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Research Paper

Effect of swing temperature and alternating airflow on drying uniformity in deep-bed wheat drying

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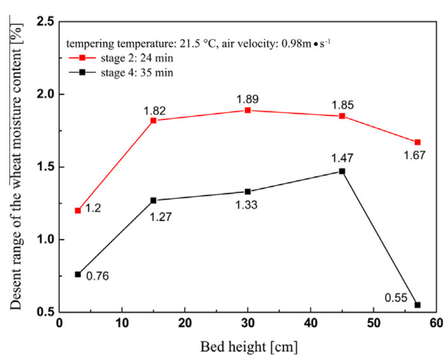
HIGHLIGHTS

- Swing temperature and alternating airflow improve drying uniformity in deep-bed wheat drying.
- Heating and tempering processes are linked and combined in both time and space.
- The effect of tempering parameters are obtained.

GRAPHICAL ABSTRACT

The descent range of the wheat moisture content in each layer at stages 2 and 4 ended in Exp. 4 (Fig. 1). The wheat moisture content in the middle layer decreased the most. The wheat moisture content in the middle layer was higher than that in the other layers, and the heat in the wheat in the upper part was transferred to the wheat in the middle part through convection at stages 2 and 4. The wheat drying uniformity at the end of stage 4 ΔW_4 was 1.87%. The wheat drying uniformity without tempering at the end of stage 4 ΔW_4 was 4.42%, which increased by 2.55% with tempering. The improvement rate was 58.7%. In summary, tempering improved the wheat drying uniformity in deep bed under the combined action of swing temperature and alternating airflow.



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ABSTRACT

Lack of timely drying after harvesting resulted in grain losses of approximately 30 million tons in China. Considering the small-scale production mode in rural China, we investigate a new fixed bed drying method that features swing temperature and alternating airflow. Heating and tempering processes are linked and combined in both time and space. The ratio range of the normal flow heating time to the reverse flow heating time with the best wheat drying uniformity under the conditions of the total heating time 78 min is from 0.733 to 0.902. The wheat drying uniformity with tempering is higher by 2.55%, with an improvement rate of 58.7%, compared with that without tempering. With the same heat supply, extending the time and changing the air velocity at the tempering stage exert minimal influence on wheat drying uniformity. Increasing the temperature at the tempering stage effectively improves the wheat drying uniformity with deep-bed and the blower power consumption reduces, but the heat efficiency decreases. Moreover, the wheat drying uniformity improves with increasing air velocity in both drying and tempering processes. According to the drying capacity and economic analysis, the STAA is better than fluidized bed.

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1. Introduction

Drying is a high-energy consumption process, accounting for 10–25% of the total energy consumption in developing countries. The thermal efficiency of drying is only 25–50%, especially in the agricultural and food processing industries [1]. Approximately 37 million tons of grains are annually machine-dried in China. Seven million tons of water requires 1.7 million tons of standard coal for drying, and drying emits large amounts of CO, CO_2, SO_2, SO_3, and other harmful gases [2]. Up to 5500–9600 kJ and 3344–4598 kJ of drying energy are consumed when removing 1 kg of H_2O in China [3] and developed countries [4], respectively. The total grain yield in China was 607.1 million tons in 2014 [5]. Statistics shows that the grain loss ratios in China was 5% because of the lack of timely drying after harvesting [6], more than that of <1% in developed countries [7]. This alarming amount indicates that the grain losses were more than 30 million tons in China.

Grain drying in China can be classified as fixed-bed, spouted-bed, and fluidized-bed drying. The equipment used in fixed-bed drying is characterized by simple structure, low cost, and easy application. The main disadvantage of fixed-bed drying is non-uniformity [8–10]. Many researchers reported that alternating airflow can reduce the moisture difference along the height of the drying chamber, such as wheat [8,11], extruded feed pellets [12], coffee [13,14], carrot [15], wood [16], and rough rice [17]. The spouted-bed drying consumes less energy compared with other technologies, the dryer used in this method has a low bed height and small size [18]. Continuous drying in a fluidized bed enlarges the drying capacity and decreases the energy consumption [19–23]. Excessive air velocity slightly influences the drying rate, increases energy consumption and wastes high-quality energy [19]. Grains burst when the stress gradient in the grains is greater than the threshold, and this phenomenon decreases grain quality [24]. Heat and moisture transfer mechanisms in grains primarily affect grain drying dynamics. The drying of freshly harvested grains to safe moisture levels encompasses a constant rate drying period and a falling rate drying period [25–27]. The required heat during drying is changing. Some scholars have studied the effect of tempering on drying and found that tempering reduces the stress in grains and energy consumption, consequently decreasing the occurrence of grain cracks and rupture [24,28–31].

