HORTSCIENCE 59(6):749–755. 2024. https://doi.org/10.21273/HORTSCI17758-24

Numerical Coupling Simulation of the Vertical Blowing Suspension Position of Tea Leaves Based on Computational Fluid Dynamics and the Discrete Element Method

Xu Zhang
Huzhou Vocational and Technical College, college of Intelligent Manufacturing and Elevator, Huzhou, 313000, China; Huzhou Key Laboratory of Robot System Integration and Intelligent Equipment, Huzhou, 313000, China; and Huzhou Vocational and Technical College, Industrial Intelligent Automation Research and Development Center, Huzhou, 313000, China

Xinyu Zhu
Huzhou Vocational and Technical College, College of Continuing Education, Huzhou, 313000, China

Kai Yu
Huzhou Vocational and Technical College, College of Intelligent Manufacturing and Elevator, Huzhou, 313000, China

Rongyang Wang
Huzhou Vocational and Technical College, College of Intelligent Manufacturing and Elevator, Huzhou, 313000, China; and Huzhou Key Laboratory of Robot System Integration and Intelligent Equipment, Huzhou, 313000, China

Keywords. coupling simulation, numerical fitting, suspension speed, tea granules

Abstract. **To provide reference for the design of the air-suction tea sorting device, the coupled numerical simulation model was established by the coupling method of computational fluid dynamics (CFD) and discrete element method (DEM) with tea of different quality as test objects, and the model was verified experimentally. Regarding tea particles of different quality, when the test tea particle mass was 0.215, the test value was located in the simulation value with a minimum error of 9 mm, which an error rate of 3.33%, and maximum error of 19 mm, with an error rate of 7.03%. When the test tea particle mass was 0.145, the minimum error of the test value was 5 mm and the error rate was 1.54%, and the maximum error was 9 mm and the error rate was 3.33%. The verification results established the accuracy of the model. During the suspension test and simulation, tea particles were affected by the air flow field of the observation tube, and tea particles fluctuated. During suspension, tea particles were attached to the inner wall of the observation tube under the action of the air flow field. An in-depth study showed that the relationship between the different distances from the initial position of the particles during suspension and the simulation time was a peak function. The extreme function is used to fit the actual trajectory, and the fitting degree is good. The fitting degree of the particle closest to the initial position was 0.9455, and the fitting degree of the particle farthest from the initial position was 0.9981.**

Received for publication 7 Feb 2024. Accepted for publication 27 Feb 2024.
Published online 25 Apr 2024.
This work was supported by the general scientific research project of Zhejiang Education Department (Y202250526), the Natural Science Foundation of Huzhou Science and Technology Bureau (2023YZ51), and the National Natural Science Foundation of China (grant number 52105283).
X.Z. is the corresponding author. E-mail: z_xu1987@163.com.

With the rapid advancement of agricultural modernization, the level of agricultural mechanization in China has continuously improved, and agricultural machinery is gradually developing in the direction of intelligence, efficiency, and energy savings. Pneumatic conveying has been widely used in a variety of agricultural equipment, such as sowing machinery, fertilization machinery, harvesting machinery, and sorting machinery (Dong et al. 2017; Qi et al. 2016; Wang et al. 2015; Xing et al. 2019). Tea is part of China's characteristic agricultural industry, which has strong seasonality and timeliness, and it is often time-consuming and costly to pick and sort it. However, the sorting technology for well-known and high-quality tea is still immature. At present, tea sorting mainly uses a drum and screen stopper (Sun et al. 2016; Yang et al. 2013; Zhang et al. 2011) and reciprocating vibration (Ren et al., 2013; Xie et al. 2012). However, there are some drawbacks to the separation of these two methods, such as loud noise, high energy consumption of the equipment, and difficult maintenance. Although some pneumatic separation products are available, low sorting accuracy is still a problem. This is because of the effects of wind on tea movement. A method of moving tea leaves has not been established; therefore, it is very important to study the suspension position of tea leaves under certain air values. The suspension velocity of agricultural materials is the basis of the design of a pneumatic conveying system and an important basis for setting a reasonable conveying gas velocity (Dai et al. 2016; Yu et al. 2018; Zhang et al. 2018). The measurement formula of suspension velocity is ideal; however, there are certain errors in practice.

Hou et al. (2018) used a vertical blowing-type suspension velocity test device for agricultural materials to measure the suspension velocity of each component of the extracted matter to be cleaned after the harvest of millet, buckwheat, and oat by a rice–wheat combine. Wang et al. (2016) designed a test device that can directly read the material suspension speed by changing the frequency to control the wind speed and using a pipeline anemometer to measure the suspension speed of irregularly shaped material particles by transposing the device. In recent years, to save test costs, researchers have tried to use the discrete element method (DEM) to establish material particles and applied computational fluid dynamics (CFD) to apply the gas phase, thereby achieving remarkable research results (Iqbal and Rauh 2016; Qian et al. 2014; Yang et al. 2015). Liu et al. (2020) simulated the motion stress process of the culm in the crushing chamber by using the CFD-DEM coupling method. Huang et al. (2016) analyzed the gas–solid two-phase flow of vegetable seeds in the separation chamber of the wind sorter by using the turbulence model of Fluent software and the DPM discrete phase model. Lei et al. (2017) used the coupled simulation method of CFD-DEM to reveal the movement law of oilwheat seeds in the seed transport pipeline of the gas-feeding type of harvester. Zhang et al. (2013) simplified the raw tea material into spherical particles and analyzed the flow field inside the tea air separator and the running track of the material using fluid mechanics. Weng et al. (2022) established the numerical simulation of the leaf collecting process of the fresh leaf pipeline by using CFD-DEM and proposed the fresh leaf particle modeling method, which was used for the discrete element simulation analysis of the interaction between the collecting pipe and fresh leaf flow and the optimization of the pipeline structure. Wen et al. (2020) established the EDEM-Fluent coupling model to simulate the suspension velocity of granular fertilizer, conducted experimental verification, and corrected the suspension velocity of each particle according to the deviation of the test.

