Design of Heat Pump Drying Device for Livestock and Human Feces

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Abstract. The composition of livestock and human feces are relatively complex. In addition to being rich in organic matter, nitrogen, phosphorus, and potassium, there are also a large number of pathogenic bacteria, parasite eggs, antibiotics, and large doses of heavy metal additives. Livestock and human feces are good organic fertilizers, but if they are used without effective treatment, they will cause great damage to the environment. Because heat pumps have the advantages of low power consumption, environmental friendliness, easy automatic control, good quality of dried products, and saving drying time, heat pumps have been used to dry seafood, grains, and other materials. This paper set chicken manure as the research object, designed a set of heat pump drying devices to reduce and harmlessly treat the chicken manure, and used FLUENT software to simulate the drying oven, and drew the conclusion that the chicken manure can be dried evenly according to the set conditions in the drying oven.

1. Introduction
Livestock and human feces are good organic fertilizers, but if they are not handled properly before being put into use, they can cause great harm to the environment. Human feces are generally treated by flushing with water, which results in waste of organic matter. For water-scarce areas, a lot of water resources are wasted, making the water shortage worse. Due to the large demand for chicken and eggs by Chinese residents, the scale of chicken breeding in China is relatively large. In 2020, there were about 1.2 billion laying hens in China, and the annual production of chicken manure was about 48 million tons. A large amount of chicken manure has caused great pressure on environmental protection [1]. The transportation of chicken manure with extremely high-water content is extremely inconvenient. This article will use chicken manure as the object to explore the reduction and harmless treatment of livestock and human feces, and creatively use the heat pump drying system to solve the problems of storage and transportation caused by the high-water content of chicken manure and environmental pollution caused by high germ content.

Many foreign experts and scholars have conducted more detailed research on the heat pump drying process. Fadhel MI [2] found that the combination of solar technology and heat pump technology can not only reduce the drying process’s dependence on fossil energy and improve energy efficiency, but also help promote the use of cogeneration in tropical areas; Hodgett DL [3] pointed out that compared with traditional dryers, heat pump dryers can save 58-75% of energy; Rossi's research [4] found that using heat pump dryers under the same conditions can save 40% energy and 40.7% drying time than using electric heating dryers to dry vegetables; Lee and Kim [5] found that the heat pump dryer takes 1-1.5 times the time of the hot air dryer, but the energy consumption was only about 33% of the energy consumption of the hot air dryer.
In the nearly 40 years since the first drying conference, the research on heat pump drying technology in China has developed rapidly and has reached the world's advanced level. Yang Zhao [6] has applied artificial intelligence control technology to the heat pump control system. It is verified through experiments that fuzzy control can improve the temperature control accuracy during the drying process, reduce temperature fluctuations, and analyze the instantaneous superheat change of the temperature rise and fall conversion.

Heat pump drying is used in the drying of various materials due to its high efficiency, energy-saving, and recyclable drying medium. This article will design a set of heat pump drying devices for chicken manure drying, and simulate the drying oven with FLUENT.

2. Design of heat pump drying device

The principle of the heat pump drying device is as follows. When the humid air flows through the heat pump evaporator, the internal low-pressure refrigerant absorbs the heat of the air and changes from liquid to gas, and the air cools and discharges most of the condensed water. The low-pressure refrigerant vapor from the evaporator is boosted by the compressor and sent to the condenser. When the dehumidified dry and cold air flows through the condenser, the internal high-pressure refrigerant releases heat due to condensation. The external air is heated to hot air and returns to the drying oven to continue drying. The high-pressure refrigerant flowing out of the condenser is depressurized by the expansion valve and then flows into the evaporator to continue the next cycle.

Heat pump drying technology is currently used in the drying of grain, seafood, sludge, etc. The drying device mainly includes a drying oven and a heat pump drying unit. This chapter has designed a breakthrough heat pump chicken manure drying device, which specifically includes the design of the drying oven, evaporator, and condenser [7].

