Simulation Study of Rice Cleaning Based on DEM-CFD Coupling Method

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Abstract: In mechanized rice harvesting, the performance of the cleaning device is one of the important factors that affect the overall efficiency of the combine-harvester. To study the influence of different parameters on the cleaning efficiency, the influence of airflow velocity and the inclination angle on the cleaning effect was analyzed. Both simulation and experimental results prove that the increase of airflow velocity and the inclination angle will reduce the impurity rate of rice and increase the entrainment loss rate. The addition of a vibrating sieve to the device reduces the trash rate of rice, but the entrained loss rate increases accordingly. After tilting the sieve surface by 10°, a reduction in both the impurity rate and the entrainment loss rate of rice was found in combination with the force analysis of the particles on the sieve surface. The effect of the device structure on the internal flow field distribution was analyzed by comparing the eddy viscosity and velocity flow lines inside the three scavenging device structures. Simulation after calibration of rice moisture content revealed that humid rice cleaning was not effective.

Keywords: rice; cleaning; impurity rate; entrainment loss rate; DEM-CFD coupling

1. Introduction

Rice cleaning is an extremely important part of the working process of the combine-harvester. The main function of the cleaning device is to separate the short stalks and weeds from the rice mixture obtained after threshing, to ensure that the impurity rate and loss rate of rice after cleaning meets the specified requirements [1–3].

Since rice cleaning is a complex coupled gas-solid two-phase flow process, it is difficult to describe it by conventional methods. Using field experiments to optimize the design of cleaning devices is difficult to study the dynamic process, and the results are easily affected by the external environment. However, the use of DEM (Discrete Element Method) or CFD (Computational Fluid Dynamics) for simulation cannot describe the interaction between airflow and rice, or rice can only be regarded as a porous media model, and the influence of the rice model on airflow cannot be accurately calculated [4,5]. Therefore, many scholars have begun to explore the feasibility and accuracy of simulation research on grain sorting based on DEM-CFD coupling. The DEM-CFD method is a computational method that can characterize properties such as particle geometry and collision motion as well as analyze fluid distribution based on a multiphase flow model, which is more comprehensive for the simulation of fluid-particle systems than the traditional gas-solid two-phase flow model [6–9]. In recent years, the simulation study of grain cleaning using the DEM-CFD method has become a hot research topic in agricultural machinery simulation. Feng et al. [10] used the DEM-CFD method to study the movement of particles in different stages of the sieving process and the influence of the airflow velocity on the sieve on the degree of particle dispersion and pointed out that the particle at the sieve head has the lowest degree of dispersion, while the middle of the sieve is the opposite. Dai et al. [11] simulated the cleaning process of flax threshing materials and their movement in the cyclone separator.
The addition of a vibrating sieve to the separator improved the cleaning effect, and the comparison of experimental results verified the accuracy of the simulation. Yuan [12] found through DEM-CFD simulation that both the airflow velocity and aperture in the cylindrical sieve have an effect on the loss rate of grain separation, and the airflow velocity is conducive to the separation of grain mixtures. Wang et al. [13] designed a countersunk sieve and used the DEM-CFD method to simulate the sieving process of the corn mixture, and obtained the effect law of angle of sidewall around sieve hole and airflow speed on the efficiency of corn cleaning. The above scholars have conducted simulation studies on various types of cleaning devices and verified the accuracy of the coupled DEM-CFD method through experiments. Due to the special characteristics of rice with random size and its own properties easily affected by storage conditions, the phenomenon of impurity and entrainment loss in rice cleaning still exists. This paper simulates the process of rice cleaning based on the DEM-CFD method, and obtains the influence of airflow velocity and inlet inclination angle on the cleaning efficiency, and compares the experimental result to prove the accuracy of the conclusions. The effect of frequency and inclination angle of sieve surface on the results and the difference of flow field distribution inside the device with different cleaning methods were analyzed. A moisture content calibration experiment was conducted on rice and its impurities, and the effect of cleaning results on humid rice was discussed. The conclusions obtained can provide a reference basis for the design of the rice cleaning device.