In this study, a vertical-blowing tea suspension model was established based on the CFD-DEM coupling simulation method. According to the experimental data, the simulation parameters were provided and the coupling model was verified under the same experimental conditions. Through simulation, the suspended state of tea was analyzed, the influence of air flow on tea was mastered, and the trajectory of tea particles affected by the air flow field at different distances from the initial surface under the same air intake volume with certain thicknesses was mastered. Based on these studies, the gas–solid two-phase coupling theory for tea suspension was formed. According to the coupling model, the moving distance of tea of different quality under different wind speeds was determined. This study provides a theoretical basis for the development of air-suction tea leaf sorting equipment for the later stage.

Materials and Methods

Test materials and equipment. The bench test of this study aimed to verify the coupling model, through which different suspension speeds of fresh tea leaves with different weights are calibrated. Therefore, to facilitate the test observations, large leaves of tea were selected as the research object (Fig. 1A). The average length of the leaves was 37 mm, and the average width was 13 mm. The weight of the test tea was measured by a scientific balance. A single tea leaf was weighed (Fig. 1B), and the weight range of the tea measured was between 0.102 and 0.215 g. A split-type anemometer (Fig. 1C) was used to measure the tea suspension velocity. The anemometer can record the maximum wind speed, minimum wind speed, and average wind speed over a period of time.

Coupled simulation mathematical model. The coupling simulation based on CFD-EDEM in this study mainly focused on gas–solid coupling. The gas phase is a continuous phase, and the law of motion follows the continuity equation and momentum equation in fluid mechanics. In the discrete element, the motion parameters of the particles can be solved according to Newton's second law of motion. In the negative pressure gas phase, the fresh tea leaves were subjected to the drag force of gravity and particle–air interaction. In this study, the secondary influence was ignored, and the drag force between the particle and the airflow field and the particle's own gravity were mainly considered.

The gas phase continuity governing equation is expressed as follows (Ebrahimi et al. 2014; Kruger et al. 2011; Vashisth and Grace 2012; Weng et al. 2022):

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right) + \nabla \cdot \left(\alpha_g \rho_g v_g\right) = 0 \quad [1]$$

The momentum equation is expressed as:

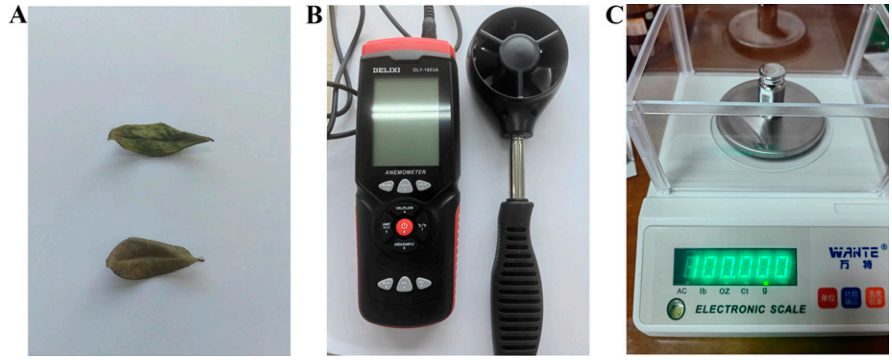

Fig. 1. Test materials and equipment.

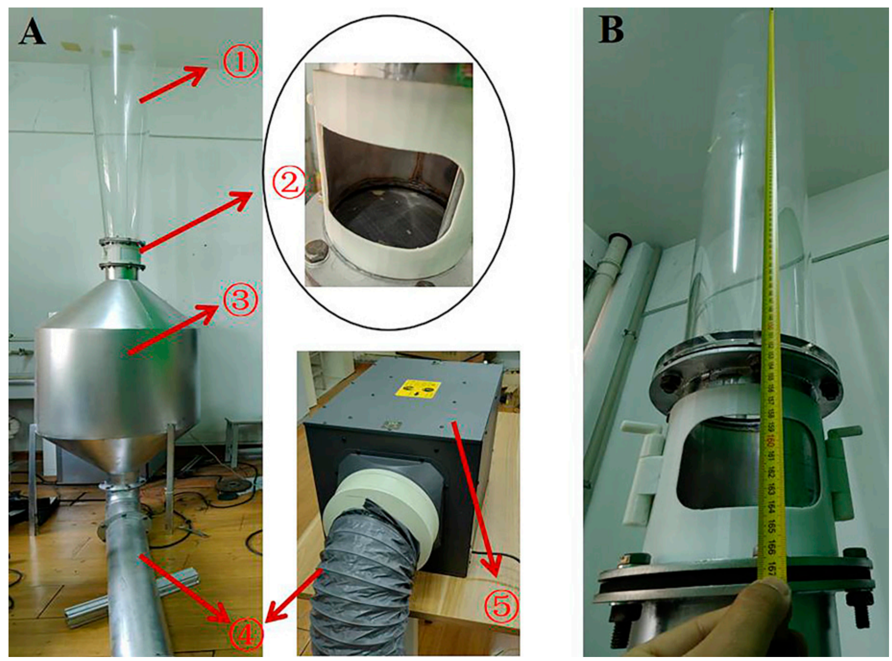

Fig. 2. Tea material suspension speed test bench.

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g v_g\right) + \nabla \cdot \left(\alpha_g \rho_g v_g \tau_g\right) = \underline{\alpha_g} \nabla \cdot P_g + \nabla \cdot \left(\alpha_g \rho_g\right) + \alpha_g \rho_g g - S \quad [2]$$

where α_g is the voidage ratio, ρ_g is fluid density, v_g is the velocity vector, P_g is the gas phase pressure, τ_g is the gas viscosity, g is acceleration of gravity, and S represents the momentum exchange between the gas and solid phases. During gas–solid coupling simulation (CFD-DEM), the momentum exchange of two phases is realized by drag force, and its expression is as follows:

$$S = \frac{1}{\Delta V}\sum_{i=1}^{n} f_{drag,i} \quad [3]$$

where ΔV is the volume of the control body and $f_{drag,i}$ is the drag force of fluid. Among them, the drag force is calculated by the following empirical formula:

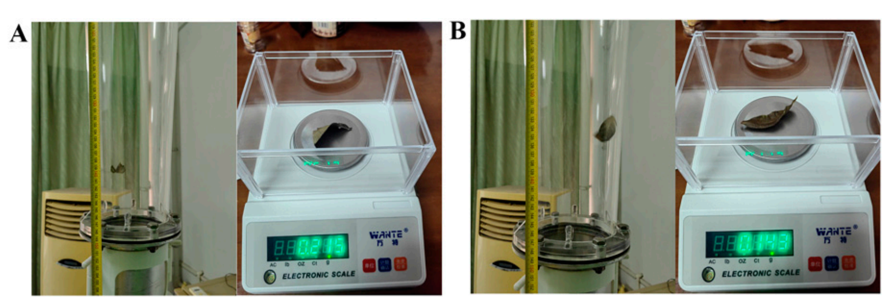

Fig. 3. Tea suspension test (relatively stable position).

