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Research Paper

Numerical simulation of moisture-heat coupling in belt dryer and structure optimization

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HIGHLIGHTS

- We added the viscous dissipation term in the energy equation.
- We used the porous medium model and the evaporation model in the calculation process.
- When material thickness increases, the "ripple" phenomenon disappears.
- Material thickness has the largest influence on moisture uniformity, followed by velocity.
- Wing defector reduces areca-nut moisture content and improves moisture content uniformity.

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ABSTRACT

In order to improve internal air flow field of belt dryer and increase moisture standard deviation of drying material in dryer, we used FLUENT software to study influences of material thickness, air velocity, air temperature and air relative humidity on material moisture content and uniformity in dryer on the basis of computational fluid mechanics and heat and mass transfer theory. Viscous dissipation was added to the energy equation. Porous medium model and evaporation model were used to improve result accuracy. A comparison between the moisture content of material inside the dryer was made when no deflector, a common deflector and a wing deflector are applied. Results show that air velocity in each measuring point is consistent with the numerical simulation. Material thickness had the largest influence on moisture content uniformity among four factors, followed by drying air velocity. The result of variance of material moisture content indicates that the thicker material thickness was, the better moisture content uniformity would be. When test conditions were shown as follows: 80 mm thickness; 343 K inlet air temperature; 1.5 m/s air velocity; 0.24 air initial humidity, moisture standard deviation of material was optimal. The wing deflector reduced material moisture content as a whole and moisture content uniformity was improved.

1. Introduction

Belt dryer is a continuous drying equipment, which has the advantages of no damage to the surface of the material. It is suitable for the drying of vegetables, such as traditional Chinese medicine and so on [1,2]. It has been a hot point in the research and application of drying machine [3–7], and the main reason is that the process and structure of the dryer are not reasonable. L.Q. Hao [8] found that the process structure was the main factor that affected the moisture unevenness of corn after drying. It was suggested that the air flow should be reduced properly in the mixed flow dryer. F.D. Román and O. Hensel [9] have provided four drying designs of round bale and simulated flow field inside the dryer. It was showed that the simplest dryer provides a deficient air distribution and inadequate drying, but an improved air distribution and drying uniformity to other designed dryer. Insufficient height of the ventilation duct was also one of the reasons why the horizontal airflow was not smooth and the drying was uneven [10]. In addition, the unreasonable working parameters (including hot air velocity [8,11,12], hot air temperature [11,12], material layer thickness [8,12,13], hot air humidity [12], material layer length and conveyor belt speed [13] and other factors) leaded to uneven distribution of material moisture.

It is difficult and expensive (sensor expensive) to obtain the internal flow field and moisture distribution in the working state of the dryer [14], even so, there are still the error of measuring instrument, limited measuring range and so on. Numerical simula-

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tion is a good method to adjust and optimize the operating parameters, which can predict the heat and flow field under different conditions [15,16]. Comparing the experimental and predicted (extracted for the CFD analysis) data revealed a very good correlation coefficient of 99.9% and 86.5% for drying air temperature and air velocity in the drying chamber, respectively [17]. It provided the reliability of the numerical simulation results. This approach has also been touted by structural engineers, since it can be used to predict the improved results in a computer, which has brought great convenience for the engineers. For example, L. Czétány and P. Láng [18] used Fluent software to simulate the flow field and temperature field of 3 different structures of ventilation system. In addition to the commonly used FLUENT software, there are scholars [19,20] using C/C++ language programming method for the drying process of belt dryer numerical calculation. To analyze moisture transfer during convective drying, a simultaneous heat and moisture transfer model was developed based on Fick's diffusion equation [21]. The model accurately predicted moisture loss as a function of drying time and position for the potato and carrot samples during convective hot air drying and further demonstrates the importance and improved accuracy of obtaining diffusion coefficients and its temperature dependence under isothermal conditions. Karim and Kumar [22] have developed a multiphase porous media model describing the physics of intermittent microwave convective drying (IMCD) process. In another work [23], they have taken shrinkage and pore evolution into consideration and gave a improvement model (IMCD2). Simulated results are validated against experimental data. An empirical model calculating moisture evaporation from a particle and droplet was proposed and validated by Wawrzyniak [24]. It was said that the model can be applied to the installations for dewatering.

