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DESIGN AND TESTING OF THE SEED CONVEYING SYSTEM FOR EDIBLE SUNFLOWER COMBINE HARVESTER

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Based on the overall structural layout of the 4KHZ-330 *edible sunflower combine harvester, a combined screw-pneumatic seed conveying system was designed to minimize contact and impact between seeds and rigid components, thereby reducing seed damage during conveying on the premise of ensuring efficient and stable transport. The motion characteristics of seeds within the conveying pipeline were analyzed, and the main factors affecting particle velocity were identified. The rationality of the system was verified through CFD-EDEM coupled numerical simulation of the gas-solid two-phase flow. The simulation results show that the maximum seed velocity in the pipeline is* 8 m/s*, and the maximum force on seeds is* 20.5 N*, which is smaller the damage threshold force for sunflower seeds. A field test indicated that the operation of the harvester is stably with smooth seed conveying and no clogging. Under various tested conditions, the maximum production rate is* 0.87 ha/h*, and the maximum seed damage rate is* 1.71%*. All performance metrics meet the required standards. It provides technical support for the improvement and optimization of conveying systems in the mechanized harvesting of the edible sunflowers.*

Keywords: Edible sunflower, Combine harvester, Screw conveying, Pneumatic conveying, CFD-EDEM

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1 Introduction

Sunflower, as a characteristic economic crop, is mainly used for oil and food purposes. In 2023, the sunflower planting area in China is 7.26×10^5 ha, with edible sunflower consumption accounting for approximately 70% of the total [1]. As a major producer of edible sunflower, China has a market value of nearly 50 billion yuan in its seed-to-commodity industry chain. The export volume of Chinese edible sunflower products has been increasing annually, indicating that its edible sunflower industry is already at the forefront globally [2].

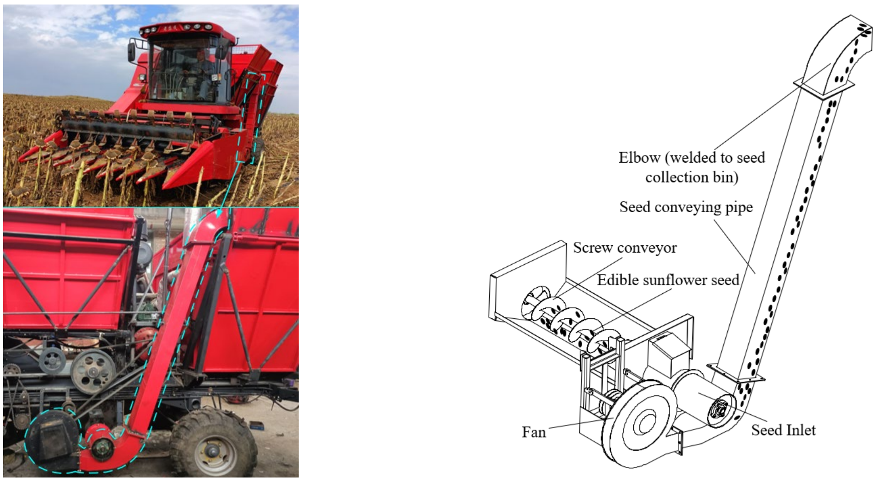
Harvesting is a critical stage in the edible sunflower production process. Mature edible sunflower seeds, with a moisture content ranging from 15% to 25%, are highly susceptible to mechanical damage during harvest. Currently, segmented harvesting remains the primary method for edible sunflowers in China [3, 4]. To enhance the level of mechanized harvesting and promote the sustainable development of the industry, we developed the 4KHZ-330 combine harvester for edible sunflower. This machine integrates multiple functions including cutting, threshing, cleaning, conveying, seed collection, and sunflower capitulum collection. A key advantage of this harvester is its use of screw-pneumatic conveying for seed transport, which significantly reduces seed damage rates [5].