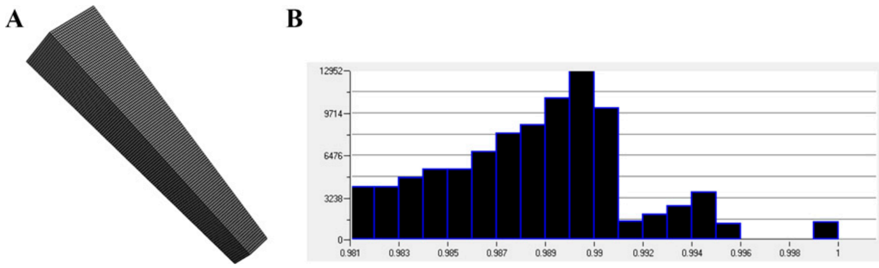

Fig. 4. Grid model of the observation tube and mass histogram of the grid element.

$$f_{drag,i} = 3.35 \times 10^{-5} \times \frac{\beta_i}{1-\alpha_i}(u_i - v_i) \quad [4]$$

where α_i represents the local voidage of discrete element particles, β_i is the local momentum exchange coefficient of discrete element particles, u_i is the virtual gas velocity at the center of the particle i, and v_i is the velocity of the particle.

According to the characteristics of the turbulence model and its applicable scope, the *Realizable k*-ε turbulence model is adopted in the calculation of the model. The transport equations of k and ε in the *Realizable k*-ε model are, respectively:

$$\frac{\partial(\rho\mu_j\varepsilon)}{\partial x_j} = \left(\mu + \frac{\mu t}{\sigma_\varepsilon}\right)\nabla^2\varepsilon + C_1 S\rho\varepsilon - C_2\frac{\rho\varepsilon^2}{k+\sqrt{v\varepsilon}} \quad [5]$$

where, μ is hydrodynamic viscosity, $C_1 = max\left[0.43, \frac{\gamma}{\gamma+5}\right]$, $C_2 = 1$, $\sigma_\varepsilon = 1.2$, and ∇ is a Laplace operator. The governing equation of fresh tea leaf particles at any time is as follows:

$$m_i\frac{dv_i}{dt} = m_i g + f_{drag,i} \quad [6]$$

$$I_i\frac{dw_i}{dt} = \sum_{j=1}^{k_i} T_{ij} \quad [7]$$

where, m_i, v_i, w_i, and I_i are the mass, velocity, angular velocity, and moment of inertia of the particle, k_i is the number of colliding particles, k_i is particle torque, $m_i g$ is particle gravity, and $f_{drag,i}$ is the drag force of fluid.

Tea suspension velocity test and coupling simulation result verification

Test bench construction. The tea suspension speed test bench (Fig. 2A) comprises the tea suspension observation tube (1), a tea outlet with a grid cross-section (2), steady flow tank (3), air duct (4), and frequency conversion fan (5). The tea leaves are placed in the tea outlet with a grid cross-section (2), and the wind speed is measured at that point by an anemometer when it is stable. The length of the mesh surface of the tea suspension observation tube 1 from the top to the tea outlet 2 is 1665 mm (Fig. 2B).

Tea suspension test. Before the test, the suspension of tea leaves in the air flow field was investigated using a pretest to adjust the wind speed suitable for tea suspension. If the wind speed is too high, then the tea will be ejected from the upper mouth of the observation tube; however, if the wind speed is too low, then the tea could not be suspended or would be suspended intermittently. During the pretest, because of the different weight of each tea, it was found that its suspension had large fluctuations and could not be sufficiently unified. Therefore, after the pretest, to overcome these problems, the suspension speed of a single tea was measured during the test. Because the wind speed has certain fluctuations, the point where tea leaves are suspended for a long time was selected as the simulation verification location (Fig. 3). Two tea leaves were selected for the suspension speed test and weighed. Figure 3A shows that the weight of tea was 0.215 g, and that its suspension height was 270 mm. Figure 3B shows that the weight of tea was 0.143 g, and that its suspension height was 325 mm.

Discrete element model setup. To simplify the simulation calculation, only CFD-DEM coupling simulation was performed for the observation tube. The model was divided into large and small end faces, and the small end face was a cuboid with a side length of 140 mm at the entrance of the measurement tube. The large end face of the model was cuboid, with a side length of 300 mm, and the length of the observation tube was 1400 mm. The particle parameters were set in EDEM software, and Poisson's ratio and density of tea particles were selected as 0.4 and 700 kg/m^3. According to the shear modulus of tea leaves measured (Zhang and Zhu 2023; Zhang et al. 2024) during the previous stage, the average shear modulus was 3.3 MPa, and the quality of a single tea was measured by a scientific research balance (Fig. 3). A particle factory was created 20 mm above the ground to generate tea particles. To simplify simulation time and improve efficiency, spherical particles were used instead. The Hertz-Mindlin (No Slip) model was selected for the discrete element model, which is accurate and efficient for force calculations. In this model, the normal force component is based on the Hertzian contact theory, whereas the tangential force model is based on Middlin-Deresiewicz's research theory. Both the normal force and tangential force have damping components. Tangential friction obeys Coulomb's law of friction, and rolling friction independently directs the constant torque model through contact.

Finite element meshing. In the finite element model, CFD-IDEM was used to divide the grid. In this study, the observation tube was divided into tetrahedral structured grids, with a total of 253,488 grids (Fig. 4A). The grid quality was good, and the minimum cell mass was 0.981.

