A HEAT PUMP SYSTEM FOR *LENTINULA EDODES* DRYING AND ITS DRYING PROPERTY

by

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The traditional drying of Lentinula edodes is by hot gases obtained by burning coal or wood. This process wastes a lot of energy, increases carbon emissions, and rises the burden of the environment. This article presents a heat pump system for Lentinula edodes drying. Optimal conditions for drying process is obtained by using orthogonal test. Experiment results show that the heat pump system is reasonable, reliable, and practicable. Optimal drying process, compared to the traditional one , significantly improvs the drying quality.

Key words: heat pump, drying, *Lentinula edodes*, orthogonal test

Introduction

The *Lentinula edodes* is a high protein, low fat nutritional food, but fresh *Lentinula edodes* is not easy to save, so it is usually needed to be dried after picking. The traditional drying room produce heat by burning coal or wood. The process consumes energy, produces a lot of flue gas, and pollutes the environment, and *Lentinula edodes* easily absorb harmful substances, seriously affecting the quality of product obtained. The traditional drying process must strictly control the amount of fuel, otherwise a small error will cause coking which will seriously affect the drying quality of *Lentinula edodes*. In addition, the traditional drying system has the problem of heating imbalance, so it needs to overturn the *Lentinula edodes* up and down repeatedly, wasting time and making the full process inefficient. There is also an electric heating drying, but it directly converts electric energy into heat, which consumes a large amount of energy and has a high operating cost. In view of the previous situation, this paper designs the drying process using heat pump system. The results show that the new technology using air as a heat carrier results in remarkable energy saving, reduces exhaust emissions, and has a high degree of automation. Drying effect is better than traditional drying process.

The advantage of the heat pump *Lentinula edodes* drying room

The heat pump drying system using heat transferred from the environment. The heat generated by heat pump is the sum of the consumption of electricity and the transfer of heat from environment. Compared to the traditional drying and electric heating, the heat pump drying system is energy-efficient, has no pollutant emissions during the operation, and friendlier

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to the environment [1]. The specific moisture extraction rates of the heat pump drying system is in the range 1-4 kg/kWh, the average value is 2.5 kg/kWh [2]. The heat pump drying system has the advantages in the drying process: *Lentinula edodes* is heated evenly, without turning over, can have high degree of automation, and control of parameters is easy. The system will automatically heat and remove humidity according to the parameters settled, and it is no need for care. The heat pump drying is a gentle drying method which is close to the natural dry. The evaporation rate of surface water is close to that of internal moisture, it reduces *Lentinula edodes* heat denaturation and discoloration. The loss of nutrients is less, protect the color, aroma, taste, save individual form and effective components effectively, so *Lentinula edodes* with heat pump drying has an excellent quality and prominent level [3].

System design of heat pump *Lentinula edodes* drying room

The heat pump *Lentinula edodes* drying system is divided into five parts, which are: heating system, ventilation and dehumidification system, intelligent control system, material room, and heating room. Heating system is consisted of the heat pump units of hot temperature and electric auxiliary heating equipment which ensures the heat for the heating room to provide stability and reliability throughout the year. Ventilation and dehumidification system ensure the warm air circulation in the normal operation, and discharge the humid air according to the requirements of the material room, and maintain the drying capacity by adding fresh air during the process. Temperature and humidity monitoring system can monitor temperature and humidity of drying room and transmit data to the intelligent real time control system. Intelligent control system can control the temperature, humidity and humidity elimination and other operations according to settled drying parameters. There are mobile material vehicles in the material room, with the tray for material placed on the vehicle. The return air channel is set above the material room. In addition, material room is equipped with two exhaust fans. Condenser and circulating fan are installed in the heating room. The warm air is supplied to the material room by the circulating fan from the bottom of the heating chamber, while the upper part in the heating room is connected with the return airway returning warm air in the drying room. The internal structure of the drying room is shown in fig. 1, the overall view is shown in fig. 2.

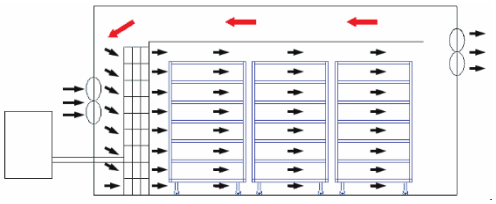

Figure 1. The internal structure of the heat pump drying room

Figure 2. Overall view of the heat pump room

Study on drying process of the heat pump drying room

The heat pump drying room was designed for 500 kg capacity of the wet *Lentinula edodes*. The drying room is made of 100 mm thick polyurethane color steel plate. The drying room is mainly composed of the material room and the heating room. The material room in-

ternal size is 3200 × 2400 × 2300 mm (length × width × height), and the heating room internal size is 1500 × 2400 × 2300 mm (length × width × height). The return airway is on the top of the material room, and the exhaust fan is near the door and has a return air baffles. The mobile material vehicle is made of aluminum alloy, and there are total of seven layers up and down, the interval between each layer is 20 cm. The distance between the top of the mobile material vehicle and the return airway above the drying room is also 20 cm.

