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Experiment research on grain drying process in the heat pump assisted fluidized beds

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Abstract: A heat pump assisted fluidized bed grain drying experimental system was developed. Based on this system, a serial of experiments was performed under four kinds of air cycle conditions. According to the experimental analysis, an appropriate drying medium-air cycle for the heat pump assisted fluidized bed drying equipment was decided, which is different from the commonly used heat pump assisted drying system. The experimental results concerning the drying operation performance of the new system show that the averaged coefficient of performance (COP) can reach more than 2.5. The economical evaluation was performed and the power consumption for removing a kilogram water from grains was about 0.485 kW·h/kg (H_2O), which shows its reasonable commercial efficiency and great application potentiality in future market.

Key words: heat pump, fluidized bed, grain, drying, air recycle

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1 Introduction

Nowadays there is an urgent need for the development of high capacity and high quality grain drying equipment in the agriculture of China [1]. As the society and agriculture develop quickly, it is of important practical value to develop the efficient, energy saving, non-pollution and even movable drying equipment to match the mechanization harvestry [2]. Traditional methods of drying involve the direct combustion of fossil fuel together with controlled ventilation. Such methods are obviously inefficient, with efficiencies never exceeding 20%, not to mention the fact that expensive primary energy is depleted only to produce low grade heat [3].

The traditional drying methods have been prevailing domestically up to now, not only for grain drying but also for other materials such as wood, cement, ceramics and medicine *etc.* As the power supply structure improved greatly by the hydropower and nuclear power development policy of the government of China, the research on the heat pump assisted drying system is of special meanings, due to the fact that a portion of power usually can supply more than 2 portions of heat energy for drying by using a heat pump. Recently there are quite a few scholars [4-8] finding their interests in heat pump assisted drying area and the great potentiality in future for heat pump applications in drying area. However the researches [9, 10] mostly concentrate on the low temperature heat pump with the hot medium temperature lower than 55°C. There was still a blank in the high temperature heat pump assisted drying system with temperatures above 70°C and especially for the system with grain drying and heat pump working together, which is the great motivation of the present paper. Besides the gas-solid fluidized beds have obtained widely applications in drying area with so obvious advantages such as high gas-solid contact surface, high heat and mass transfer rates, easy to be mechanically operated, usually with great continuous production capability and high quality of drying due to its uniform temperature field [11, 12].

This paper combined the both advantages of heat pump and fluidized bed to develop a new type of grain drying experimental system. Based on this system, a serial of experiments was performed under different conditions. According to the experimental analysis, an appropriate drying medium-air cycle for the new type heat pump assisted fluidized bed drying equipment was decided, which is different from the traditional heat pump assisted drying system. The research results

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also show the optimistic future and the potential market competition ability of this new equipment.

2 Experiment

In a drying system with a heat pump and a fluidized bed together, there are three material flows: the grain flow, the refrigerant flow and the drying medium-air flow. This air flow relates the grain flow to be dried and the refrigerant flow of the heat pump together and become the medium transferring the moisture and heat between the both, in which the flow rate, temperature, velocity and humidity of the air influence the working condition of the heat pump, whereas the working condition of the heat pump also affects the temperature and humidity of the air and further influences the drying process. Here the air circulation in the system is vital not only to the working performance of the heat pump and the drying process but also to the final structure of the whole equipment. Hence the experimental system was designed as shown in **figure 1**, which includes mainly four parts: fluidized bed drying room, heat pump, tube connection and several valves.

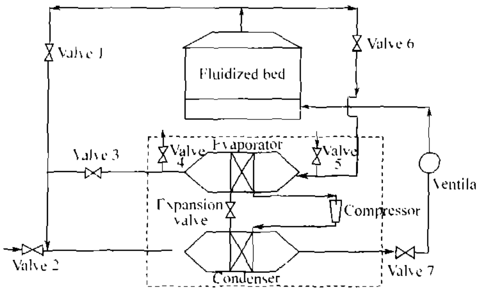

Figure 1 Schematic of the experimental system for heat pump assisted fluidized bed grain drying.

This system can realize four types of air circulation by adjusting different valves. Type one: close valves 1, 2, 4, 5 and open valves 3, 6, 7, in which the air discharged from the fluidized bed flows only through the evaporator of the heat pump and then the condenser where it is heated and finally into the fluidized bed, performing a close circuit circulation. Type two: close valves 2, 3, 6 and open valves 1, 4, 5, 7, in which the air discharged from the fluidized bed flows directly through the condenser and then into the fluidized bed, performing a close circulation, and the air from circumstance flows through the evaporator of the heat pump. Type 3: close valves 1, 3, 5 and open valves 2, 4, 6, 7, in which the air discharged from the fluidized bed flows completely through the evaporator and then into the ambient, whereas the ambient air is absorbed through the condenser by the ventilator and then flows into the fluidized bed, performing an open circulation. Type 4: open all the valves and adjusting their turndown ratio, in which the air discharged from the fluidized bed splits into two parts, one mixing with some ambient air flows into the evaporator and then into the ambient, the other mixing with the ambient air flows into the condenser and then into the fluidized bed, performing an half close and half open air circulation.