Finite element simulation of boundary conditions. During the numerical simulation, the influence caused by heat exchange was ignored, that is, the energy equation was not considered. The flow field belonged to turbulent flow, the working medium was air, there was no phase change, and there was no chemical reaction in the calculation process. A separate implicit solver based on pressure was used to solve the numerical simulation. To improve the calculation accuracy and reduce the numerical diffusion, the momentum, turbulent kinetic energy, and turbulent dissipation rate were adopted in the second order upwind discrete scheme. The pressure–velocity coupled SIMPLEC algorithm was selected. The working

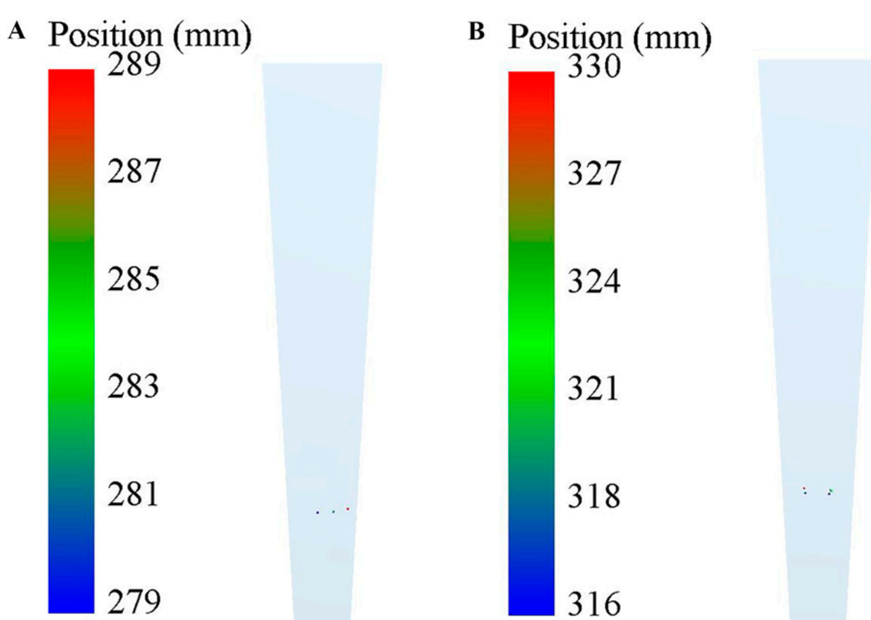

Fig. 5. Suspension position of particles.

environment was set to the standard atmosphere. The model velocity inlet wind speed was measured by the anemometer, and its average value was taken. Air flowed out of the fluid domain at a constant speed, with the small end face as the inlet and the large end face as the outlet.

Coupling model verification. According to the test, the wind speed measured by the anemometer at the entrance of the observation tube (average value, 6 m/s) and the tea quality measured by the balance (Fig. 3) were simulated (Fig. 5). The position where the tea particles remained in stable condition when the mass of fresh tea leaves was set at 0.215 g was observed (Fig. 5A), and the distance between the particles and the small end entrance was 279 to 289 mm. When the particles were relatively stable, the suspension height of tea leaves was 270 mm, and the simulated value was greater than the measured value, with a minimum error of 9 mm and error rate of 3.33%. The maximum error was 19 mm and the error rate was 7.03%. The position where tea particles remained in stable condition when the mass of fresh tea leaves was set at 0.143 g was observed (Fig. 5B), and the distance between the particles and the entrance of the small end face was 316 to 330 mm. When the particles were relatively stable, the suspended height of tea leaves was 325 mm, and the measured value was between the simulated value, with a minimum error of 5 mm and error rate of 1.54%. The maximum error was 9 mm and the error rate was 3.33%. In conclusion, the established CFD-DEM coupled tea particle suspension model had high accuracy. Therefore, this model can be used to simulate and analyze the suspended height of tea under different initial wind speeds.

Coupling simulation analysis of fresh tea suspension under fixed wind speeds

Through the verification of the simulation results of the coupling model established by the aforementioned work, it was shown that the CFD-DEM coupling model established during this study had high accuracy and was more consistent with the actual test effect. Therefore, the coupling simulation analysis can be performed according to the changes in the initial conditions, such as the differences in the initial wind speed and tea quality.

Analysis of particle maximum motion position. Using the coupling model established during this study, the motion position of 400 tea particles in the observation tube at each simulated time was analyzed under a given wind speed of 9 m/s. As shown in Fig. 6, when the simulation time was 0 to 1.8 s, and the interval time was 0.09 s, at 0.09 s, the tea particles began to move upward, layer by layer, under the influence of wind power, and the maximum displacement of the tea particles in the top layer was 86 mm from the wind speed inlet. At 0.18 s, the maximum displacement of the top layer of tea particles was 230 mm, which was an increase of 144 mm compared with the previous time period. At 0.27 s, the maximum displacement of the top layer of tea particles was 358 mm, which was an increase of 144 mm compared with the previous time period. At 0.36 s, the maximum displacement of tea particles in the top layer was 468 mm, which was 110 mm higher than that of the previous period. At 0.45 s, the maximum displacement of the top layer of tea particles is 544 mm, which was an increase of 76 mm compared with the previous time period. At 0.54 s, the maximum displacement of the top layer of tea particles was 544 mm, which was an increase of 76 mm compared with the previous time period. At 0.63 s, the maximum displacement of the top layer of tea particles was 601 mm, which was

