Theoretical analysis of open-circuit ground source heat pump drying system

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Abstract. In order to apply the ground source heat pump in the drying industry, a set of open-circuit ground source heat pump drying system was designed for theoretical analysis and compared with the closed air source heat pump drying system. The results are shown below: When the drying temperature (air temperature required for drying) is 40°C-60°C, the system performance coefficient (COP) of the drying system is 3.2-5.2. Dehumidification per unit energy consumption (SMER) is affected by the external ambient temperature. The highest and lowest SMER corresponding to the ambient temperature of 20°C are 4.4 and 1.4, and the highest and lowest SMER corresponding to the ambient temperature of -10°C are 2.6 and 1.1. When the ambient temperature is high and the drying temperature of drying materials is low (less than 50°C or so), the open-circuit ground source heat pump drying system has a slight advantage over the closed air source heat pump drying system, and SMER is higher.

1. Introduction
Drying is a process with high energy consumption, accounting for 9%-25% of the total energy consumption in developed countries[1]. In China, drying also consumes a large amount of energy every year. In today's advocacy of energy conservation and environmental protection, it is very important to reduce the energy consumption of drying. At present, the drying methods in China mainly include microwave drying, vacuum drying, infrared drying, heat pump drying and so on[2]. Among them, heat pump drying is the most widely used. Heat pump drying is mainly air source heat pump drying in China, and the application of ground source heat pump drying is relatively few, only Yu Shulong applies ground source heat pump to grain drying[3], and almost all vegetables are dried by air source heat pump drying. Due to the characteristics of soil and underground water, the ground source heat pump is relatively stable and energy saving compared with the air source heat pump, therefore, the author want to apply the ground source heat pump in the drying, design a set of ground source heat pump drying system and compare the energy consumption of the system with the air source heat pump drying system by theoretical analysis, hoping to provide some reference for the application of ground source heat pump in drying.

2. Ground source heat pump drying system
This paper designs a set of ground source heat pump drying system as shown in Figure 1.
Figure 1. Open-circuit ground source heat pump drying system schematic diagram

The drying system includes three parts: heat pump working medium circulation, drying medium circulation and circulating water in buried pipe. The heat pump working medium absorbs heat in the evaporator into saturated steam and then enters the compressor to be adiabatic compression, and then enters the condenser to release heat to dry medium into saturated liquid, and then enters the throttle valve to throttle down pressure, and finally enters the evaporator again to absorb heat to complete the cycle[4]; The external air enters the condenser to absorb the heat of the working medium of the heat pump, the high temperature and low humidity air enters the drying chamber to dry materials by equal enthalpy, and the cooled and humidified air enters the auxiliary cooler to release heat and then exits the system; The circulating water enters the buried pipe to absorb the heat of the underground soil, then enters the auxiliary cooler to absorb heat again, and then enters the evaporator to release heat to the working medium of the heat pump. The cooling circulating water enters the buried pipe to absorb the heat of the underground soil again to complete the cycle.

The drying system takes the underground soil as the heat source, so that the system has a stable and high evaporation temperature, due to the characteristics of water, the heat exchange between water and the working medium of the heat pump has a small temperature difference and the heat exchange between the circulating water and the drying medium in the auxiliary heat exchanger can further increase the evaporation temperature, which is conducive to reducing the energy consumption of the system.

The lgP-H diagram of heat pump working medium cycle is shown in Figure 2

Figure 2  lgP-H diagram of heat pump working medium cycle

The system heating efficiency (COP) and Dehumidification per unit energy consumption (SMER) were used as the evaluation indexes of the drying system performance[5].

\[ COP = \frac{Q_e}{W} \] (1)
\[ \text{SMER} = \frac{m}{W} \quad (2) \]
\[ W = W_c + W_p \quad (3) \]

Where: \( Q_e \) — heating capacity of system, kw; \( m \) — drying water quantity of system, kg; \( W \) — power consumption of the system, kw; \( W_c \) — power consumption of the compressor, kw; \( W_p \) — power consumption ground source side water pump, kw;

3. Results of theoretical analysis

The system uses refrigerant R134a. The paper simulates the drying process of the system with MATLAB, and obtains the change of COP and SMER with the parameters.

The temperature of the underground soil is set at 17°C, the evaporation temperature is determined by the temperature of the circulating water entering the evaporator and the temperature difference between it and the circulating water is 5°C. The temperature difference between the drying medium temperature entering the drying chamber and the condensing temperature is 7°C. The drying medium is cooled at 15°C in the drying chamber.

When the external air temperature is 0°C and the relative humidity is 50%, the changes of system COP and SMER with different drying temperature (temperature of drying medium entering the drying chamber) \( T \) are shown in Figure 3.

![Figure 3](image_url)

Figure 3  Graph of the relationship between COP, SMER and dry operating temperature

As can be seen from Figure 3, COP and SMER of the system show an overall downward trend with the increase of drying temperature, and there are slight fluctuations during the downward trend.

The main power consumption of the system is compressor power consumption and ground source side water pump power consumption. With the increase of drying temperature, the condensation temperature and the compressor outlet pressure will rise, the increase of compressor pressure ratio leads to the increase of compressor power consumption, and the increase of condensation temperature will lead to the decrease of heat production and cooling capacity per unit time of the heat pump unit, thus reducing the circulating water flow that needs to enter the evaporator, so that the power consumption of ground source side pump is reduced, however, the overall power consumption of the system increases, so the COP and SMER of the system decrease.

