Optimization Analysis of System and Air Distribution for Solar and Heat Pump Multi-energy Complementary Zanthoxylum Drying

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Abstract. Crops have high moisture content and are easily deteriorated, requiring dry storage. However, the drying energy consumption is relatively large and the drying quality of materials is often affected by the uneven distribution of indoor airflow. Author takes Zanthoxylum as an example and designs two solar and heat pump drying systems in which the heat pump evaporator and the heat pipe are used to recover the waste heat respectively. The energy efficiency is compared and analyzed, the result shows that when the heat evaporator is used to recover the waste heat, the energy efficiency is higher and COP of the heat pump can reach 4.06. Based on the optimized system, the FLUENT software is used to simulate the airflow organization of the two types that supplying below and returning upward, and the side-supplying and side-returning. The results show that the airflow in the drying chamber has better uniformity when using the side-supplying and side-returning, which satisfies the requirements of Zanthoxylum drying.

1.Introduction
The problem of drying crops is a major problem that restricts the development of agricultural industry[1]. So the energy consumption of agricultural products drying is also a problem to be solved[2]. In recent years, many scholars have tried to combine solar energy and heat pumps to achieve drying purposes. Biguang, Z. [3] conducted an experimental study on solar heat pump combined drying wood, and found that the energy saving rate of combined drying was more than 70%, and the heating coefficient of the heat pump was increased by more than 2.0. Salehi [4] conducted research on solar-heat pump systems, and showed that solar and heat pump drying can greatly improve drying efficiency and shorten drying time. In addition, the uneven distribution of the air distribution is the main reason for the low drying efficiency [5]. Quanquan, L. [6] used CFD to simulate and analyze the airflow organization in the drying room, and proposed an optimized airflow plan for adding baffles, concluding that the airflow of drying room is uniform when three baffles are installed. Zhaoxin, M. [7] proposed measures to increase the deflector, modify the structure of the kiln body and optimize the material stack gap, so as to solve the problem of uneven distribution of wind speed inside the wood drying kiln, the results show that the proposed measures can reach requirement.

The above research reflects to a certain extent the high efficiency and energy saving of solar-heat pump combined drying, namely the importance of optimizing the airflow organization of the drying chamber. Therefore, this paper takes Zanthoxylum as an example, designed two solar and heat pump drying systems, obtained the optimal system through comparative analysis, and then compared and
analyzed the effect of two airflow organization that supplying below and returning upward, and the side-supplying and side-returning on the drying uniformity.

2. Drying system

2.1. Construction of a solar-heat pump combined drying system for Zanthoxylum

For the energy-saving and multi-energy complementary drying mode, the solar and heat pump combined drying system of Zanthoxylum is shown in Figure 1.

![Diagram of solar-heat pump combined drying system](image)

The diagram shows two types of solar and heat pump drying systems:

- System 1: Using heat pump evaporator to recover waste heat
- System 2: Using heat pipe to recover waste heat

The diagram includes the following components:
- 1-solar collection; 2-evaporator; 3-condenser; 4-compressor; 5-Expansion valve; 6-drying chamber; 7-The electromagnetic valve; 8-fan; 9-Heat pipe recovery;

Figure 1. Two types of Solar and heat pump drying system

System 1 and 2 both include three parts, namely the solar collection system, the heat pump system and the waste heat recovery system. Moreover, three working modes can be realized, that is in sunny periods, solar energy is used to dry alone. The two solar heat collection systems operate on the same principle, that is, outdoor fresh air is introduced into the solar heat collector and is heated. Finally, the circulating fan sends the air heated into the drying room. When solar radiation is weak, such as rainy or dark nights, the heat pump is used to dry alone; the outdoor air enters the evaporator, and the temperature is reduced to below the dewpoint to complete the dehumidification process, and then the dehumidified air enters the condenser to be reheated until it meets requirements. Finally, the reheated air is sent to the drying chamber. When the intensity of solar radiation is small or the drying load is too large, solar-heat pump combined drying is working. The outdoor air enters the solar collector and is heated, but it can’t meet the drying requirements, so it does not enter the drying room directly, but enters the condenser to reheat, and then the reheated air is sent into the drying chamber.

2.2. Dry air circulation process

Zanthoxylum’s drying process concludes three periods. The first stage is constant-rate drying, that is, fresh wet Zanthoxylum is heated in the drying room, and its skin shrinks due to the evaporation of a large amount of water. The temperature of the drying room is set to 47°C, the relative humidity is 50%, and the duration is 5h; The second stage is reduced-speed drying, that is, reheating on the basis of the first stage, so that the drying room has been maintained at a high temperature of 68°C. The drying speed begins to slow down, and the water migration speed inside the Zanthoxylum is lower than the surface water evaporation speed. And the relative humidity in the drying room is 50% and it is maintained for 3 hours[1][12].