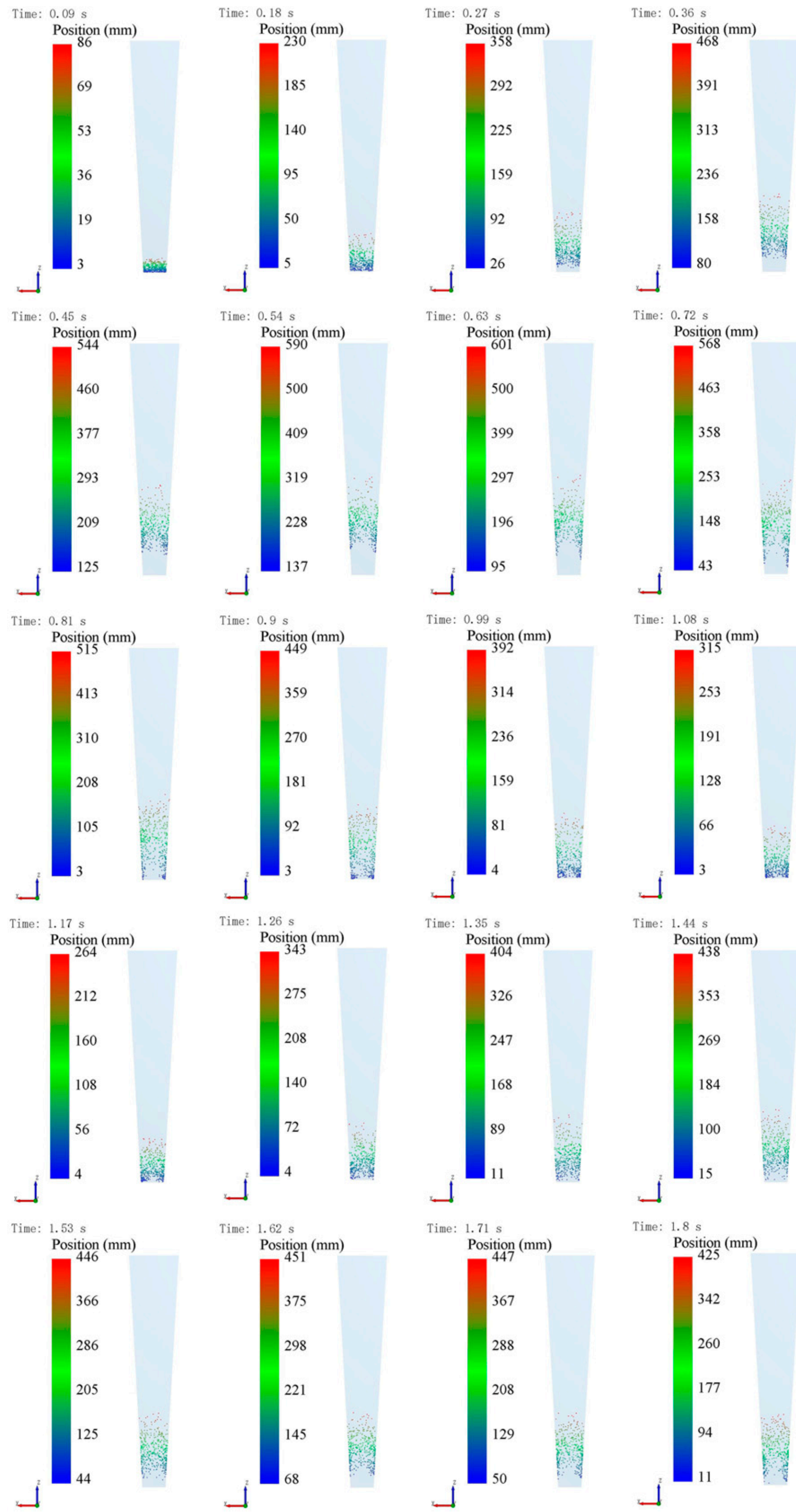

Fig. 6. State of suspended movement of tea particles at different times from 0 to 1.8 s.

an increase of 57 mm compared with the previous time period, and the tea particles were in the farthest ascending position at the selected time. At 0.72 s, the maximum displacement of tea particles in the top layer was 568 mm, which was a decrease of 33 mm compared with that during the previous period, indicating that from this moment on, tea particles began to fall under the action of air flow. At 0.81 s, the maximum displacement of the top layer of tea particles was 515 mm, which was a decrease of 53 mm compared with that during the previous time period. At 0.9 s, the maximum displacement of the top layer of tea particles was 449 mm, which was a decrease of 66 mm compared with that during the previous period. At 0.99 s, the maximum displacement of the top layer of tea particles was 392 mm, which was a decrease of 57 mm compared with that during the previous period. At 1.08 s, the maximum displacement of the top layer of tea particles was 315 mm, which was a decrease of 77 mm compared with that during the previous period. At 1.17 s, the maximum displacement of the top layer of tea particles was 264 mm, which was a decrease of 51 mm compared with that during the previous time period. At 1.26 s, the maximum displacement of tea particles in the top layer was 343 mm, which was an increase of 79 mm compared with that during the previous period, indicating that tea particles begin to rise under the action of air flow from this moment on. At 1.35 s, the maximum displacement of the top layer of tea particles was 404 mm, which was an increase of 61 mm compared with that during the previous period. At 1.44 s, the maximum displacement of the top layer of tea particles was 438 mm, which was an increase of 34 mm compared with that during the previous period. At 1.53 s, the maximum displacement of the top layer of tea particles was 446 mm, which was an increase of 8 mm compared with that during the previous period. At 1.62 s, the maximum displacement of the top layer of tea particles was 451 mm, which was an increase of 5 mm compared with that during the previous period. At 1.71 s, the maximum displacement of tea particles in the top layer was 447 mm, which was a decrease of 4 mm compared with that during the previous period. At 1.53 to 1.71 s, tea particles were in a relatively balanced state under the air flow field in the observation tube, and the fluctuation was small. At 1.8 s, the maximum displacement of the top layer of tea particles was 425 mm, which was a decrease of 22 mm compared with that during the previous period.

In summary, the suspended state of tea particles at each simulated time showed that tea particles are affected by the air flow field of the observed pipe, and tea particles fluctuate, similar to the phenomenon in the experiment because of the constant change in the pipe diameter, resulting in the air velocity decreasing with the increase in the position and tea particles falling under the action of gravity. Some rising tea particles will cause some other tea particles to fall when they interfere with the airflow field. During the simulation at various times, it was found that tea particles attached to the inside of the wall of the observation tube under the action of air flow, especially within 0.54 to 0.81 s, mainly because when the air flow passed through the observation tube, the air flow rate gradually decreased from the center of the pipe to the wall. The surface of discrete element particles produced pressure differences, and the air flow pushed the particles to rise (Fig. 7). When the air flow velocity near the pipe wall is less than the suspension velocity of tea particles, the particles tend to fall under the action of gravity and slide down the inclined wall of the observation tube. This phenomenon is similar to that observed by Wen et al. (2020).