The system is affected by ambient temperature. In order to observe the system's working condition at different ambient temperatures, the paper theoretically calculates the system's SMER under different ambient temperatures, and the results are shown in Figure 4.
Figure 4  Graph of the relationship between SMER and ambient temperature

It can be seen from Figure 4 that the SMER of the system decreases with the decrease of ambient temperature. When the drying temperature is 40-60℃, the highest and lowest SMER corresponding to the ambient temperature of 20℃ are 4.4 and 1.4, and the highest and lowest SMER corresponding to the ambient temperature of -10℃ are 2.6 and 1.1.

Under the same drying condition, with the decrease of the ambient temperature (the temperature of the air entering the condenser decreases), the air temperature difference between the inlet and outlet of the condenser increases, resulting in the decrease of the air mass flow required by the system and the decrease of the moisture carried out by the air in the drying chamber, so the SMER of the system decreases.

4. Comparison and analysis

4.1. Closed air source heat pump drying system

From the perspective of the cycle of drying medium, heat pump drying methods has three kinds of open, semi-closed and closed[6], at present, heat pump drying mode commonly used in our country is closed air source heat pump drying, its SMER is higher than the other two drying methods, at about 4. The schematic diagram of the system is shown in Figure 5.

Figure 5  Schematic diagram of closed air source heat pump drying system

Closed air source heat pump drying system is composed of two independent cycles, that is, the heat pump working medium heating cycle and drying medium (air) drying cycle, the two independent cycles are connected through the condenser and evaporator, The working medium of the heat pump condenses into liquid in the condenser, and the heat released is used to heat the air, The heat pump working medium is cooled into saturated vapor in the evaporator, and the absorbed heat is used to cool
and dehumidify the dry medium. After the drying medium leaves the drying chamber, it removes certain moisture and becomes low temperature and low humidity air in evaporator, and then flows through the condenser and is heated to the set temperature, and then enters the drying chamber to complete the circulation of the drying medium.

4.2. Contrast results

In order to better evaluate the drying system designed in this paper, this system was compared with the closed air source heat pump drying system, and the SMER sizes of the two drying systems were compared at different drying temperatures T. The results are shown in Figure 6.

![Figure 6](image-url)

Figure 6  Comparison of SMER for different drying systems

As can be seen from Figure 6, you can see that when the ambient temperature 0 °C, the SMER of this system is less than the closed air source heat pump drying system, when the ambient temperature is 20 °C, with the improvement of drying temperature, its SMER gradually changed from greater than the closed air source heat pump drying system to lower than the closed air source heat pump drying system, the critical drying temperature of about 50 °C.

The drying system is an open-circuit ground source heat pump drying system. Compared with the open-circuit drying system, the advantage of the closed drying system is that it can recycle the exhaust gas from the evaporator into the condenser, the temperature of the exhaust gas entering the condenser is higher than the ambient temperature, which can reduce the required heat of the system and reduce the power consumption of the compressor. The disadvantage is that the evaporation capacity of the evaporator is not high and can't completely drain the water like the open-circuit drying system.

When the ambient temperature is low, such as 0°C, the advantages of closed drying system are obvious. under different drying temperature, open-circuit ground source heat pump drying system SMER were smaller than closed air source heat pump drying system, but when the ambient temperature is higher, such as 20 °C, the air temperature entering the condenser of the open-circuit ground source heat pump drying system is higher, which leads to the advantage of the closed drying system recycling the waste heat of the exhaust gas is not obvious, when the drying temperature is low, the air temperature out of the drying chamber is low, which leads to the low evaporation temperature of the closed air source heat pump drying system, due to the characteristics of underground soil and water and the circulating water being reheated in the auxiliary cooler, the evaporation temperature of the open-circuit ground source heat pump drying system can be kept at a higher level, because of the above three reasons, when the drying temperature is low, the power consumption of the open-circuit ground source heat pump drying system is lower than that of the closed air source heat pump drying system, in addition, the open-circuit ground source heat pump drying system can drain all the water out of the system, therefore, the open-circuit ground source heat pump drying system SMER is higher than the closed air source heat pump drying system, however, with the increase of drying temperature, the evaporation temperature of the closed air source heat pump drying system gradually increases, the
power consumption of the system gradually decreases, leading to its SMER is gradually higher than that of the open-circuit ground source heat pump drying system.

Contrast by above knowable, open-type ground source heat pump drying system relative to the closed air source heat pump drying system have advantages and disadvantages. When the air temperature is high in the dry area, the drying temperature of the dry material is not high (about 50°C or less), the open-circuit ground source heat pump drying system has a slight advantage over the closed air source heat pump drying system, and can consider using open-circuit ground source heat pump drying system to dry materials.

5. Conclusion
In this paper, a set of ground source heat pump drying system is designed. The theoretical calculation and analysis of the drying system are carried out through MATLAB, and compared with the closed air source heat pump is made. The conclusions are as follows: When the drying temperature (air temperature required for drying) is 40°C-60°C, the COP of the drying system is 3.2-5.2, SMER is affected by the external ambient temperature. The highest and lowest SMER corresponding to the ambient temperature of 20°C are 4.4 and 1.4, and the highest and lowest SMER corresponding to the ambient temperature of -10°C are 2.6 and 1.1.

The ground source heat pump drying system was compared with the closed air source heat pump drying system, when the ambient temperature is high and the drying temperature of drying materials is low (less than 50°C or so), the source heat pump drying system has a slight advantage over the closed air source heat pump drying system, and SMER is higher.

Ground source heat pump has many advantages over air source heat pump. The drying system is an open-circuit ground source heat pump drying system. We can continue to study how to combine ground source heat pump and closed drying for drying materials, playing the advantages of ground source heat pump to reduce the energy loss of material drying.

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