The purpose of the system designed is mainly to dry the 5t Zanthoxylum with initial moisture content 60% (wet basis). After drying, the moisture content is required to reach 10% (wet basis). Based on the calculation of the drying theory, the dehumidification capacity is 2777.78kg, the heat load Q is
305.8Kw, the wet load W is 444.44kg/h, and the air volume \(G_f\) is 110700kg/h.

While the Zanthoxylum is being dried in the drying room, exhaust gas is continuously discharged to the outside and fresh air is introduced. The Study[8] have shown that when the amount of recycled waste gas accounts for 1/3 of the exhaust gas discharged from the drying chamber, the drying effect is better. Since the solar collector heats the air directly, the process is simple. This section mainly discusses the air circulation process in the heat pump and heat recovery system. The operating principle of heat recovery is as follows: In system1, the exhaust gas discharged from the drying chamber and outdoor fresh air enter the heat pump evaporator together to participate in the heat pump drying process. In system 2, the heat pipe heat exchanger recovers part of the exhaust gas discharged from the drying chamber to heat the outdoor fresh air. The heated air and part of the heat exchanged exhaust gas enter the heat pump evaporator to cool down and dehumidify.

According to the mixing state of exhaust gas and fresh air and the difference of heat recovery principle, the enthalpy and humidity diagrams of air treatment each system can be drawn respectively, namely Figure 2 and 3. The air parameters at each point are shown in Table 1.

**Figure 2. Enthalpy diagram of system 1**

**Figure 3. Enthalpy diagram of system 2**

**Table 1. The air state parameters of the heat pump evaporator and condenser in System 1&2**

| system | equipment | point | process | Tem ℃ | RH   | Moisture content g/(kg·a) | Enthalpy KJ/(kg·k) |
|--------|-----------|-------|---------|--------|------|---------------------------|-------------------|
| system1 | evaporator | 0     | inlet   | 36.2   | 63.2%| 25.7                      | 102.5             |
|        |           | 1     | cool down to dew point | 28.1 | 100% | 25.7 | 93.9 |
|        |           | 1-2   | condensation and dehumidification | Moisture content of point2 is 24.36g/(kg·a) | |
|        | condenser | 2     | outlet  | 27.2   | 100% | 24.4                      | 89.6              |
|        |           | 3     | inlet   | 27.2   | 100% | 24.4 | 89.6 |
| system2 | evaporator | 0     | inlet   | 35.9   | 64.8%| 25.8                      | 102.5             |
|        |           | 1     | cool down to dew point | 28.2 | 100% | 24.38 | 90.63 |
|        |           | 1-2   | condensation and dehumidification | Moisture content of point2 is 23.1g/(kg·a) | |
|        | condenser | 2     | outlet  | 26.3   | 100% | 23.1                      | 85.4              |
|        |           | 3     | inlet   | 26.3   | 100% | 23.1 | 85.4 |
|        |           |       | outlet  | 67     | 12.6%| 23.1 | 128.3 |
In Figure 2, it is $\frac{2}{3} G_f$ fresh air that is mixed with $\frac{1}{3} G_f$ exhaust gas. In Figure 3, the heat pipe heat exchanger recovers part of the exhaust gas discharged from the drying chamber to heat the fresh outdoor air. The heated air and part of the exhaust gas after the heat exchange enter the heat pump evaporator to cool down and dehumidify. Then the principle of two system are the same. After the mixed air enters the heat pump evaporator (point 0), it is cooled to the dew point (point 1). If the temperature continues to drop, condensation and dehumidification will begin (point 1-2), the amount of water removed is approximately 1/3 of the amount of dehydration in this stage. The cooled and dehumidified mixed air (point 2) enters the condenser for heating until it reaches the drying temperature (point 3), and is sent to the drying room (indoor point). The corresponding state parameters can be calculated according to the following equation:

$$G_f = \frac{1000M_r}{(d_1 - d_2)}$$

Where $M_r$ means dehydration, kg/h.

In the cycle, the condensing temperature can be taken as the temperature of the air leaving the condenser plus 10°C, and the evaporation temperature can be taken as the air temperature after the evaporator is cooled and dehumidified, minus 10°C, and the superheat is taken as 5°C [9]. Then checking the pressure enthalpy diagram of R134a, based on the principle of heat pump refrigerant cycle, we can get the design parameters that is showed in Table 2.

| number | Evaporator area /m² | Condenser area /m² | Heat Pump heating capacity, KJ/h | Compressor power/Kw | COP |
|--------|---------------------|--------------------|---------------------------------|--------------------|-----|
| system1 | 773.91 | 411.02 | 1100877.63 | 75.18 | 4.06 |
| system2 | 873.36 | 406.6 | 1100877.63 | 83.71 | 3.62 |