Relationship between tea particles at different positions and simulation time during suspension. To simulate the relationship between different suspension positions of a certain number of tea particles under the observation tube and the simulation time, the different heights of tea particles from the initial position were taken as the Y-axis and the simulation time was taken as the X-axis. The particles at different positions were now defined. According to the cloud images under different simulation times (Fig. 6), there are six distance values under each set of cloud images. On the cloud image, the maximum distance value to the minimum distance value were defined as follows: tea particle location A, tea particle location B, tea particle location C, tea particle location D, tea particle location E, and tea particle location F. Figure 8 shows the variation trend of different distances from the initial position and the simulated time during the suspension of particles. According to the variation trend of positions at different times, the tea particles moved first under the influence of air flow, and the movement distance

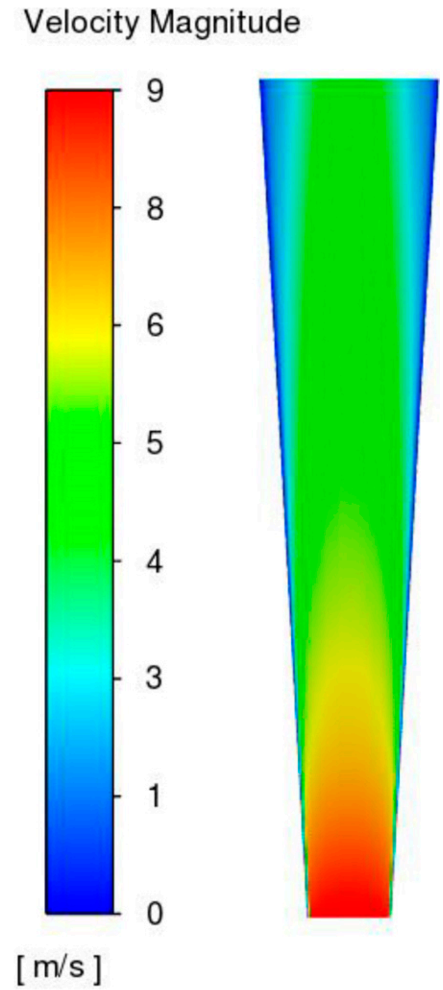

Fig. 7. Velocity cloud image of the air flow field inside the observation tube.

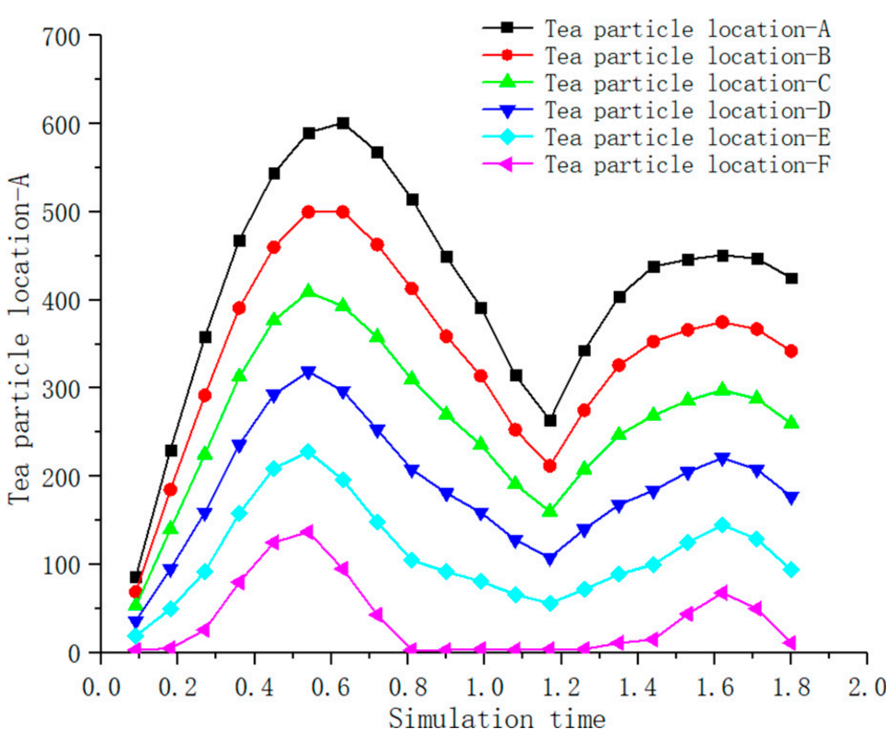

Fig. 8. Variation trend of different distances from the initial position and simulation time during particle suspension.

of the upper particles was greater than that of the lower particles during the whole period under a certain wind speed. In the simulation time, the particles are affected by the air flow field, and the movement of particles is in the form of wave peak. Among them, tea particle location A and tea particle location B reach the peak at 0.6 s. Tea particle location C, tea particle location D, tea particle location E, and tea particle location F reach the peak at 0.5 s. When approaching 1.2 s, the tea particles in each group appeared as waves, indicating that the suspension of tea particles in the observation tube was affected by the air flow length, and the phenomenon of instability appeared. During the simulation time of 1.2 to 1.8 s, the movement of particles in each layer was relatively stable, especially during the period of 1.4 to 1.7 s, and the change range was smaller than that during 0 to 1.2 s, mainly because there were more tea particles in the observation tube, which had a certain obstruction effect on the upward air flow field.

The suspended particle function model was established. According to the variation trend of different distances from the initial position of particles in the suspension process and the simulation time (Fig. 8), it was found that tea particle location A, tea particle location B, tea particle location C, tea particle location D, tea particle location E, and tea particle location F had certain motion rules at the first wave peak, that is, the simulation time of 0 to 1.2 s. Its motion law can be described by nonlinear curve fitting (Fig. 9). The curve fit degree of tea particle location A was 0.9981. The curve fit degree of tea particle location B was 0.9969. The curve fit degree of tea particle location C was 0.9932. The curve fit degree of tea particle location D was 0.9860. The curve fit degree of tea particle location E was 0.9791. The curve fit degree of tea particle location F was 0.9455. The fitting equation is as follows:

$$\text{double } z = \frac{(x - x_c)}{w} \qquad [8]$$

$$y = y_0 + A \times e^{e^{(-z)} - z + 1} \qquad [9]$$

where, y_0, x_c, w, and A are fitting parameters. The parameter values are shown in Fig. 9.