2. Simulation Model

2.1. Geometric Model

Figure 1a is a schematic diagram of the cleaning device model. The wall thickness of the model is 2 mm, the length is 200 mm, the height is 160 mm, and the width is 80 mm. Rice enters the device from the material inlet, the airflow enters the device from the left side inlet, and there are three outlets on the device.

![Figure 1a](image)

Figure 1. Rice cleaning device. (a) Simulation model; (b) experiment device. 1. Blower; 2. Ventilation pipe; 3. Air inlet; 4. Material inlet; 5. Outlet 3; 6. Outlet 1; 7. Outlet 2; 8. Hand-held anemometer; 9. Airflow speed adjustment switch; 10. Base plate.

The experiment device in Figure 1b was designed to verify the accuracy of the simulation. The cleaning device is fixed to the base plate by two supports; the position of the support and the device can be adjusted along the straight slot on the base plate, and the fixed position of the device is higher than the base plate in order to collect rice. The ends of the ventilation pipe are fixed to the blower and the conversion port by a hose clamp, and the ventilation pipe and the device are connected by a removable adapter port. The main body of the device is formed by 3D printing, the side panels are made of transparent Plexiglas for easy observation, the rated voltage of the blower is 220 V, the power is 60 W, the velocity is 2800 rpm, and the operating voltage of the speed switch is AC 180–250 V (50 Hz/60 Hz).
The wall thickness of the ventilation pipe is 0.63 mm, and the inner diameter is 50 mm. The model of the high-precision anemometer is Biaozhi GM816, and the range is 0–30 m/s.

2.2. Particle Model

South Japonica 9108 was selected as the rice variety in the simulation and experiment. Because the rice belongs to the three-axis size unequal particles, only the long axis and short axis of the rice are simply measured. Figure 2 shows the measurement results of three kinds of particles. From the figure, it can be seen that the long axis of the rice is 7 mm and the short axis is 3 mm; the length of the rice stalk is 6 mm, the diameter is 4 mm, and the width of broken rice straw is 3 mm and the length is 6 mm.

Figure 2. Particle measurement results (a) Rice (b) Rice straw (c) Broken rice straw.

Based on the measured data in Figure 2, the three types of particles are modeled in EDEM using the “overlapping multi-sphere clump method (OMCM)” [14,15]. Figure 3 is a schematic diagram of the size of the particle cross-section and the particle model after filling. The rice particle is filled with 13 spheres of different diameters, and the rice stalk is filled with 4 spheres with a radius of 2 mm and 16 spheres with a radius of 1 mm. The broken rice stalk is filled with 36 spheres with a radius of 0.5 mm. Although the rice stalk can be regarded as a hollow cylinder and the broken rice stalk are curved surface flakes, the contact between the rice stalks, broken rice stalks, and other particles occur on the surface of the particles during the cleaning process. Therefore, the rice stalk and broken rice stalk formed by filling and combining multiple spherical particles meets the simulation requirements. In the EDEM particle attribute setting, the mass of real rice stalk and broken rice stalk are manually entered to ensure the authenticity of the simulation. The material properties of the cleaning device and the particles are shown in Table 1 [16,17].

| Material                | Poisson's Ratio | Shear Modulus (Pa) | Density (kg/m³) |
|-------------------------|-----------------|--------------------|-----------------|
| Rice                    | 0.30            | 2.000 × 10⁶        | 1380            |
| Rice straw              | 0.40            | 1.000 × 10⁶        | 100             |
| Broken rice stalk       | 0.40            | 1.000 × 10⁶        | 100             |
| Cleaning device         | 0.29            | 7.992 × 10¹⁰       | 7861            |

2.3. DEM-CFD Coupled Model

Figure 4 is a schematic diagram of the Fluent-EDEM coupling simulation process. First, Fluent calculates the flow field at a certain time point to convergence, and the flow field information is converted into the fluid drag force acting on the particles in EDEM through the drag force model. Second, EDEM calculates the external force (fluid drag force, gravity and collision force, etc.) on each particle, and updates the particle’s position, velocity and other information accordingly. Finally, these particle properties are added to the CFD calculation in the form of momentum sinks, thereby affecting the flow field, and obtaining the flow field law and the law of particle system motion parameters.
2.3.1 Equations of Motion of Particles

