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# Simulation of Heat and Moisture Coupling Transfer Characteristics of Grain Pile Drying Process Based On DEM-CFD

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***Abstract -*** In order to study the heat and moisture coupling transfer characteristics of grain piles during drying. In this study, the discrete element method (DEM) was used to simulate the random accumulation process of soybean particles, and the contact between particles was processed. Based on the principle of local mass and thermal non-equilibrium, a heat and moisture coupled transfer model of flow and double-diffusion during drying of grain pile was established. The heat and moisture transfer characteristics of grain piles under different drying conditions were analysed by discrete element method and computational fluid dynamics (DEM-CFD). The results showed that, compared with heat transfer, the moisture diffusion and convective mass transfer coefficients inside soybean particles were smaller, and the moisture content changed more slowly. Both the drying air temperature and the initial moisture content of the grain pile had a great influence on the drying rate, but the effect of the initial moisture content was more obvious. Under the same drying conditions, the drying rates of grain piles with initial moisture content of 22, 28 and 32% (d.b.) were 6.2, 10.0 and 12.6%(d.b.)/h (in the first 1h), respectively.

***Keywords*: ** DEM-CFD coupling; grain pile; double-diffusion model; heat and moisture transfer

## 1. Introduction

Due to the high moisture content of newly harvested grain, it needs to be dried to store moisture safely before storage. Convective drying using heated air and solar radiation drying are two commonly used methods, with the former usually being chosen on industrial [1]. Drying is a complex heat-moisture coupled transfer process [2]. Due to its importance and complexity, hot air convective drying has always been the focus worthy of further research.

In the former research, most scholars did not consider the influence of the non-uniform pore distribution of grain particles on the airflow characteristics during the random accumulation process [3-5]. The grain pile is considered as a porous medium with uniform porosity distribution, and the particle-particle and particle-fluid interactions are ignored. At the same time, particle-particle and particle-fluid are considered to be in local mass and thermal equilibrium (LMTE). The coupled method of discrete element method and computational fluid dynamics (DEM-CFD) has been widely used in biomass drying and chemical mass transfer [6,7], which can more realistically simulate the heat and mass transfer in the drying process of grain piles.

In this study, the discrete element method was used to construct the grain pile, the grain information was imported into the pre-processing software and the contact between the grains was processed, and a double-diffusion heat and moisture transfer model was established. The DEM-CFD coupling method was used to analyse the air flow, temperature and moisture transfer during the drying process, in order to provide a reference for the follow-up multi-field coupling research in the heterogeneous pore structure of grain piles.

## 2. Model Building and Condition Setting

### 2.1. Discrete element model

The discrete element software EDEM was used to simulate the random accumulation process of particles. The parameters of soybean particles are shown in Table 1 [8]. During the accumulation process, spherical soybean particles with a diameter of 6.6mm are produced on the top of the model, and fall under the action of gravity to form accumulations. In this study, it is assumed that the velocity of particles is less than $10^{-7}$m/s to reach stability. Afterwards, the spatial coordinate information and diameter of soybean particles were derived, and the geometric model of the grain pile was reconstructed using commercial modeling software, as shown in Fig. 1.

Table 1: Soybean discrete element simulation parameters

| Parameter | Symbol | Value |
|---|---|---|
| Soybean diameter (mm) | $d_g$ | 6.6 |
| Density (kg/m³) | $\rho_g$ | 1213 |
| Poisson ratio | $\upsilon$ | 0.4 |
| Elastic modulus (MPa) | $E$ | 61 |
| Coefficient of restitution | $e$ | 0.03 |
| Coefficient of static friction | $\omega$ | 0.2 |
| Coefficient of rolling friction | $\omega_r$ | 0.03 |

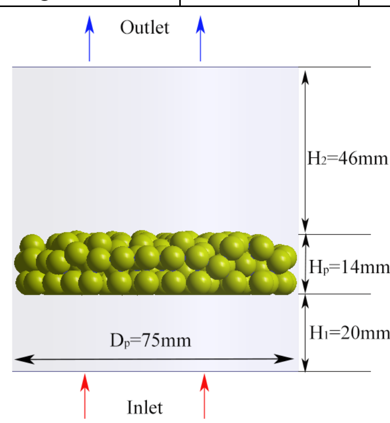


Fig.1 Geometric model of grain pile

## 2.2. Meshing

Since there are point contacts or narrow gaps between the reconstructed spherical particles, it is not conducive to mesh generation. When meshing directly, a large deflection occurs near the contact point, making it difficult for the simulation to converge. The existing processing methods mainly include gap, overlap, bridges and caps [9]. The first two methods will cause a large change in the pore structure of the grain pile. The bridging and caps methods only deal with local contact points, which ensures the accuracy of the geometric model. This study adopts the bridges method, and the dimensions of cylindrical bridges are calculated by equations (1) and (2). To ensure the best calculation results of particle-particle and particle-wall heat transfer [10], the meshing of the geometric model is shown in Fig. 2.