3 Parameter measurements and principles

In this experiment, the parameters need to be measured are the temperatures at the inlet and the outlet of the fluidized bed and the evaporator and the condenser, the flow quantities of the air through the evaporator, the condenser and the fluidized bed respectively, the high and the low pressures of the refrigerant. All the temperature measurements adopted digital temperature sensors which were calibrated by the liquid in the glass thermometer from 0 to 100°C. The hot spherical wind velocity meter was used to measure the flow velocity and then to get the flow quantity. The power of the compressor was calculated based on its phase current measured by a multimeter. The refrigerant pressures were measured by elastic tube manometers.

The performance parameters of the system can be calculated based on these measured parameters by following formulae.

The air flow quantity:

$V=(\sum u/N)\times A\times 3600$, m³/h;

The refrigerating output from the evaporator:

$Q_e=V_e\cdot\rho_{air}\cdot C_p(t_{OE}-t_{IE})/3600$, kW;

The heating output from the condenser:

$Q_c=V_c\cdot\rho_{air}\cdot C_p(t_{OC}-t_{IC})/3600$, kW;

The compressor power:

$P=3\times\bar{I}_p\times V_p=(I_1+I_2+I_3)\times 220/1000$, kW;

The coefficient of the performance (COP) of the heat pump:

$\mathrm{COP}=\frac{Q_c}{P}$;

The flow rate of refrigerant:

$X=\eta_c\cdot P/W$, kg/s;

The theoretical refrigerating output from the evaporator:

$\mathrm{LQ}_e=X\times q_e$, kW;

The theoretical heating output from the condenser:

$\mathrm{LQ}_c=X\times q_c$, kW;

The theoretical coefficient of the performance of the heat pump:

$$\mathrm{LCOP} = \frac{\mathrm{L}Q_c}{P};$$

Here the theoretical cycle refers to the ideal thermodynamic cycle corresponding to the high and low pressures measured in the experiment.

4 Experimental results and analysis

4.1 Effects of air circulation type

In order to get the effect from different air circulations on the drying process, we conducted four types of air circulation experiments, keeping all the other conditions the same, such as the air flow quantity and the inlet temperatures *etc.* and found that the temperature at the inlet of the fluidized bed is the highest in type 2, that in type 1 is the lowest and that in type 3 is slightly higher than that in type 1, that in type 4 is between that in types 2 and 3. This is because in type 2, the air circulates only through the condenser and the heat wasted is comparatively small resulting in the high temperature at the outlet of the condenser. The humidity of the air at the inlet of the fluidized bed was also higher, since the air discharged from the fluidized bed did not remove its moisture. However, in fact the connection tube was not closely sealed, therefore there was some fresh air from ambient flowed into the condenser. That is like such a circulation: close valves 3, 6 and open all the other valves, in which the air discharged from the fluidized bed, mixing with the ambient air flowed through the condenser and then into the fluidized bed, meanwhile some air from the fluidized bed flowed into the ambient through the interspace between the fluidized bed and its blastcap. In this experiment system, 10%-20% fresh air was estimated mixing into the flow in air circulation between the condenser and the fluidized bed. Hence type 2 with a certain fresh air ratio can be chosen as the best air circulation used in the following experiments.

4.2 Effects of air flow quantity through the evaporator

Two experiments were performed. In one experiment, 100 kg grains were put into the fluidized bed with a moisture of about 25% (its denominator contains no water), and then the system was started and the airflow through the evaporator was kept relatively low at about 500 m^3/h. The performances of the heat pump are shown in **figures 2-4**. In the other experiment, the system was started firstly and the airflow through the evaporator was kept high at about 2500 m^3/h, after the temperature at the outlet of the condenser reached about 70°C, 100 kg grains with a moisture of 27% were put into the fluidized bed. The heat pump performances are shown in **figures 5-7**. The air flow through the condenser is about the same of 1650 m^3/h for both experiments.