Computational particle mechanics can describe the interaction and contact mechanical behavior between particles. Considering the contact between rice and other particles and the change of particle velocity based on the contact force, the Hertz–Mindlin (no-slip) contact model is used for simulation in EDEM. According to Hertz contact theory, the motion equation of particle $i$ is [18–21]:

$$
\sum_{j} \left( m_i \frac{d^2 \vec{r}_{ij}}{dt^2} + \vec{F}_{ij} + \vec{F}_{\text{drag}} + \vec{F}_{\text{gravity}} + \vec{F}_{\text{coll}} \right) = 0
$$

Here, $m_i$ is the mass of particle $i$, $\vec{r}_{ij}$ is the relative position vector between particles $i$ and $j$, $\vec{F}_{ij}$ is the contact force, $\vec{F}_{\text{drag}}$ is the drag force, $\vec{F}_{\text{gravity}}$ is the gravity force, and $\vec{F}_{\text{coll}}$ is the collision force.

Figure 3. Particle measurement results: (a) rice; (b) rice straw; (c) broken rice straw.

Figure 4. EDEM-Fluent coupling process.

2.3.1. Equations of Motion of Particles

Iterate the flow field to convergence in Fluent

Calculate fluid drag on particles, etc.

Calculation of particle motion behavior in EDEM

Update the position, velocity and other parameters of particles

Introduce the motion parameters of particles into the fluid in the form of momentum
contact model is used for simulation in EDEM. According to Hertz contact theory, the motion equation of particle $i$ is [18–21]:

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \mathbf{g} + \sum_{j=1}^{n_i} (\mathbf{F}_{n,ij} + \mathbf{F}_{t,ij})$$

(1)

$$l_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_i} (\mathbf{M}_{t,ij} + \mathbf{M}_{r,ij})$$

(2)

where $\mathbf{v}_i$ is the velocity of particle $i$; $\omega_i$ is the angular velocity of particle $i$; $l_i$ is the rotational inertia of particle $i$; $m_i$ is the mass of particle $i$; $\mathbf{g}$ is the acceleration of gravity; $F_{n,ij}$ is the normal component force; $F_{t,ij}$ is the tangential component force; $M_{t,ij}$ is the tangential moment; $M_{r,ij}$ is the rolling friction moment.

The formulas for solving force and moment are:

$$F_{n,ij} = -\frac{4}{3} E^* \sqrt{R^* (\delta_n)^2} n_c - \frac{5}{6} k_n m^* \frac{2 \ln \varepsilon}{\sqrt{\ln^2 \varepsilon + \pi^2}} (\mathbf{v}_{n,ij} \cdot \mathbf{n}_c) n_c$$

(3)

$$F_{t,ij} = -8G^* \sqrt{R^* \delta_n \delta_t} - \frac{5}{6} k_t m^* \frac{2 \ln \varepsilon}{\sqrt{\ln^2 \varepsilon + \pi^2}} (\mathbf{v}_{t,ij} \cdot \mathbf{n}_c) n_c$$

(4)

$$M_{t,ij} = -\mu F_{t,ij} \cdot R_i \cdot \omega_i$$

(5)

$$M_{r,ij} = R_i F_{n,ij}$$

(6)

where $E^*$ is the equivalent elastic modulus; $R^*$ is the equivalent radius; $m^*$ is the equivalent mass; $G^*$ is the equivalent shear modulus; $\varepsilon$ is the elastic recovery coefficient; $\delta_n$ is the normal overlap; $k_n$ is the normal stiffness; $k_t$ is the tangential stiffness; $n_c$ is the unit vector connecting the centers of two particles; $\mathbf{v}_{n,ij}$ is the relative normal velocity of particle $i$ to particle $j$; $\mathbf{v}_{t,ij}$ is the relative tangential velocity of particle $i$ to particle $j$; $\mu$ is the coefficient of rolling friction; $R_i$ is the unit direction vector of particle $i$ centroid to contact point; $\omega$ is the angular velocity unit vector of the particle $i$ contact point.