$$\mathrm{d}_b = 0.1\mathrm{d}_g \tag{1}$$

$$\mathrm{h}_b = 2(R - \sqrt{R^2 - (\frac{d_b}{2})^2}) \tag{2}$$

Where $\mathrm{d}_g$ is the diameter of soybean, mm; $\mathrm{d}_b$ is the diameter of the bridge, mm; $R$ is the radius of soybean, mm; $\mathrm{h}_b$ is the height of the bridge, mm.

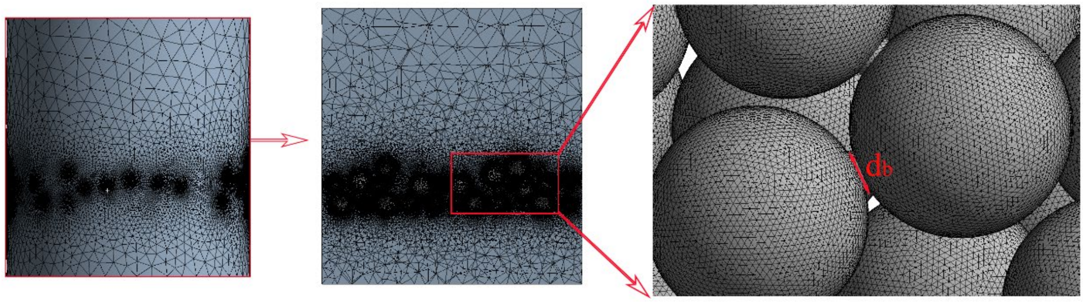



Fig. 2 Meshing

### 2.3. Simulation conditions

In this study, the air inlet adopts velocity inlet, the velocity is 0.9m/s, and the outlet adopts pressure outlet. The governing equations are solved by the pressure-velocity method in a steady state, and the pressure-velocity coupled solver uses the SIMPLE algorithm. In order to obtain more accurate results, the convergence residuals are all set to $10^{-5}$. The simulation conditions shown in Table 2 were used to study the effects of drying air temperature and initial moisture content of grain piles on the drying rate.

Table 2: Simulation conditions of drying [11]

| Case | Drying air temperature $\theta$(°C) | Initial moisture content%(d.b.) |
|---|---|---|
| 1 | 45 | 19 |
| 2 | 60 | 19 |
| 3 | 70 | 19 |
| 4 | 70 | 22 |
| 5 | 70 | 28 |
| 6 | 70 | 32 |

### 2.4. Validation of the model

In order to verify the grain pile model, the Ergun [12] and Carman [13] equations were used to study the pressure drop under ventilation conditions:

$$-\frac{\Delta P}{H_p} = 150\mu\frac{(1-\bar{\varepsilon})^2}{\bar{\varepsilon}^3}\frac{u}{d_g^2} + 1.75\rho\frac{(1-\bar{\varepsilon})}{\bar{\varepsilon}^3}\frac{u^2}{d_g} \tag{3}$$

$$-\frac{\Delta P}{H_p} = 180\mu\frac{(1-\bar{\varepsilon})^2}{\bar{\varepsilon}^3}\frac{u}{d_g^2} + 2.871\rho\frac{(1-\bar{\varepsilon})^{1.1}}{\bar{\varepsilon}^3}\frac{u^{1.9}}{d_g} \tag{4}$$

Where $u$ is the inlet velocity, m/s; $H_p$ is the height of the grain pile, m; $\mu$ is the kinematic viscosity coefficient of the fluid, Pa·s.

Fig. 3 shows the comparison results of simulated and empirical equations. It can be seen that the simulation results of this study and the calculation results of Ergun equation show the same distribution trend, and the relative error between the two is less than 10%. It shows that the model and method used in this study are reasonable.

