm. the spacing between two adjacent baboon curtains is 120 mm. While in the experimental, there are ten baboon curtains used and every one put 9 kg mushroom.

System operating characteristics: Based on the requirement of drying process, the basic characteristics of the experiment are listed in Table 1.

RESULTS AND ANALYSIS

Drying experiments were performed on April 6, 2012 during 11:00 A.M. - 10:10 P.M. In the following figures, the drying time is reduced to 0 to 670 min.

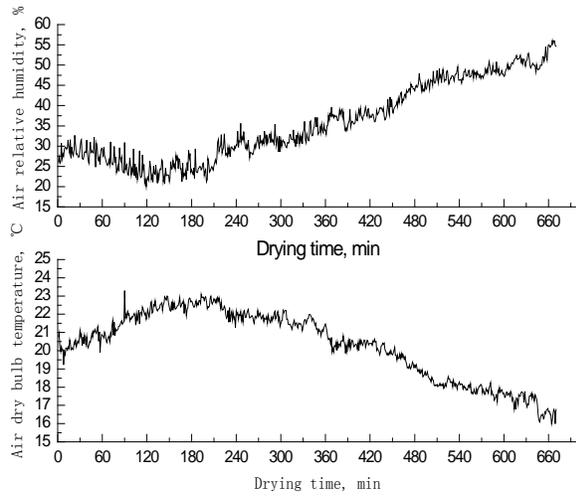


Fig. 3: Ambient air temperature and humidity during drying process

Ambient air temperature and humidity, Inlet and outlet air temperatures of drying chamber, electricity consumption, evaporating temperature and condensing temperature were monitored and recorded. Figure 3 shows the ambient air temperature and humidity during the drying process.

The compressor performance: The drying process lasted 670 min, but the compressor works intermittently and total working time is about 8 h. Figure 4 shows the input power of the compressor during the process. The average input power range is between 2300 to 2500 kW.

In the experiment two pressure sensors are installed at the compressor section line and discharge line to detect the refrigerant pressure. The evaporating temperature and condensing temperature shown in Fig. 5 are saturation temperature and there are calculated by corresponding pressures. The two pressures associate with compressor on or off, Fig. 5 show the data when compressor switches on.

The variation of air properties in the drying chamber: The drying process lasted 670 min. Figure 6 and 7 show the air dry point temperature and relative humidity which were recorded by sensors which are put in the drying chamber. The first stage lasted 330 min until the temperature rises to 45°C. Then Open the door of drying chamber to swap the baboon curtains with mushroom between the bottom and the upper. From 340 min drying access to second stage, the compressor stops frequently and run for about 15 min and keeps stop 5 min in one pass. At the 600 min reopen the door and weight mushroom, moisture content of the drying mushroom is about 14%. Later drying pass to third