In conclusion, the variation trend of different distances from the initial position and simulation time in the suspension process of

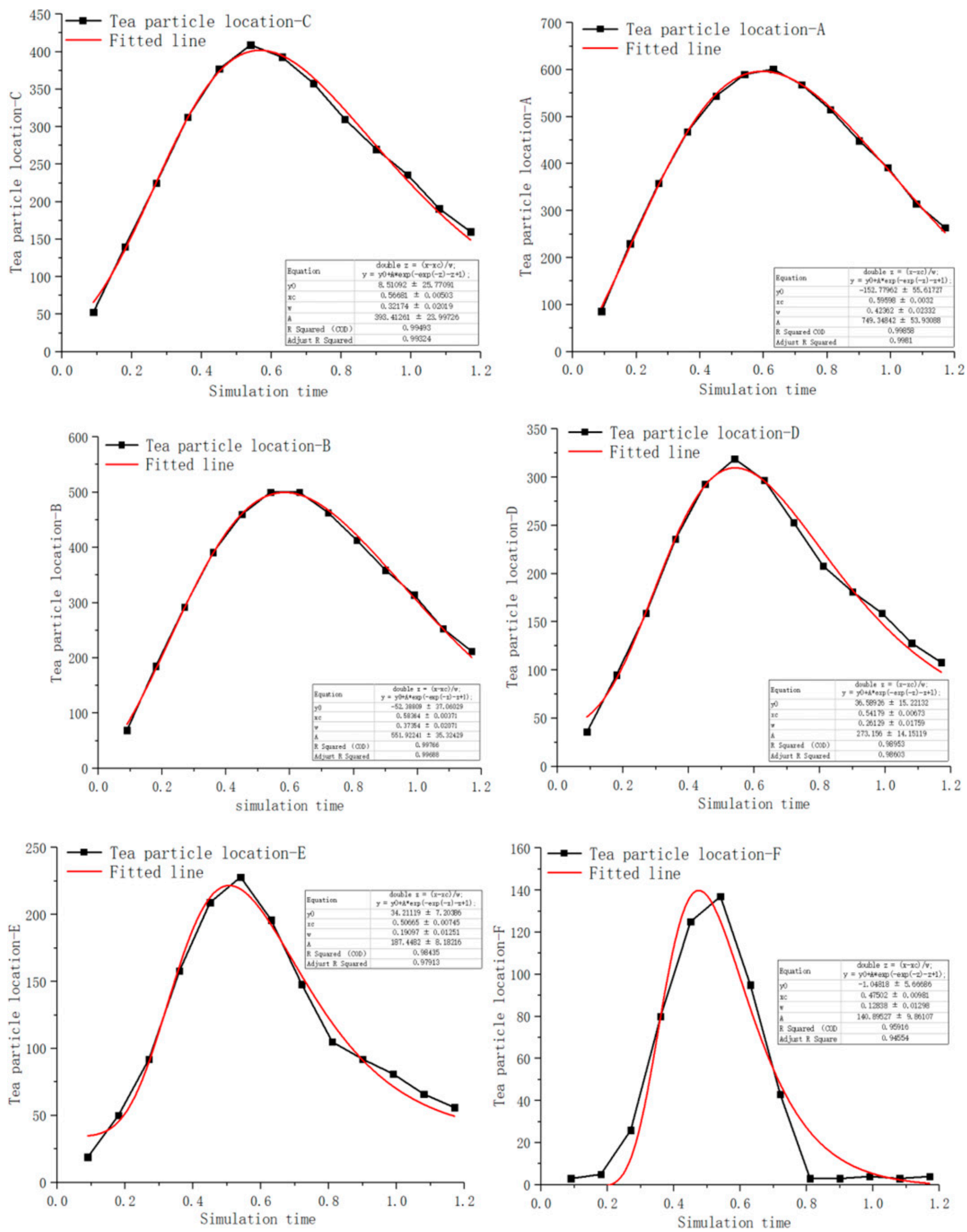

Fig. 9. Function fitting of different distances from the initial position and simulation time during particle suspension.

particles meets the extreme function of the peak functions. The function reflects the motion form of suspended particles in the air flow.

Conclusion

The CFD-DEM coupling model of tea particle suspension was established, and this model was tested and verified. Under the same wind speed, by optimizing the parameters of the coupling model, for tea particles of different quality, when the mass of the test tea particles was 0.215, the test value was at the simulated value with a minimum error of 9 mm, with an error rate of 3.33%, and maximum error of 19 mm, with an error rate of 7.03%. When the test tea particle mass was 0.145, the minimum error of the test value was 5 mm, with an error rate of 1.54%, and the maximum error was 9 mm, with an error rate of 3.33%. In summary, the established model is accurate, and the results of the coupling model can be analyzed. The tea particles are affected by the air flow field of the observation tube, and the tea particles fluctuate. During the suspension of tea particles, the tea particles are attached to the inner wall of the observation tube under the action of the air flow field. Through an in-depth study, it was found that the relationship between different distances from the initial position of particles and simulation time in the suspension process is a peak function. The extreme function is used to fit the actual trajectory, and the fitting degree is better. Among them, the fitting degree of the particles closest to the initial position was 0.9455, and the fitting degree of the particles farthest from the initial position was 0.9981.

References Cited

Dai Y-Z, Luo X-W, Wang Z-M, Zeng S, Zang Y, Yang W-W, Zhang Y-H, Wang B-L, Xing H. 2016. Design and experiment of pneumatic cluster type rice seed separator. Nongye Gongcheng Xuebao. 32(24):36–42.

Dong S, Yuan C-J, Gu C, Yang F. 2017. Research review of intelligent agricultural machinery control platform based on multidisciplinary technology integration. Nongye Gongcheng Xuebao. 33(8):1–11. https://doi.org/10.11975/j.issn.1002-6819.2017.08.001.

Ebrahimi M, Crapper M, Ooi J-Y. 2014. Experimental and simulation studies of dilute horizontal pneumatic conveying. Particul Sci Technol. 32(2):206–213. https://doi.org/10.1080/02726351.2013.851133.

Hou H-M, Cui Q-L, Guo Y-M, Zhang Y-Q, Zhang D, Lai S-T, Liu J-L. 2018. Design and experiment of Air-blown suspension speed measuring device for grain and oil crop extraction. Nongye Gongcheng Xuebao. 34(16):43–49. https://doi.org/10.11975/j.issn.1002-6819.2018.16.006.

Huang Z-Y, Li T, Yu Z-C, Zhu C-G, Zhao C-Y. 2016. Simulation and experiment of gas-solid two-phase flow in separation chamber of vegetable seed wind sifter. Nongye Jixie Xuebao. 47(5):70–76. https://doi.org/10.6041/j.issn.1000-1298.2016.05.010.

Iqbal N, Rauh C. 2016. Coupling of discrete element model (dem) with computational fluid mechanics (cfd): A validation study. Appl Math Comput. 277:154–163. https://doi.org/10.1016/j.amc.2015.12.037.