2.1. Drying oven

The outer surface of the drying oven is insulated with polyurethane color steel sandwich panels to minimize heat loss and ensure the drying efficiency of the system. The inner surface is made of stainless steel sheets. The main considerations are corrosion resistance and acid and alkali resistance.

2.1.1. Calculation of air consumption required to evaporate water in chicken manure. The dry air consumption is calculated as Eq (1).

\[ l_1 = \frac{m}{x_2 - x_1} \]  

Eq (1), \( l_1 \) represents the dry air consumption, \( m \) represents the amount of water removed from chicken manure, \( x_2 \) represents the moisture content of the air at the outlet of the drying oven, and \( x_1 \) represents the moisture content of the air at the inlet of the drying oven.

The air consumption required for the chicken manure to be preheated to the wet-bulb temperature of the air in the drying oven is \( l_2 \),

\[ l_2 = \frac{Q_y}{C_{p,a}(t_1 - t_2)} \]  

Eq (2), \( Q_y \) represents the heat consumption power of preheating chicken manure, \( l_2 \) represents the corresponding specific heat of air at the inlet temperature of the drying air, \( t_1 \) and \( t_2 \) represents the inlet temperature of the drying air and the inlet temperature of the drying air, respectively. Then the total air consumption required is as Eq (3).

\[ l = l_1 + l_2 \]
After calculating the data, the dry air consumption is 1469 kg/h, the budget air consumption is 39 kg/h, and the actual air consumption is 1659 kg/h considering the 10% equipment leakage.

2.1.2. Drying wind speed and time. According to related studies, when the airflow velocity is greater than 2 m/s, the drying rate increases little, and it is easy to cause the dispersion of chicken manure particles. The best airflow velocity for chicken manure drying is 1.5 m/s. In addition to the constant-rate drying stage, there is also a slow-down stage in the drying of chicken manure, and the final drying time is about 3 hours.

2.1.3. Transmission design. The mesh belt should have good acid and alkali resistance, abrasion resistance, and high-temperature impact resistance.

The belt length and running speed of the mesh belt are calculated as Eq (4).

\[ L = \frac{G_w \tau}{\rho_v h B} \]  

(4)

Eq (4), \( L \) represents the length of the mesh belt, \( G_w \) represents the amount of wet material handled, \( \tau \) represents the total drying time, and \( B \) represents the bandwidth of the mesh belt. The speed of the mesh belt is as Eq (5).

\[ u = \frac{L}{\tau} \]  

(5)

The calculated length and width of the mesh belt are 1770 mm and 590 mm respectively, divided into 3 layers, each layer is 590×590 mm, and the running speed is 0.6 m/s.

2.2. Condenser

The structure parameters of the condenser are shown in Table 1. The heat transfer coefficient of the condenser is shown in Table 2.

Table 1. Condenser structure parameter table

| Parameter                                              | Parameter value | Unit |
|--------------------------------------------------------|-----------------|------|
| External surface area per unit length of the base pipe | 0.023445        | m²   |
| Fin area per unit length of the base tube              | 0.265123        | m²   |
| Total external surface area per unit length of the base pipe | 0.288568 | m²   |
| The surface area of the intermediate interface between the inner and outer walls of the base pipe per unit length | 0.023864 | m²   |
| The surface area of the inner wall per unit length of the base pipe | 0.022608 | m²   |
Table 2. Condenser heat transfer coefficient table

| Parameter                                | Parameter value | Unit       |
|------------------------------------------|-----------------|------------|
| Airside heat transfer coefficient        | 56.8            | W/(m²·k)  |
| Heat transfer coefficient on the working fluid side | 1568            | W/(m²·k)  |
| Condenser heat transfer coefficient      | 38.4            | W/(m²·k)  |

The evaporator used a finned tube evaporator with a design evaporating temperature of 20°C. The evaporator design process was similar to that of a condenser, but it must be considered that the surface of the evaporator will produce condensed water and affect its heat transfer coefficient.

2.3. The overall design of the heat pump drying device

The composition of the heat pump drying device mainly includes a drying oven, a heat pump unit, etc. The selection of the heat pump unit compressor is mainly based on the cooling capacity at the evaporating temperature and the condensing temperature under the designed working conditions.