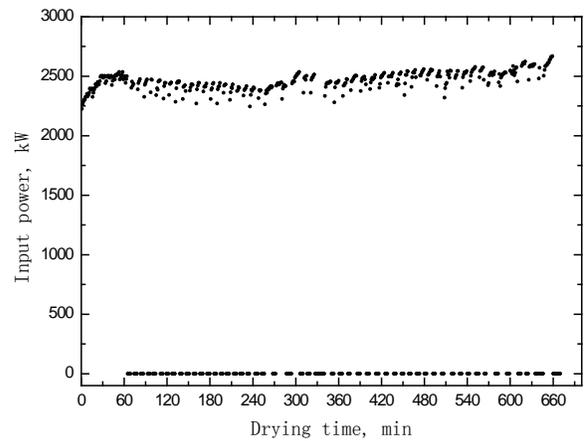


Fig. 4: Input power of compressor during drying process

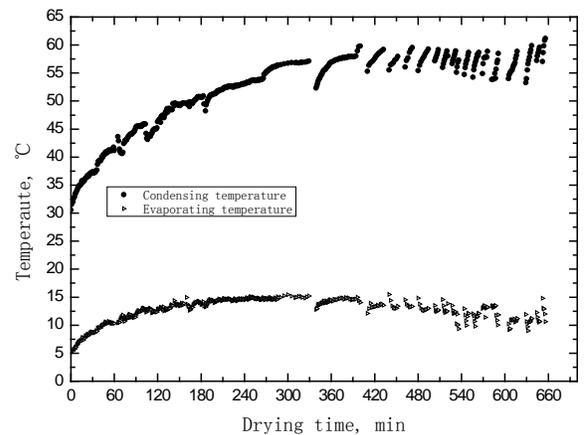


Fig. 5: Evaporating temperature and condensing temperature at compressor working

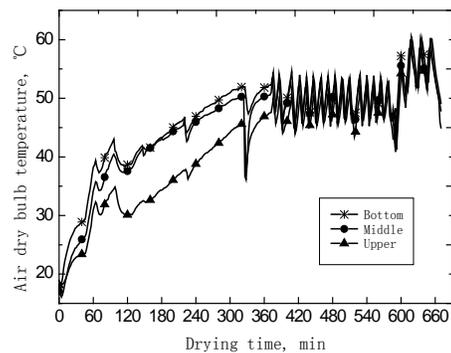


Fig. 6: Air dry point temperature in the drying chamber

stage. At the end of third stage compressor switch off firstly and condenser fan continue to run about 10 min then shut down, the most of mushrooms are dried.

Figure 6 shows that the heating rate is about 0.1°C/min in the beginning of drying process and in the first stage air distribution is uniform in the lower

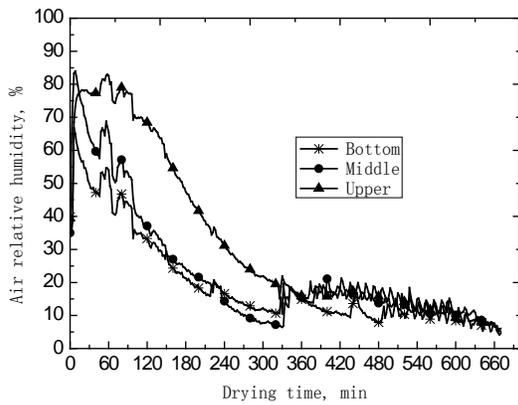


Fig. 7: Air relative humidity in the drying chamber

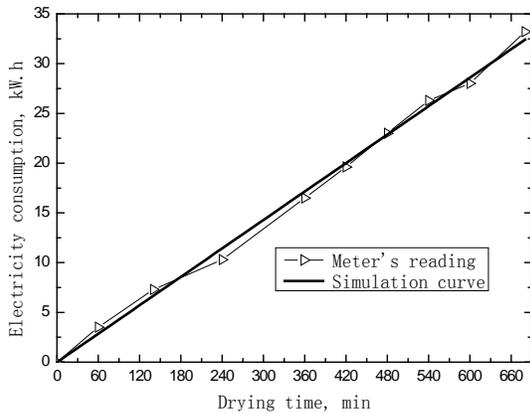


Fig. 8: Power consumption for drying mushroom

part and the maximum air temperature difference is less than 3°C, while uneven distribution of air temperature in the upper part and maximum air temperature difference between the upper part and middle part is 9°C. In the second stage, air distribution is more uniform in whole chamber after the baboon curtains with mushroom exchanged the position, it means that the upper mushroom were put at the bottom, inversely the bottom were lifted to the top. Air temperature fluctuation at 60~120 min is caused by adjusted the angles of air inlet and air outlet. The bigger air temperature difference is caused by structure of drying chamber and air supply method. The abnormal relative humidity shown in Fig. 7 is associated with the air temperature fluctuation.

The air temperature drop down at 330 min is because of opening the door of drying chamber. The uniform temperature distribution at second stage and third stage is due to airflow organization change after the baboon curtain exchanged positions.

Electricity consumption: Figure 8 indicates the relationship between electricity consumption and drying time. The whole drying process used about