2.3.2. Control Equations for the Gas Phase

In the EDEM-Fluent coupling the interaction of rice and other particles with the flow field inside the cleaning device is simplified to a gas-solid two-phase flow motion in a turbulent state, where the gas is incompressible and the heat transfer is neglected. The continuity equation and momentum equation of the gas phase in the model are:

$$\frac{\partial \varepsilon_f \rho_f}{\partial t} + \nabla \cdot (\rho_f \varepsilon_f \mathbf{v}_f) = 0$$

(7)

$$\frac{\partial \varepsilon_f \rho_f}{\partial t} + \nabla \cdot (\rho_f \varepsilon_f \mathbf{v}_f \mu \mathbf{v}_f) = -\nabla \varepsilon_f P + \nabla \left( \varepsilon_f \tau_g \right) + \rho_f \varepsilon_f g - S$$

(8)

where $\rho_f$ is the gas density, $\mathbf{v}_f$ is the fluid flow rate, $\varepsilon_f$ is the volume fraction term of the gas, $\tau_g$ is the gas viscous stress tensor, $P$ is the pressure on the gas micro-element, $\nabla$ is the Hamiltonian differential operator, and $S$ is the momentum sink.

3. Simulation Analysis

3.1. Effect of Airflow Velocity and Inclination Angle

The ratio of the number of rice, rice straws, and broken rice straws in the simulation is set to 4:1:0.25; the total weight of rice in the experiment is 493.78 g (about 12,000), the total weight of rice straw is 20.31 g (about 3000), and the total weight of broken rice straws is 0.46 g (about 750). The airflow inlet velocity of the experimental device and the airflow inlet of the simulation model are both adjusted to 5 m/s, and the mixed particles entered
the device through outlet 1. According to the change of the average position of the three particles in Figure 5, it can be seen that the particles have three different trajectories inside the device. The rice will move horizontally after being affected by the airflow and finally fall into outlet 1. The horizontal displacement of the rice stalks is larger than that of the rice, and it falls into outlet 2 after making an oblique throwing motion. The horizontal displacement of the broken rice stalks is larger than that of rice and rice stalks. After being thrown obliquely, the rice stalks contact the sidewall of outlet 2 and then fall into outlet 2.

In the simulated particle trajectory and the transient graph of the experiment in Figure 5b, the velocity vector trajectories of rice stalks and broken rice stalks are similar to those in the experiment.

\[ C_I = \frac{V_S(s, t) + V_f(s, t)}{V_I(s, t)} \% \]  \hspace{1cm} \text{(9)}

where \( V_S(s, t) \) and \( V_f(s, t) \) is the volume of rice stalk and broken rice stalk at time \( t \) in area \( s \), respectively, and \( V_I(s, t) \) is the volume of all materials at time \( t \) in area \( s \).

The entrainment loss rate \( E_L \) is:

\[ E_L = \frac{N_{II}}{N_I + N_{II}} \% \]  \hspace{1cm} \text{(10)}

where \( N_I \) is the total quantity of rice collected at outlet 1; \( N_{II} \) is the total quantity of rice collected at outlet 2.

The experimental results in Figure 5b show that the rice collected at outlet 1 is mixed with some rice stalks. In addition, the rice will be entrained by impurities in the process and cause losses. To quantitatively describe the impurity rate of rice and the entrainment loss of rice in the flow field after cleaning, the impurity rate and entrainment loss rate are introduced as evaluation criteria. The calculation formula of the impurity rate is:

\[ C_I = \frac{V_S(s, t) + V_f(s, t)}{V_I(s, t)} \% \]

where \( V_S(s, t) \) and \( V_f(s, t) \) is the volume of rice stalk and broken rice stalk at time \( t \) in area \( s \), respectively, and \( V_I(s, t) \) is the volume of all materials at time \( t \) in area \( s \).

The statistical results at the outlet of the simulation and the number of particles collected by the trough at the outlet of the experimental device are substituted into formulas (9) and (10) respectively to obtain the cleaning results in Figure 6. In the figure, when the airflow inclination angle \( \beta \) is 0, the impurity rate (entrainment loss rate) of rice with airflow velocity of 5 m/s, 7 m/s, and 9 m/s are 10.575% (0.066%), 2.162% (0.351%), and 0.307% (1.275%), respectively. Under the same cleaning parameters, the impurity rate (entrainment loss rate) of rice was 11.528% (0.117%), 3.464% (0.669%), and 0.721% (1.541%) respectively.
The comparison shows that the simulation and experimental results have the same changing trends, but the particle mass and volume in the simulation are the average values after measurement. In the experiment, there is dried-out rice and insect-eaten hollow rice whose quality is less than the average, and the volume of rice straw also had randomness. During the experiment, the dried-out rice and insect-eaten hollow rice with a mass less than the average entered outlet 2 with impurities, and the rice stalks with a mass greater than the average could not be separated after the airflow and entered outlet 1, which ultimately caused the experiment result to be larger than the simulation result.