These results indicate that the heat and temperature must be controlled in accordance to the heat and mass transfer characteristics in grains. The present paper investigates a new fixed-bed drying method that features swing temperature and alternating airflow (STAA). Normal flow with a high temperature is pumped into the drying chamber from the bottom inlet. Subsequently, normal flow with a low or moderate temperature is pumped into the drying chamber from the bottom inlet when the heat is sufficient to dry a certain amount of wheat. The wheat in the lower part of the chamber is subjected to high-temperature heating and tempering on the spot. Meanwhile, the heat that dries the wheat in the lower part of the chamber at a high temperature is eliminated by low- or moderate-temperature air and is used to dry the wheat in the middle part of the chamber. Afterward, the flow direction changes, and the abovementioned process is repeated. Heating and tempering processes are linked and combined in both time and space. The time at a high, middle, or low temperature is controlled, and external drying conditions and drying kinetics in the grains are coordinated with each other. Meanwhile, the exhaust temperature is close to the ambient temperature as much as possible, thereby decreasing or removing the heat recovery equipment investment. This study investigated the effects of the ratio of the normal flow heating time to the reverse flow time, tempering temperature, tempering time, and air velocity on deep-bed drying characteristics. Then the drying capacity and economic analysis were compared between STAA and fluidized bed.

2. Experiment

The thick-layered fixed-bed drying equipment used in this study includes a drying chamber, a heating cabinet, an air reversing device, intake and exhaust ports, and pipelines (Fig. 1). The length, width, and height of the drying chamber were 19, 19, and 70 cm, respectively. The drying chamber is divided into 10 layers by 10 layered baffles along its height. Wheat-containing plates with a length, width, and height of 19, 19, and 6 cm, respectively, were placed on the layered baffles. The plates were numbered 1–10 from bottom to top. A 1 cm space was allocated above the plate, and copper-constantan thermocouples were placed at the center of the space. A thermocouple was also placed under the lowest layered baffle. Eleven thermocouples numbered 1–11 from bottom to top were present. The plate 6 cm in height was filled with wheat. The 11 thermocouples measured the temperature at heights of 0, 6, 12, 18, 24, 30, 36, 42, 48, 54, and 60 cm. Air velocity was measured using an air flow and velocity transmitter. The precision of the measurements of temperature and air velocity were of ±0.3 °C and ±0.067 m s^{-1}, respectively. During the experiment, the plates in the drying chamber were weighed to record weight change. Then, moisture loss was weighed using a digital electronic balance (Amput, Shenzhen, China, model APTP457A), which has 0–10,000 g measurement range with an accuracy of ±0.1 g. In this study, moisture content corresponded to the relative moisture content. The blower provided power for air circulation in the drying system. A square and finned electric heater was used in the heating cabinet. The air reversing device controlled the valve switch status to achieve alternating airflow. The control system consisted of the Siemens S7-200 series PLC Module and its associated relays and other components. In addition, wheat was placed in a thermostat (103 °C) after each drying experiment for absolute drying to calibrate the moisture content of the wheat during drying and thus ensure the experimental data accuracy.

Wheat used in the experiment was produced in Liaocheng, Shandong Province and harvested in June 2014. The wheat variety was 'Jimai22'. The wheat samples were naturally dried and then stored at ambient temperature. The initial wheat moisture content was 11.03% as measured using the thermostat. The wheat moisture content was rewetted from 11.03% to 25.00% to simulate the fresh wheat moisture content. The drying characteristics of wheat rewetted after 2 days were similar to those of fresh wheat. The blower and heater were employed before the experiment to start preheating the pipeline and the drying chamber. Then, each plate containing 1400 g of wheat was loaded into the drying chamber for the drying experiment.

In this experiment, swing temperature corresponded to periodically changing drying medium temperature. Alternating airflow meant changing flow direction, including the normal and reverse flows. The frequency of airflow direction change increases, and the single drying time decreases. The penetration depth of heat along the bed height decreases because of the evaporation of wheat in the lower or upper part of the drying chamber. This leads to the lack of drying intensity for wheat in the middle part of the drying chamber. The more the frequency of airflow direction change increases, the worse the drying uniformity is. Increasing the frequency of airflow direction change is not conducive to drying uniformity, and the airflow direction changed only once. Experimental procedure was divided into four stages:

In the normal flow heating stage, hot air was pumped into the drying chamber from the bottom inlet. The stage ended when the heat was sufficient to dry a certain amount of wheat. The plates