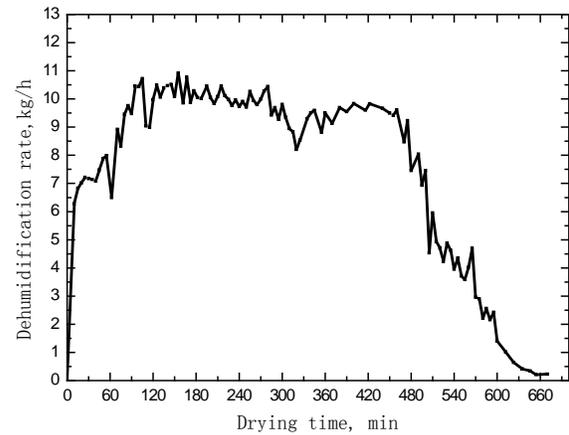


Fig. 9: Dehydration rate of the mushroom during the drying process

33.2 kW/h of electricity. Following linear Eq. (1) obtained by a curve fitting method can be used to calculate the power consumption and its standard deviation is in 0.001:

$$W_t = -0.001 + 0.0477 \times t \quad (1)$$

t = Drying time, min

Wt = Power consumption in t minutes, kWh

The electronic devices of the drying system include compressor, condenser fan and evaporator fan. Condenser fan work continuously until the end of drying process, it spends 11.2 kWh of electricity and accounts for about 30% of total power consumption. The compressor and evaporator fan work synchronously and they work intermittently from second drying stage. Evaporator fan just use 0.5 kWh of electricity and compressor use 21.5 kWh of electricity.

Dehumidifying capacity: An amount of desiccant satisfies the set of integral Eq. (2):

$$M_w = \int_0^t \frac{r \times t}{60} dt \quad (2)$$

t = Drying time, min

r = Dehumidification rate, kg/h

Mw = an amount of desiccant, kg

Figure 9 show the dehumidification rate calculated through air side temperature leaving condenser, air side relative humidity leaving condenser, air temperature leaving drying chamber, air relative humidity leaving drying chamber and air flow rate of dry air.

Dehumidification rate of heat pump system correlate significantly with the air relative humidity in

drying chamber (Zhang *et al.*, 2006). From begin to 120 min, dehumidification rate gradually increase; from 120 to 270 min, dehumidification rate tends to be constant speed and keep up 10 kg/h; from 270 to 330 min, Dehumidification rate decrease and sustain downward trend, so open the door and exchange the position of baboon curtain with mushroom. Then enter the second drying stage and from 360 to 480 min, dehumidification rate tends to be constant speed and keep up 9.5 kg/h, from 480 to the end, dehumidification rate continue to fall and in the final hour the dehumidification rate get close to 0.2 kg/h.

Based on the value shown in Fig. 9 and Eq. (2), the water evaporated from mushroom is about 77.7 kg. At the end of drying process, to weigh the dried mushroom 14.8 kg. The fresh mushroom is 90 kg, so 75.2 kg water is evaporated. Compared the calculated value and the measured value, their error is 3.3%.

The Specific Moisture Extraction Rate (SMER), this can be defined as the energy required to remove 1 kg of water and may be related to the power input to the compressor (SMER_{hp}) or to the total power to the dryer including the fan power and the efficiencies of the electrical devices (SMER_{total}), as given by Schmidt *et al.* (1998), Hawlader *et al.* (1998) and Jia *et al.* (1990):

$$SMER_{hp} = \frac{M_w}{W_c} = \frac{75.2}{21.5} = 3.5 \quad (3)$$

$$SMER_{total} = \frac{M_w}{W_{total}} = \frac{75.2}{33.2} = 2.3 \quad (4)$$

CONCLUSION

A prototype heat pump drying system was designed, constructed and tested for drying mushroom. From the results presented in this study, the following main conclusions may be drawn for the dryer investigated.

Air flow distribution in the drying chamber is fairly uneven; particularly in the early stage of drying air temperature at the top is lower than that in lower part. The reason is fresh mushrooms are soft, have small gaps and bigger air resistance. At the last stage, Mushroom lose water and shrink, so gaps among mushrooms enlarge, finally the air resistance decrease and air flow distribution tend to uniform.

SMER_{hp} is 3.5 kg/kWh and yet SMER_{total} just is 2.3 kg/kWh, the gap is due to input power of condenser fan is bigger, in future new design should use high efficient fan and save energy.

Exchange of baboon curtains is not reasonable, the structure of drying chamber should be improved and find a good way to replace the method and don't need to exchange baboon curtains.

Automatization and intelligence is used in the heat pump dryer controlled system. Compared to wood-fired dryer and coal-fired dryer, heat pump dryer don't need someone to look after and very convenient to use. Otherwise, the electric charge used by the heat pump dryer is less than the labor cost which spends on looking after the conventional dryer.

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