Orthogonal experiment design is a method that study multifactor and multilevel. This method is based on orthogonality to select some representative points from the comprehensive test to test, and through the analysis of these points to analysis the results of a comprehensive test situation. Orthogonal test design is an efficient and fast experimental design method [4, 5].

Based on the traditional drying process, the process of the heat pump drying room has three factors – drying time, moisture removal and circulating wind speed. By consulting data given in [6, 7], for the heat pump drying room drying process, the drying time time has been chosen as 17 and 20 hours. The moisture removal in the drying process is determined by the moisture removal temperature difference. For example, when the target wet bulb temperature is set to t_a °C, and the moisture removal temperature difference is 4 °C, at the moment when the drying room wet bulb temperature reaches (t_a – 4) °C, the fan will activate automatically to dehumidification, and when the moisture removal temperature difference is set 2 °C, the fan will activate when the drying room wet bulb temperature reached (t_a – 2) °C, so the moisture removal is relatively small. The circulating wind speed in the drying room have two levels, 2 m/s and 3 m/s. The design scheme is shown in tab. 1.

Table 1. Orthogonal test factor level table

Factor levels	Drying time, [h]	Moisture removal temperature difference, [°C]	Circulating wind speed [ms^{-1}]
1	17	2	2
2	20	4	3

Quality of the product (moisture content, shape, color and aroma of *Lentinula edodes* after drying under different conditions)can be evaluated in the range of 0-10 points. The higher the score the better the *Lentinula edodes* quality.

This orthogonal test is a three-factor two-level test, so according to this orthogonal table $L_4(2^3)$ [8], only need four tests to understand the overall situation of eight tests. The combinations of the trials and the test results are shown in tab. 2.

It can be seen from tab. 2 that the main factors influencing the quality of dried *Lentinula edodes* are: moisture removal temperature difference, drying time, and circulating wind speed. The optimal combination of factors is: drying time 20 hours, drying process set the moisture removal temperature difference to 4 °C, the circulating wind speed is 3 m/s. Therefore, the best drying process of the heat pump type drying room is: the whole drying process is last 20 hours, the drying starting temperature is 35 °C, the temperature slowly increases to 62 °C during the drying process, circulating wind speed is 3 m/s, drying process set the wet temperature difference to 4 °C. The wet and dry bulb temperature target of the heat pump drying room in dissimilar stages are shown in tab. 3. This drying parameter can avoid the *Lentinula edodes* pores to close in the drying process, so that the internal moisture can be evaporated out smoothly [9].

Table 2. Orthogonal test scheme and results table

No.	Factor			Index
	Drying time [h]	Moisture removal temperature difference, [°C]	Circulating wind speed, [ms^{-1}]	Drying quality
1	1 (17)	1 (2)	1 (2)	8.25
2	1 (17)	2 (4)	2 (3)	8.75
3	2 (20)	1 (2)	2 (3)	8.7
4	2 (20)	2 (4)	1 (2)	8.95
K1	17	16.95	17.2	
K2	17.65	17.7	17.7	
k1	8.5	8.475	8.6	
k2	8.825	8.85	8.85	
R	0.325	0.375	0.25	
Primary and secondary order	Moisture removal temperature difference > drying time > circulating wind speed			
Optimum level	20	4	3	
Optimal combination	Drying time 20 h, moisture removal temperature difference 4 °C, circulating wind speed 3 m/s			

Table 3. The wet and dry bulb temperature target in dissimilar stages

Stage parameter	1	2	3	4	5	6	7	8	9	10
Dry bulb temperature, [°C]	35	38	40	42	44	47	50	55	58	62
Wet bulb temperature, [°C]	29	29	30	31	32	33	34	35	36	36
Working hours, [h]	2	2	2	2	2	2	2	2	2	2

Drying characteristics of optimum drying process

Experiments carried out on the best drying process conditions show that the drying process is practicable, the quality of *Lentinula edodes* after drying by the heat pump drying room is good, the water content of final product meets the storage requirements, has a better appearance, color and aroma, compared to traditional *Lentinula edodes* drying room. The quality of the *Lentinula edodes* drying by heat pump drying room is a significant improvement.

In the experiments under the best drying process, the temperature of the dry and wet bulb in the drying room was monitored. The temperature change curve of the dry and wet bulb during the drying process is shown on fig. 3, the moisture content of drying room drying medium change is shown on fig. 4.