2.3. COP analysis of Heat pump
According to the different principles of heat pump evaporator and heat pipe heat exchanger for dry exhaust gas heat recovery, from Tables 1 and 2, it can be seen that the relative humidity of the mixed air entering the evaporator is respectively 63.2% and 64.8%, the compressor power consumption is respectively 75.18Kw and 83.71Kw, and the final heat pump COP is 4.06 and 3.62, respectively. It can be seen that the heat pump cop of system1 is higher than that of system2. When the relative humidity of the air entering the heat pump evaporator increases, the drying energy efficiency ratio of the heat pump decreases. The higher the temperature of the air which is out of the evaporator, the higher the heating power and COP of the system. This shows that reducing the relative humidity of the ambient air appropriately and using heat recovery to increase the evaporation temperature of the heat pump can increase the heat supply coefficient of the heat pump, which is consistent with the research of Huilong.L.[10]. Comparing the COP values of the heat pumps of the two systems, it can be seen that when the heat pump evaporator is used to recover exhaust gas from the drying chamber, the drying efficiency is the best.

3. Numerical simulation

3.1. Simulation process
Based on system1, Author applies two types of airflow organization form of drying chambers: type1 is supplying below and returning upward, and type2 is the side-supplying and side-returning.

Considering the simplification of the simulation, the load of the drying chamber can be appropriately reduced, and the three stages of Zanthoxylum drying can be converted into a constant rate period. Therefore, this paper takes 1t of Zanthoxylum as an example, the water content of Zanthoxylum is processed from 60% (wet basis) to 10%, and the temperature in the drying room does not exceed 68 °C.
Simplifying the model, it can be assumed that the airflow in the drying chamber is a continuous incompressible ideal gas, and it obeys the law of conservation of mass, the law of conservation of momentum, and the law of conservation of energy. According to the indoor air flow pattern, there is turbulence in the room, which follows the k-epsilon two equation model. The dimensions and boundary conditions of the drying chamber are set as shown in the table 3. The geometric model is shown in Figure 4.

![Fig 4: Two types of models](image)

**Table 3. The size and boundary condition settings of each part in the drying room**

| Type | Set up |
|------|--------|
| Number and size of drying tray | 10 and 1.2m×0.6m |
| Number and size of trolleys | 9 and 1.4m×0.8 m×2.3m |
| Drying room size | 5.8m×4.6 m×2.5 m |
| Inlet conditions | velocity inlet condition, velocity is 1.4m/s, temperature is 88℃ (361K). The direction is perpendicular to the inlet section |
| Outlet conditions | Pressure outlet, outlet gauge pressure is 0pa, no backflow |
| Wall conditions | there is no slippage on the boundary, and the convection heat transfer coefficient is selected as the wall thermal boundary condition, and the heat transfer coefficient is set to 28W/(m2.K) |

### 3.2. velocity distribution in drying chamber

It can be seen from Figure 5(a) that when the airflow enters the drying chamber from the lower side of the drying chamber, the airflow velocity is very high, and then it starts to flow upward due to its own density and pressure. When the airflow passes through the layer, it is resisted by

![Fig 5: XZ plane, Y=1m velocity cloud of type1&2](image)
the material, and the airflow velocity gradually decrease. And when the airflow flows to the air outlets, and the wind velocity increases sharply, which is caused by the sudden decrease of the cross-sectional area. It can be seen that the air distribution inside the drying chamber is not very uniform. As shown in Figure 5(b), the air velocity distribution in the whole drying chamber is relatively uniform and the velocity is high, especially at the air inlet and outlet, the air velocity increases.

As is shown in Figure 6, the air velocity distribution in the drying chamber is not very uniform and the velocity fluctuates greatly in type1, and it is generally very low, which does not meet the requirements for the drying of Zanthoxylum. However, airflow velocity distribution is relatively uniform in type2, and the airflow velocity is also high, which can reach the requirements of 0.6-1.0m/s for Zanthoxyllum drying.

4. Conclusions

Based on the operating principle of the solar and heat pump drying system and the theory of computational fluid dynamics, this paper compares and analyzes the differences between the two combined drying systems with different heat recovery, and FLUENT software is used to simulate and analyze the airflow uniformity when the drying chamber adopts two airflow organizations, Which draws the following conclusions:

1) Appropriately reduce the relative humidity of the ambient air and use heat recovery to increase the evaporation temperature of heat pump, which can improve the energy efficiency ratio of the heat pump.

2) Compared with the effect of heat pipe heat exchanger, the effect is better when the heat pump evaporator is used to recover exhaust gas from the drying chamber.

3) When adopting the form of supplying below and returning upward, the velocity in the drying chamber is generally low, and the indoor air flow is unevenly distributed. When using the form of side-supplying and side-returning, the airflow distribution in the drying chamber is relatively more uniform, the air velocity is higher, which shows that the effect of the side-supplying and side-returning is better and can meet the requirements.

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