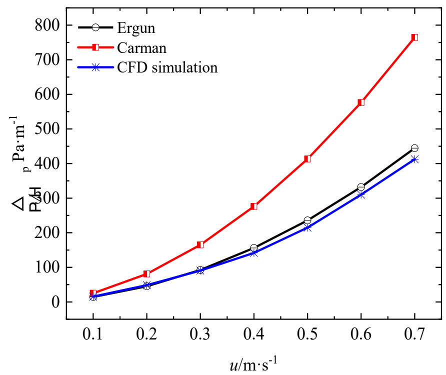



Fig.3 Comparison of pressure drop simulation results and empirical equation results

# 3. Results

## 3.1. Velocity and pressure distribution

Fig. 4 shows the velocity and pressure distribution of the grain pile at the X=0 plane when the drying air velocity is 0.9m/s. It can be seen that along the axial direction, when the airflow at the inlet contacts the particles, an obstacle is formed, making the velocity distribution uneven. Due to the random distribution of particles, the fluid channel is more complicated, resulting in a large difference in velocity distribution. However, due to the wall effect, the porosity of the contact between soybean particles and the wall is large, and the velocity near the wall is relatively high. At the same time, the pressure gradually decreases along the axial direction, and presents a stratification phenomenon. Due to the blocking of particles inside the grain pile, the internal pressure changes obviously.

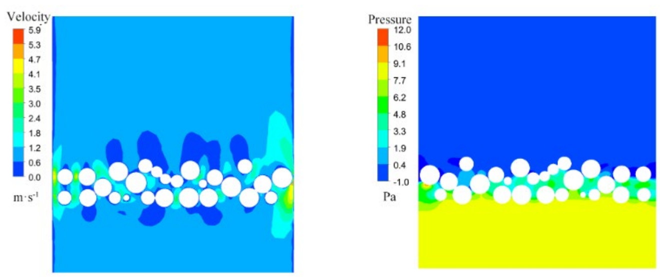
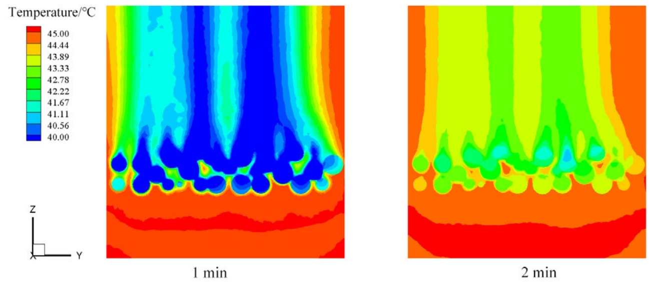



Fig. 4 Velocity and pressure distribution

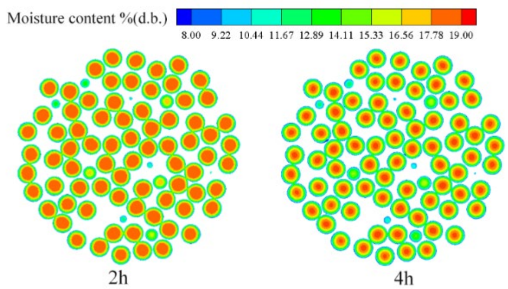
## 3.2. Temperature and moisture content distribution

The temperature and moisture changes of grain piles under the convective drying conditions given in Table 2 were studied. The temperature and moisture changes in Case 1 are shown in Fig. 5. The soybeans near the air inlet are in direct contact with the hot air, making the temperature change faster. Because the heat conduction resistance inside the soybean particle is much greater than the convection resistance on the surface, the internal temperature distribution is uneven.

It can be seen from Fig. 5(b) that soybean particles present an obvious moisture gradient, and the internal moisture content is always greater than the surface. Compared with heat transfer, the moisture diffusion and convective mass transfer coefficients in soybean particles are smaller, so that the interior of soybeans is still in a state of high moisture after 2 hours of drying.