Kruger T, Varnik F, Raabe D. 2011. Efficient and accurate simulations of deformable particles immersed in a fluid using acombined immersed boundary lattice Boltzmann finite element method. Comput Math Appl. 61(12):3458–3505. https://doi.org/10.1016/j.camwa.2010.03.057.

Lei X-L, Liao Y-T, Zhang W-Y, Li S-S, Wang D, Liao Q-X. 2017. Simulation and experiment of gas-solid two-phase flow in pipeline of oil wheat and gas feed collector. Nongye Jixie Xuebao. 48(3):57–68. https://doi.org/10.6041/j.issn.1000-1298.2017.03.007.

Liu P, He J, Zhang Z-Q, Lu C-Y, Zhang Z-G, Lin H. 2020. Analysis and test of straw breaking motion characteristics of straw returning machine based on CFD-DEM. Nongye Jixie Xuebao. 51(Supp.1):244–253. https://doi.org/10.6041/j.issn.1000-1298.2020.S1.028.

Qi X-Y, Zhou Z-Y, Yang C, Luo X-W, Gu X-Y, Zang Y, Liu W-L. 2016. Design and experiment of key parts of pneumatic variable-rate fertilizer applicator for rice product. Nongye Gongcheng Xuebao. 32(6):20–26. https://doi.org/10.11975/j.issn.1002-6819.2016.06.003.

Qian F, Huang N, Lu J, Han Y. 2014. CFD–DEM simulation of the filtration performance for fibrous media based on the mimic structure. Comput Chem Eng. 71:478–488. https://doi.org/10.1016/j.compchemeng.2014.09.018.

Ren G-X, Fan Q-Y, He X, He X-J, Li W-C, Wang J, Tang X-L. 2013. Development and experiment of raw material sorting machine for bulk tea leaves. Science and Technology of Food Industry. 34(7):290–292, 304.

Sun L-L, Yan Y-B, Tang H-H. 2016. Study on main parameters of tea fresh leaf classifier. Agriculture and Technology 36(1):38–39, 43. https://doi.org/10.11974/nyyjs.20160132013.

Vashisth S, Grace J-R. 2012. Simulation of granular transport of geldart type-A, -B, and -D particles through a 90° elbow. American Chemical Society. 2012(4). https://doi.org/10.1021/ie200647e.

Wang L-J, Li Y, Liang C, Ma J-C, Zhou X-W. 2015. Motion law of maize mixture in cross air-and-screen cleaning device. Nongye Gongcheng Xuebao. 46(9):122–127. https://doi.org/10.6041/j.issn.1000-1298.2015.09.018.

Wang W, Wang Y-N, Tian Z-H, Wang P. 2016. Design and experimental study of material suspension velocity test bench. Chinese Journal of Agricultural Mechanization. 37(6):44–46. https://doi.org/10.13733/j.jcam.issn.2095-5553.2016.06.11.

Wen X-Y, Jia L-H, Zhang S-W, Yuan H-F, Wang G, Chen T-Y. 2020. Test of particle fertilizer suspension velocity based on EDEM-Fluent coupling. Journal of Agricultural Machinery. 51(3):9. https://doi.org/10.6041/j.issn.1000-1298.2020.03.008.

Weng X-X, Chen C-Q, Wang G, Wei Z-B, Jiang L, Hu X-R. 2022. Study on numerical simulation of collecting process of fresh leaf pipe by machine based on CFD-DEM. Nongye Jixie Xuebao. 53(11):424–432. https://doi.org/10.6041/j.issn.1000-1298.2022.11.044.

Xie J, Zhang X-Q, Wang C-J. 2012. Tea sieving experiment based on three-translation parallel mechanism. Nongye Jixie Xuebao. 43(10):101–104. https://doi.org/10.6041/j.issn.1000-1298.2012.10.018.

Xing H, Zhang Y, Wang Z-M, Luo X-W, Pei J, He S-Y, Xu P. 2019. Design and parameter optimization of rice pneumatic seeding metering device with adjustable seeding rate. Nongye Gongcheng Xuebao. 35(4):20–28. https://doi.org/10.11975/j.issn.1002-6819.2019.04.003.

Yang S, Luo K, Ke Z, Qiu K, Fan J. 2015. Numerical study of a lab-scale double slot-rectangular spouted bed with the parallel CFD-DEM coupling approach. Powder Technology. 272:85–99. https://doi.org/10.1016/j.powtec.2014.11.035.

Yang Y-J, Chen L-H, Fu H-P, Li W, Liu H-Y, Liu W-Y, Bao X-C. 2013. Development of a fresh leaf classifier for tea. Hunan Agricultural Machinery. 40(5):106–108, 110. https://doi.org/10.3969/j.issn.1007-8320.2013.05.060.

Yu X-R, Geng R-Y, Du R-C, Jin C-Q, Yang S-D, Lu X-F. 2018. Design and experiment of Pneumatic Conveying Wheat no-tillage fertilization seeder. Nongye Jixie Xuebao. 49(Supplement):141–148.

Zhang L-L, Dong J-F, Tang M, Cai W-Z, Wen Z-J, Luo Y-P. 2011. Study on the technique of picking and classifying fresh leaves from famous tea machine. Journal of Zhejiang University. 35(5):593–598. https://doi.org/10.3785/j.issn.1008-9209.2011.12.212.

Zhang X, Yang T, Qiao X, Zhong J, Ou C-J, Wang S-F, Zhao Z-F. 2013. Analysis of influence of airflow field on drift trajectory and quality of tea. Tea Science. 33(1):60-66. https://doi.org/CNKI:SUN:CYKK.0.2013-01-014.

Zhang X, Zhu X-Y. 2023. Simulation and experiment on the falling pattern of fresh tea leaves based on discrete elements. HortScience. 58(9):1057–1067. https://doi.org/10.21273/HORTSCI17300-23.

Zhang X, Zhu X-Y, Wang R-Y. 2024. Simulation and identification of multiscale falling morphology of fresh tea leaves at different transport speeds based on discrete element method. HortScience. 59(2):167–172. https://doi.org/10.21273/HORTSCI17548-23.

Zhang X-H, Wang Y-X, Gong L, Gu C-J, Fan G-J. 2018. Design and experiment of seed distribution system of wheat pneumatic collector. Nongye Jixie Xuebao. 49(3):59–67.