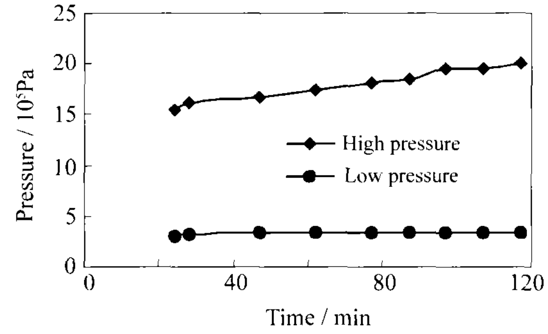

Figure 2 Pressure variation of the refrigerant in the drying process at V_e=500 m^3/h.

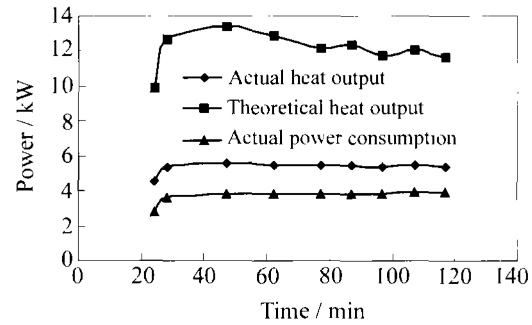

Figure 3 Performance of the heat pump in the drying process at V_e=500 m^3/h.

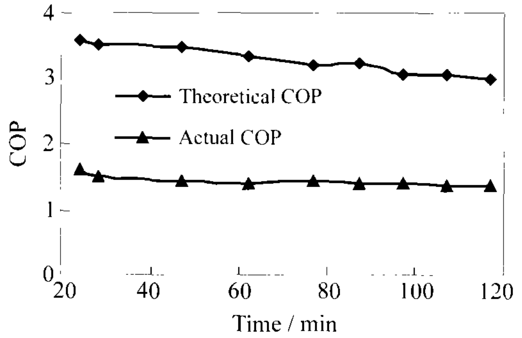

Figure 4 COP of the heat pump at V_e=500 m^3/h.

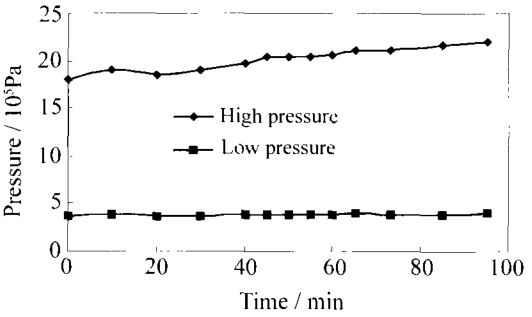

Figure 5 Pressure variation of the refrigerant in the drying process at V_e=2500 m^3/h.

In figures 3, 4 and 6, 7, the theoretical results are all calculated from the ideal refrigeration circulation respectively corresponding to the high and low pressures of the refrigerant in figures 2 and 5. The comparison between figures 3 and 6 shows that the heat output from the condenser greatly increases by increasing the air flow through the evaporator and the COP is much closer to the ideal value in figure 7 than that in figure 4. Thus the airflow quantity through the evaporator is very important to the performance of the heat pump. In fact, the growing of the air flow quantity through the evaporator greatly enhances the heat transfer rate between the air and the surface of the evaporator resulting the working medium in it absorb more heat at the same temperature difference. The theoretical analysis also show that as the airflow increases further, the heat absorbed by the evaporator will reach its peak and then level off.

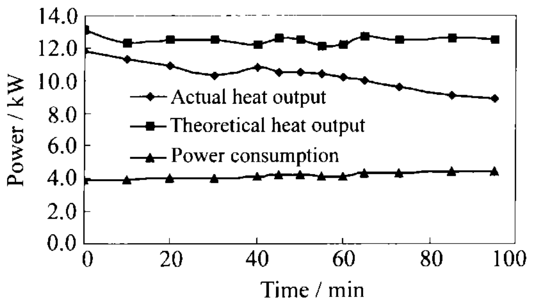

Figure 6 Performance of the heat pump in the drying process at V_e=2500 m^3/h.

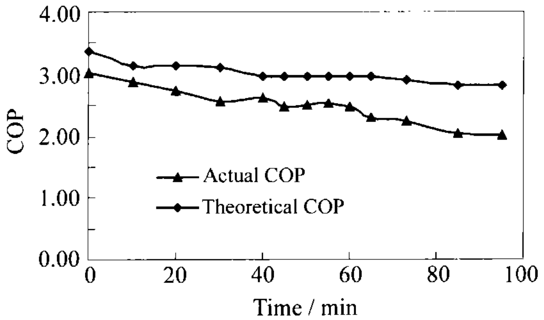

Figure 7 COP of the heat pump at V_e=2500 m^3/h.