![Figure 6. Rice impurity rate and entrainment loss rate under different parameters.](image)

In aerodynamics, the flight coefficient of an object is defined as the inverse ratio of the force of the airflow to its gravity, and its magnitude reflects the displacement of the object in the flow field. Therefore, the greater the horizontal force of the three kinds of particles inside the cleaning device is subjected to the airflow, the greater the displacement produced. Combining the statistical results in Figure 6, it can be seen that when the airflow tilt angle is 0, increasing the airflow velocity, the impurity rate of rice is significantly reduced, and the entrainment loss rate has increased. When the airflow inlet is rotated counterclockwise, the area where the airflow acts inside the device will extend upwards. Combining the calculation results of the speed changes of the two impurities in Figure 7, it can be seen that the larger the airflow tilt angle, the greater the velocity of the particles in the flow. The increase in speed indicates that the displacement of the three particles has increased, and finally the impurity rate of rice has decreased, and the entrainment loss rate has increased.

### 3.2. Effect of Cleaning Method

To analyze the influence of the cleaning method on the cleaning effect and to compare the difference in the effect of air separation and air-sieve cleaning, a horizontal sieve was added above outlet 1 in the device. The position of the sieve is shown in Figure 8, the length of the sieve surface is 70 mm, the width is 60 mm, and the thickness is 2 mm. In the simulation, the airflow velocity was set to 5 m/s with a poor cleaning effect, the vibration frequency was 10 Hz and the amplitude was 1 mm. It can be seen from the particle trajectory diagram in the device that the particles entering the cleaning device will accumulate temporarily on the sieve under the condition of having a vibrating sieve. Some of these particles enter outlet 2 (impurity outlet) along the direction of the screen surface,
and the some enter outlet 1 (rice outlet) through the screen hole. Since the width of the sieve hole is smaller than the width of the rice straw, the rice straw on the sieve surface cannot pass through the sieve hole and can only enter outlet 2 along the sieve surface, and some of the rice straw still enters the outlet 1 along the sieve surface.

![Figure 7](image_url1)  
**Figure 7.** Velocity of rice stalks under different airflow inclination angles.

![Figure 8](image_url2)  
**Figure 8.** Transient diagram of the particles in the air-sieve cleaning device.

From the simulation results with different parameters in Figure 9, it can be seen that when the vibration frequency of the sieve surface is 10 Hz and the amplitude is 1 mm, the impurity rate of rice is 5.588% and the entrainment loss rate after statistics is 1.607%. By comparison, it is found that when the airflow velocity is the same as 5 m/s, the impurity rate decreases by 4.987%, and the entrainment loss rate increases by 1.541% after adding the vibrating sieve. When the frequency was changed to 20 Hz, the impurity rate of rice decreased by 0.446% and the entrainment loss rate increased by 1.618% compared with the simulation results with a frequency of 10 Hz. Compared with the simulation results when only airflow is used for cleaning, it is found that the impurity rate of rice during air-sieve cleaning (20 Hz) is reduced by 4.987%, and the entrainment loss rate is increased by 1.541%. When the airflow velocity and amplitude remain unchanged, although increasing the
vibration frequency can reduce the impurity rate of rice, the increase in frequency will result in a significant increase in the entrainment loss rate of rice.

By rotating the sieve counterclockwise by 10° at a vibration frequency of 20 Hz, the simulation results showed that the impurity rate of the rice is 3.286% and the entrainment loss rate is 1.844%. By contrast, when the inclination angle of the sieve is 0, the impurity rate of rice is reduced by 1.856%, and the entrainment loss rate is also reduced by 1.381%.