As can be seen from fig. 3, dry bulb temperature rises rapidly in the initial stage of drying. This is because the ambient temperature is lower, and the dry bulb temperature target of the drying room is set to 35 °C in the initial stage. The bulb temperature rises quickly from the ambient temperature to about 35 °C in the first hour. During the whole drying process, the dry bulb temperature in the drying room is in a state of uniform rise. From the same reason the wet bulb temperature also rises quickly in the initial stage of drying, but during the whole

drying process, the wet bulb temperature in the drying room shows slowly rising then gradually decline. From the thermodynamic knowledge can be seen, when the moisture content of wet air is constant, the wet bulb temperature will increase with the increase of dry bulb temperature [10], therefore, the temperature and humidity curve in the figures shows that the moisture content in the drying room is decreasing during the whole drying process.

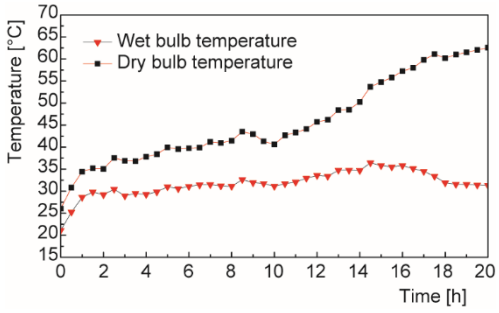

Figure 3. Temperature and humidity curves of heat pump *Lentinula edodes* drying room

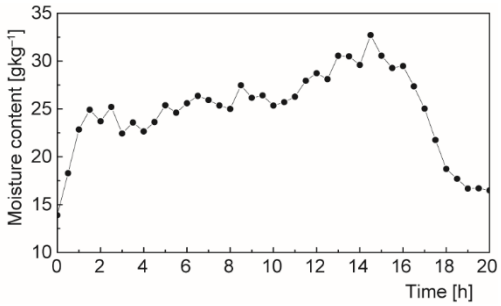

Figure 4. Relative humidity curves of the heat pump *Lentinula edodes* drying room

As can be seen from fig. 4, the drying medium moisture content rapidly increases at first, and then slowly increases and after that quickly reduces, finally in to relatively stable level. This is because in the beginning of the drying process, the water inside the *Lentinula edodes* began to evaporate quickly, so the moisture content rapidly increases in the beginning of the drying process. In the middle of drying period, the water inside the *Lentinula edodes* continuoulys evaporate, while the wet air is also discharged from the drying room, but water evaporation rate is slightly larger than the drying room moisture removal rate. So the water content of the drying medium in the middle of drying process showed a relatively stable but slowly rising state. At the end of drying period, the water inside the *Lentinula edodes* is almost completely discharged, but the drying room was still be dehumidifying, so the water content of the drying medium in the drying room decreases rapidly at the end of drying period.

The experiment used the fresh *Lentinula edodes* from Xixia County, Nanyang City, Henan Province, as shown in fig. 5(a). The *Lentinula edodes* which was dried by the traditional drying room is shown in fig. 5(b). The color compared to fresh *Lentinula edodes* has a tremendous change. The *Lentinula edodes* dried by the traditional drying room usually have some cracks on its surface, and serious shrinkage, aroma is not good, rehydration is often poor, which all make low grade products. The *Lentinula edodes* dried by the heat pump dry-

Figure 5. Comparison of the mushrooms appearance; (a) fresh *Lentinula edodes* before drying, (b) the *Lentinula edodes* drying in traditional room, (c) the *Lentinula edodes* drying in heat pump drying room

ing room is shown in fig. 5(c). Compared to the traditional drying ways, *Lentinula edodes* dried by heat pump drying room has no obvious shrinkage, similar color as the fresh *Lentinula edodes*, rich aroma, and maintain the unique aroma of *Lentinula edodes.* Rehydration is also better.

Conclusion

Air is a relatively clean energy carrier, the heat pump drying room transfering the heat from air to drying product has many advantages - operation costs are low, the drying process can achieve automatic control that greatly enhance the efficiency. In addition, the heat pump drying is a mild drying method. The *Lentinula edodes* drying by the heat pump drying room has a good color, rich aroma, no obvious shrinkage, high product level. In this paper, a heat pump *Lentinula edodes* drying room was designed and tested, and optimal drying process was obtained for *Lentinula edodes* using orthogonal test. The tests showed that the design of the *Lentinula edodes* heat pump drying room is reasonable and reliable, the quality of *Lentinula edodes* dried by the heat pump drying room is good, the water content meets the storage requirements. *Lentinula edodes* has a good appearance, color and aroma, compared to traditional drying. The quality drying by heat pump drying room has a significant advantages and this technology should be promoted widely.

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