(a)



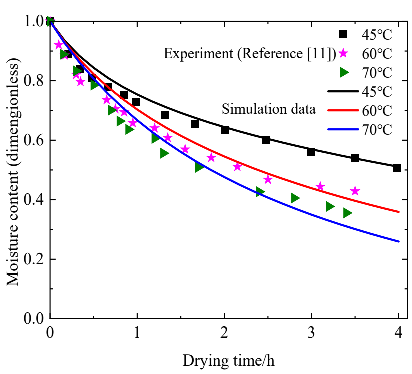

(b)

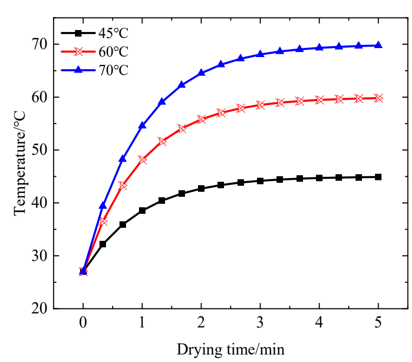
Fig. 5 Changes of temperature and moisture content in grain piles

### 3.3. Effect of drying air temperature on drying

The drying curves obtained under the conditions of Cases 1, 2 and 3 are shown in Fig. 6. At drying air temperatures of 45°C, 60°C, and 70°C, the drying rates of grain piles were 2.7%(d.b.)/h, 3.3%(d.b.)/h, and 4.0%(d.b.)/h (in the first 1 h), respectively. As the drying air temperature increases, the moisture diffusion coefficient increases, thereby accelerating the drying rate. At the beginning of drying, the change in moisture content is more obvious, and as time goes on, the drying rate will be reduced. This is because the moisture content on the soybean surface lost quickly under the action of convection, and the moisture diffusion coefficient of the grain pile is relatively low, which makes the moisture change in the late drying period small.

After drying for 5 minutes, the temperature of the grain pile tended to be stable, but the time required for the moisture content to reach a stable level was longer. This is mainly due to the fact that the mass transfer resistance in the soybean grain is greater than the heat transfer resistance, and the lower mass diffusivity makes the moisture change slower.




(a) (b)

Fig. 6 Moisture content and temperature distribution at different drying air temperatures

### 3.4. Effect of initial moisture content of grain pile on drying

The drying curves obtained under the conditions of Cases 4, 5 and 6 are shown in Fig. 7. It can be seen that the drying rates of grain piles with initial moisture content of 22% (d.b.), 28% (d.b.) and 32% (d.b.) are 6.2% (d.b.)/h, 10% (d.b.)/h 12.6%% (d.b.)/h (in the first 1 h), respectively. It is clear that as the initial moisture content of the grain pile increases, the drying rate also increases. The main reason is that when the moisture content of the grain pile increases, the moisture on the surface of soybean particles is high, and it is easier to be carried away by hot air in the form of convection. For grain piles with low moisture content, the moisture gradient between the grain pile and the air is small, combined with the low diffusion rate, making it difficult to release moisture.

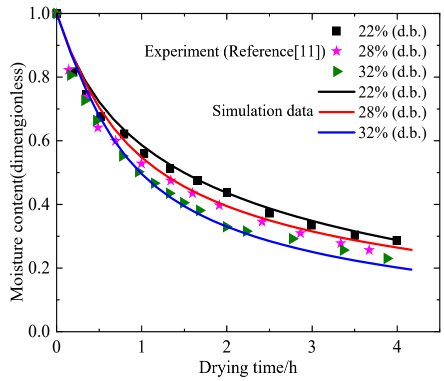



Fig.7 Drying curves at different initial moisture contents

## 4. Conclusion

In this study, the DEM-CFD coupling method was used to analyze the air flow, temperature and moisture transfer during the drying process of grain piles. The key conclusions of the work are:

(1) The porosity distribution of the grain pile is uneven, resulting in the uneven distribution of the velocity. The heat conduction resistance inside the soybean particle is greater than the convection resistance on the surface, making the internal temperature distribution uneven. Compared with heat transfer, the moisture diffusion and convective mass transfer coefficients in soybean particles are small, and the moisture content changes slowly.

(2) The temperature of the drying air has a greater effect on the drying rate. At 45°C, 60°C and 70°C, the drying rates of grain piles were 2.7%(d.b.)/h, 3.3%(d.b.)/h and 4.0%(d.b.)/h (in the first 1h), respectively.

(3) As the initial moisture content of the grain pile increases, the drying rate also increases. Under the same drying conditions, the drying rates of grain piles with initial moisture content of 22% (d.b.), 28% (d.b.) and 32% (d.b.) were 6.2% (d.b.)/h, 10.0% (d.b.)/h and 12.6%(d.b.)/h (in the first 1h), respectively. It is clear that the initial moisture content of the grain pile has a greater influence on the drying rate than the drying air temperature.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