From the point of view of heat and moisture coupling, the air flow field, temperature field and component concentration field inside the belt dryer was simulated by FLUENT software with multi-phase model, porous medium model and evaporation model. In addition, in order to make the results more accurate, the equation of viscous dissipation term was added to the governing equation.

2. Experiment

A multi-layer horizontal belt dryer self-designed by Xinyuan Chain Transmission Equipment Manufacturing Co. Ltd. was selected to test. The subject is a five-layer belted cross-flow drying system, which is composed of rack, belt chain, elevator, air inlet and outlet, and transmission drum. Length × width × height of the box is 20 m × 1.8 m × 2.5 m. The primary structure is shown in Fig. 1.

The drying air is supplied by a variable frequency blower, which enters into the dryer from the bottom and comes out from the top, and then gathered together in the centralized air duct. The heating system of the air is arranged in the pipeline at the bottom and is completed by electric heating. The temperature control system based on PLC is adopted in the experiment. The material enters from the top of the left side of the dryer through the elevator, and pass through the conveyer belt to exit from the right side of the bottom.

The five-layer conveyor belt is the 6-mesh steel wire gauze with the length and width of 19 m × 1.6 m. The height of each layer is fixed, 440 mm. The thickness of the conveyor belt and areca-nut layer are 40, 60, 80 mm, respectively. Interlayer spacing is 400, 380, 360 mm, accordingly. Structural parameter of drying air entrance is 2 m × 0.6 m × 0.2 m and structural parameter of the exit is 1.2 m × 0.6 m × 0.5 m.

The testing material is Chinese olive areca-nut from Hainan province. Before areca-nut is placed in the dryer for drying, it is cleaned, soaked, aired, divided, stripped, rinsed and filtered.

The author considers influences of material thickness, air velocity, air temperature and air initial humidity on material drying. As designing the test scheme, the author considers that 4 factors and 3 levels should be inspected. If the full assembly (3^4) is used, it needs a test for 81 times. However, if the orthogonal trial is used, just 9 points should be applied to be distributed in the testing points evenly. The orthogonal test design picks up some representative points to test from the comprehensive test according to orthogonality. These representative points are equipped with some features, including "even distribution and homogeneous/uniform design". It is a high-efficient and economic experimental design method [25]. The orthogonal experiment of the design is shown in Table 1.

3. Mathematical model and simulation

3.1. Control equation

The heat and moisture transfer model of material layer and air is established by using areca as the simulation object. Assuming that fluid is the incompressible fluid, coefficient of gas viscosity is a constant. The areca-nut applies a porous medium model. The porosity and mean diameter are used to describe particle property, and assuming that the areca-nut particle won't shrink in the drying process [26]. To simplify calculation, the mesh belt of the ventilation hole is regarded as a porous medium model [27]. The control equations are shown as follows:

(1) Continuity equation [28,29]

According to the conservation of mass, fluid net quality in and out of the control volume in unit time is equal to the reduced quality caused by density fluctuation of fluid in the interval control volume at the same interval. Air motion in drying process conforms to the law of conservation of mass. The differential equation is derived as follows:

$$\frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a u) = 0 \tag{1}$$

$$\frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a v) = 0 \tag{2}$$

$$\frac{\partial \rho_a}{\partial t} + \nabla \cdot (\rho_a w) = 0 \tag{3}$$

in which ρ_a is fluid density, kg/m^3; t is time, s; u is velocity in x direction, m/s; and v is velocity in y direction, m/s; w is velocity on the z direction, m/s.

(2) N-S equation [28,29]

According to Newton's second law, time change rate of fluid momentum should be equal to resultant force by fluid. The resultant force on infinitesimal volume is equal to the product between fluid quality and fluid accelerated speed. The differential equation is derived as:

$$\frac{\partial(\rho_a u)}{\partial t} + \nabla \cdot (\rho_a u \vec{u}) = \nabla \cdot (\mu \cdot grad u) - \frac{\partial p}{\partial x} + s_u \tag{4}$$

$$\frac{\partial(\rho_a v)}{\partial t} + \nabla \cdot (\rho_a v \vec{u}) = \nabla \cdot (\mu \cdot grad v) - \frac{\partial p}{\partial y} + s_v \tag{5}$$

$$\frac{\partial(\rho_a v)}{\partial t} + \nabla \cdot (\rho_a w \vec{u}) = \nabla \cdot (\mu \cdot grad w) - \frac{\partial p}{\partial z} + s_w \tag{6}$$