Figure 10 shows the force analysis of the rice on the sieve. When the particles move to the left side of the sieve, the rice on the sieve in the airflow field are subjected to inertia force $F_I$, friction force $F_f$, airflow force $P$, gravity force $G$, sieve reaction force $F_N$, and buoyancy force $F_b$.

\[
P = k_g \rho A_r v^2
\]

\[
F_b = \frac{\pi}{6} D_p^3 \rho g
\]

\[
F_I = m_r a_s
\]

\[
F_N = G \sin \theta_1 - F_b \sin \theta_1 + P \sin \epsilon
\]

The resultant force $F$ received by the rice in the horizontal direction of the sieve surface is:

\[
F = F_I + G \cos \theta_1 - F_b \cos \theta_1 - P \cos \epsilon - F_f
\]

\[
F = (m_r g - \frac{\pi}{6} D_p^3 \rho g) \times (\cos \theta_1 - \tan \delta \sin \theta_1) + m_r a_s + k_g \rho A_r v^2 (\cos \epsilon - \sin \epsilon \tan \delta)
\]
When $F > 0$, the particles move to the left side of the sieve and are thrown into outlet 1 by the sieve surface. Although there is still some rice falling into outlet 2 without touching the sieve or moving right along the sieve ($F < 0$), the impurity rate and entrainment loss rate of rice are reduced after the sieve is inclined.

Eddy viscosity refers to the eddy diffusion phenomenon caused when the fluid flow is in the vortex flow. At this time, the fluid can be regarded as having a great viscosity, and it also has a viscous dimension, which can describe the fluid flow state instead of its true viscosity. Figure 11 shows the eddy viscosity cloud diagram of the device under three structures: no vibrating sieve, horizontal vibrating sieve, and inclined vibrating sieve, and it can be seen from the figure that the strong eddy viscosity mainly appears in the area near the outlet 2, and the eddy viscosity at the outlet 1 of the no-sieve device in Figure 11a is larger than the eddy viscosity in the same position in the sieve cleaning device in Figure 11b,c. Combining with the corresponding velocity streamline diagrams in Figure 12, it is found that obvious eddy currents appear at outlet 2 under the three structures, and the velocity near the right wall surface is larger. When there is no sieve inside the device, a vortex flow phenomenon occurs locally at outlet 1, while when there is a sieve, the streamline at outlet 1 passes through the sieve hole, and there is no vortex flow phenomenon. In summary, the strong eddy viscosity inside the cleaning device mainly appears in the area where the airflow velocity is large and the velocity flow line appears vortex or has the trend of a vortex, and changing the inclination angle of the vibrating sieve has little effect on the distribution of eddy viscosity.

![Figure 10. Force of rice on inclined sieve surface.](image1.png)

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![Figure 11. Eddy viscosity (a) No sieve ($v = 5$ m/s) (b) Air-Sieve ($v = 5$ m/s $a = 0^\circ$) (c) Air-Sieve ($v = 5$ m/s $a = 10^\circ$).](image2.png)
When the humidity on the surface of rice increases, the inter-liquid bridging force on its surface will cause the rice to adhere to other particles. The Hertz–Mindlin (no-slip) model does not consider the adhesion force between wet particles, so the Hertz–Mindlin with JKR (Johnson Kendall-Roberts) contact model is chosen, which is based on the Hertz–Mindlin contact model, to add a normal adhesion force to describe the effect of liquid bridge force between particles and the overlap between particles. Based on the JKR theory, the normal contact force $F_{JKR}$ between particles and the overlap between particles $\delta$ are expressed as [23,24]:

$$F_{JKR} = -4\sqrt{\pi\gamma_j E^* a^3} + \frac{4E^*}{3R^*} a^3$$

$$\delta = \frac{a^2}{R^*} - \sqrt{4\pi\gamma_j a / E^*}$$

where $\gamma_j$ is the surface energy between particles; $a$ is the radius of the contact surface between particles, $E^*$ is equivalent Young’s modulus, and $R^*$ is the equivalent radius.

Since the JKR model can only simulate wet particles by adding the adhesion force between particles, it cannot be compared with the specific moisture content of the material. Therefore, it is necessary to measure the moisture content of real rice and rice straw and set the corresponding cohesive force in the simulation. The rice is humidified to simulate the wet state under poor storage conditions, and the moisture content $R_w$ of the material is defined as:

$$R_w = \frac{m_s - m_a}{m_s} \%$$

where $m_s$ is the mass of the humidified particles and $m_a$ the mass of the dry particles.