The structure diagram of the device is shown in Figure 1. The overall size of the device is 2000×620×1520 mm (length×width×height), and the length, width, and height of the drying oven are 620 mm, 620 mm, and 1520 mm, respectively. The input power of the compressor is 3000w, and the air volume of the fan is 1659 kg/h.

![Figure 1. Schematic diagram of heat pump drying device](image)

(a)Mesh belt (b)Expansion valve (c)Evaporator (d)Compressor (e)Condenser (f)Fan

3. Simulation

The gas flow field in the drying oven is relatively complicated, and it is relatively complicated to measure the temperature field inside the drying oven with experimental methods. Based on the establishment of the model and the set of data, this paper uses Fluent software to numerically simulate the temperature field in the drying oven [8], and analyze the temperature field. As the gravitational field, there is a temperature-like field in physics called the temperature field, which is the general term for the temperature distribution at each point in an object at all times. There are two major types of temperature fields, namely steady-state temperature and non-steady-state temperature field. This article studies the non-steady-state temperature field.
3.1. The establishment of the drying oven model
Because the drying oven is relatively complicated, to facilitate the simulation, the drying oven is simplified as follows: the length, width, and height of the drying oven are 620×620×1520 mm respectively, and the inlet and outlet are circular with a diameter of 50mm. The distance between the center of the circle and the ground and the top is 100mm, and the wall thickness is 10mm. The grid conveyor belt is divided into 3 layers evenly distributed in the drying oven, and the length, width, and height are 590×590×5 mm respectively. The established model is as Figure 2.

3.2. Meshing result
Due to the complexity of the model, considering the huge number of grids, because the model has symmetry, the model is cut from the middle, and the middle plane is set with a symmetry plane [9]. The regular part adopts a hexahedral grid, and the irregular part is a combination of tetrahedral grids. In this way, the number of grids is 5793128 and the number of grid nodes is 13965469.

3.3. Boundary conditions
Carry out the numerical simulation of the one-way gas flow in the drying oven, set the air temperature at the inlet to 65℃, the flow velocity to 5m/s, and the outlet to be atmospheric pressure [10], regardless of the heat exchange between the outer wall and the outside. And the initial temperature inside the drying oven is 25℃.

Figure 2. Drying oven model
3.4. Internal temperature field of the drying oven

Figure 3. Temperature field diagram

Figure 3 shows the temperature field conditions of the drying oven. Due to the existence of the grid conveyor belt and the small grid, there were four relatively independent spaces inside the through-flow belt drying oven [11]. When the temperature range of the rightmost space was roughly in the 40-50°C space, the heat began to be transferred to the second space on the right, and mainly began to transfer through the boundary, because there was a certain distance between the inner wall of the drying oven and the conveyor belt [12]. When the time was 103 seconds, the temperature of the space close to the inlet was basically between 60-65°C. It can be predicted that with time, the temperature of the entire flow-through belt space can reach about 65°C, and there is no area with lower temperatures. In this way, the bacteria in the chicken manure can be effectively eliminated, and the chicken manure can be evenly and well dried according to the set conditions, and the quality of the drying can be guaranteed.

4. Conclusion

This article designs a set of heat pump drying devices for chicken manure, which mainly includes the design of the drying oven and heat pump unit. The design of the drying oven includes the calculation of air consumption required to remove the moisture in the chicken manure, the determination of the drying wind speed and time, and the design of the mesh belt drive. The design of the heat pump unit mainly includes the design of the condenser and the evaporator and the determination of the compressor. For the drying oven, this paper uses FLUENT to analyze the temperature field and concludes that the chicken manure can be well and evenly dried. At present, heat pump drying has been widely used in the drying of marine products, grains, and other materials, but it has not been used in the drying of livestock and human feces. This article also explores the use of heat pump drying in livestock and human feces through the object of chicken manure. At the same time, we believe that more scholars will invest in this research in the future and the environmental problems caused by the use of livestock and human feces without proper treatment can be effectively solved.
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