4.3 Drying process of the heat pump assisted fluidized bed grain dryer

Figure 8 shows the temperature variations at the inlet and the outlet of the fluidized bed during the drying process under the same condition to the experiment at V_e=2500 m^3/h. It shows that both the temperatures rise gradually with time.

At such temperature variation, the wheat drying process is shown in **figure 9**, which displays the wet moisture (the fraction of the water quantity contained in the grains to its total quantity) and dry moisture (the fraction of the water quantity contained in the grains to its absolute dry quantity) variations of wheat with drying time. We can see that it takes about 60 min for the wheat to dry from a wet moisture of 21.3% to 13%.

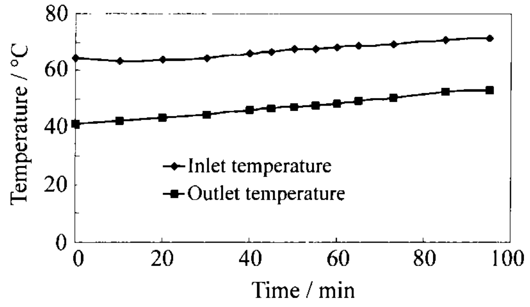

Figure 8 Temperature variations at the inlet and outlet of the fluidized bed during the drying process at V_e=2500 m^3/h.

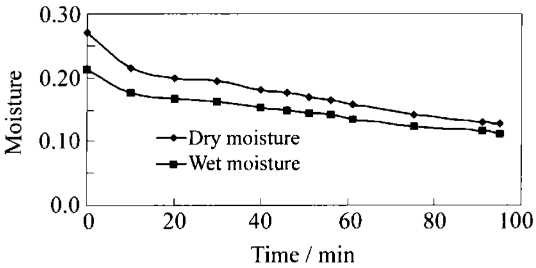

Figure 9 Wheat moisture variations during the drying-process at V_e=2500 m^3/h.

4.4 Economical evaluation

The factors affecting the commercial efficiency of the drying system are the drying time, the COP and power consumption of the heat pump. However the drying time mainly depends on the air temperature at the inlet of the fluidized bed. In order to analyze the commercial efficiency of the system, we assume that the wheat is continuously dried by the system as it was done by the most dryers in industry, the temperature at the inlet of the fluidized bed is about 70°C which was obtained in the experiment. In such assumptions, we can obtain that the drying time needed for wheat to dry from its wet moisture of 20% to 13% is about 35 min, which is deduced from another experiment [2] and will not be presented here. According to the known parameters mentioned above and the heat pump power consumption in figure 6, including the blower power consumption in the system, the averaged power consumption of the system is gotten (about 5.5 kW) during the drying process. Considering the capability of the fluidized bed is about 100 kg, we can conclude its totally power consumption per unit grain output is about 0.0321 kW·h/kg or that per unit water removed from the grain is 0.458 kW·h/kg (H_2O).

5 Conclusions

(1) The appropriate air cycle for drying grain is that the air discharged from the fluidized bed directly flows into the condenser of the heat pump with 10%-20% fresh air where it is heated and then flows into

the fluidized bed to form a circulation.

(2) The airflow through the evaporator is very important to the performance of the heat pump. The higher the flow quantity, the better the performance of the heat pump.

(3) The economical evaluation shows that if the system working at continuous state, its power consumption for removing a kilogram water from the grains is about 0.485 kW·h/kg (H_2O) and shows great potentiality in the future market.

Nomenclature

V, V_e, V_c: The flow quantities for the fluidized bed, the evaporator and the condenser, respectively;

u: The air velocity at the measured point, m/s;

N: The number of the measured points;

A: The tube across area, m^2;

Q_e, Q_c: The refrigerating and heating outputs of the heat pump, kW;

ρ_{air}: The air density, kg/m^3;

C_p: The air specific heat capacity, kJ/(kg·°C);

t_{oe}, t_{ie}: The temperatures at the inlet and the outlet of the evaporator, °C;

t_{oc}, t_{ic}: The temperatures at the inlet and the outlet of the condenser, °C;

$\bar{I}_p$: The averaged phase current of the compressor, A;

V_p: The phase voltage, V;

X: The mass flow rate of refrigerant, kg/s;

η_c: The compressor efficiency, about 0.9 here;

W: The theoretical compressor work per unit mass, kJ/kg;

LQ_e, LQ_c: The theoretical refrigerating and heating output of the heat pump, kW;

q_e, q_c: The refrigerating and heating outputs from theoretical cycle per unit mass refrigerant, kJ/kg;

COP, LCOP: The practical and theoretical coefficients of the performance of the heat pump.

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