Selecting 80 g of dried rice particles for humidification, the mass of the humidified rice is 95.8 g, and the moisture content of the rice is 16.49% according to Equation (19). The rice straw was also humidified, and the moisture content of the rice straw was 23% after measurement. The surface energy of the JKR contact model in EDEM was calibrated by corresponding the moisture content of the material with the surface energy after obtaining the moisture content by the weighing method. The experimental device is shown in Figure 13a, which consists of a funnel, a support, and a bottom plate; the funnel is fixed on the support with a distance of 70 mm between the narrow opening and the bottom plate.
The angle of repose calibration experiment is performed by using the difference in flow characteristics of wet and dry particles, and the angle of repose of the rice pile is measured after the rice is poured into the funnel and scattered onto the bottom plate. The simulation result in Figure 11a shows that the angle of repose of dry rice (surface energy = 0) is 29.5°, which is within a reasonable range of error from the experimental result (29°) in Figure 13b.

Figure 13. Moisture content calibration experiment (a) Experiment (b) Simulation.

As shown in Figure 14, the angle of repose rice with 16.49% moisture content was obtained after measurement as 35°. An attempt was made to set the corresponding surface energy value from the angle of repose of rice simulation in EDEM, and the repeated test was obtained when the rice-rice surface energy was 0.006 J m⁻² simulation results were consistent with the experimental results. The same calibration experiment was conducted for rice straw, and the corresponding values of straw-rice straw surface energy and straw-rice surface energy were obtained for 23% moisture content, respectively.

Figure 14. Measurement results of the angle of repose of rice (a) Experiment (b) Simulation.

After setting the surface energy between the materials, the rice cleaning with an air velocity of 9 m/s is simulated (Since the JKR model only considers the bonding between wet particles and does not take into account the change in particle mass after humidification, the masses of the three particles were manually corrected according to the measured results before the simulation). Figure 15 shows the statistical results of the rice impurity rate and the average impurity rate under the condition of moisture content.

The calculated entrainment loss rate of rice is 0.756%, a decrease of 0.519% compared to the results under the drying conditions. Combined with the simulation results, it can be seen that since the mass of rice containing water is larger than that under dry conditions, the flight coefficient (P/G) of the three particles becomes smaller and their displacement
in the flow field becomes smaller under the condition of being subjected to a constant horizontal force $P$ of the airflow, resulting in some of the rice straws entering the outlet 1. The presence of the liquid bridge force between the particles can bond some of the rice to the rice straw, but the increase in the mass of the rice containing water will result in it being less susceptible to entrainment of impurities into outlet 2. In summary, when wet rice was cleaned, the average impurity rate of the rice was significantly increased, and the entrainment loss rate was decreased.

![Figure 15. Impurity rate of rice.](image)

4. Conclusions

The rice, rice straw, and broken straw were modeled based on real measurement data, and the cleaning of rice was simulated using the DEM-CFD coupling method, and the experiment device was designed to verify the reliability of the simulation. The moisture content of the particles was calibrated based on Hertz–Mindlin with JKR contact model, and the influence of different parameters and cleaning methods on the results was analyzed.

1. Modeling rice, rice stalks, and broken rice stalks was based on experimental measurement data and using the "overlapping multi-sphere clump method". The rice cleaning under different airflow velocities was simulated, and the calculated impurity rate and entrainment loss rate of rice were consistent with the experimental results. The randomness of particle mass and volume, and the presence of shriveled or insect-eaten rice in the experimental results cause the experimental results to be larger than the simulated results.

2. Adding a vibrating sieve inside the device can reduce the rate of impurities, while the rate of entrainment loss will increase. Rotating the sieve surface counterclockwise by 10° can reduce both the rate of impurities and the rate of entrainment loss, and adding vibrating sieve will change the eddy viscosity distribution inside the device, and the eddy viscosity under the sieve surface appears to be significantly reduced.

3. The impurity rate and entrainment loss rate of rice under humid storage conditions are higher than the statistical results of dry rice cleaning simulation.
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