Seed transportation is a crucial component of the combine harvesting process, as it enables the efficient, rapid, and low-damage transfer of cleaned seeds to the collection bin [6]. Screw conveyors are widely used in agricultural machinery material-conveying systems due to their simple structure, high conveying efficiency, and low susceptibility to blockage [7-8]. Pneumatic conveying is a technology that uses air as a carrier medium to transport materials through a pipeline. In recent years, with the advancement of agricultural mechanization, this technology has been widely applied in agricultural material conveying [9]. For example, Wu et al. [10] designed a screw-pneumatic combined system for conveying crushed corn straw and analyzed the key factors affecting its performance. Liu et al. [11] investigated the kinematic and dynamic characteristics of sunflower seeds during pneumatic conveying and clarified the influence of structural parameters on conveying performance. Zhang [12] designed a pneumatic conveying system for a wheat combine harvester and employed the fluid-structure interaction method to investigate its conveying characteristics. Song et al. [13] used the CFD-DEM method to study the flow field characteristics in axial-flow and swirl pneumatic conveying systems for wheat. To improve seed conveying performance in combine harvesters, Lee et al. [14] analyzed the motion characteristics of seeds from different crops at varying moisture contents. Liu et al. [15] applied computer simulation to analyze the flow characteristics in the material-conveying system of a self-propelled silage harvester. Yang and Zhang [16] explored the influence of the structural and operational parameters of pneumatic conveying systems on seed crushing. Zhao [17] constructed a discrete element model of corn kernels. To address the fragile nature of peanut pods, Wei et al. [18] optimized the pneumatic conveying system by determining the optimal combination of key parameters through orthogonal experiment. In summary, most existing seed conveying systems for wheat and maize combine harvesters employ either augers or pneumatic systems. However, research on seed conveying systems specifically designed for edible sunflower combine harvesters is rarely reported. Given the high susceptibility of mature edible sunflower seeds to mechanical damage, the 4KHZ-330 edible sunflower combine harvester adopts a combined screw-pneumatic seed conveying system.

Based on the physical and mechanical properties of edible sunflower seeds and the overall structural layout of the combine harvester, this study determined the key structural and operational parameters of the seed conveying system. By analyzing the motion characteristics of seeds in the pneumatic conveying pipeline, the factors influencing seed velocity were identified. Using CFD-EDEM gas-solid two-phase flow numerical simulation, the dynamic motion characteristics of seeds within the pipeline were investigated. Finally, a field test is conducted to validate the performance of the seed conveying system's design and parameters.

2 Overall structure and working principle of the edible sunflower seed conveying system

The 4KHZ-330 combine harvester for edible sunflower employs a combined screw-pneumatic seed conveying system, primarily consisting of an screw conveyor, a fan, and conveying pipelines. Based on functional requirements, the conveying pipeline is divided into three sections: upper, middle, and lower. The lower section is connected to both the fan and the screw conveyor, while the upper section is fixed to the seed collection bin. To reduce air leakage during conveyance, a soft fiber gasket is added between the upper and middle sections of the pipeline. The specific structure is illustrated in Fig. 1. During operation, edible sunflower seeds fall from the cleaning sieve into the screw conveyor and are then pushed into the pneumatic conveying pipeline. Under the action of a stable, high-speed airflow generated by the fan, the seeds are smoothly conveyed through the delivery pipeline to the seed collection bin.



(a) Structure Diagram of the Seed Conveying System (b) Working Principle of the Seed Conveying System

Fig.1 Overall Structure and Working Principle of the Sunflower Seed Conveying System

3 Structural design of key components and analysis of pneumatic conveying parameters

3.1 Structural Parameter Design of the Screw Conveyor

The screw conveyor is a key component of the seed conveying system. Its function is to convey the cleaned seeds to the feed inlet of the pneumatic conveying pipeline, directly influencing the overall layout and conveying efficiency of the pneumatic system. Based on existing designs for combine harvesters and practical experience, the outer diameter of the screw blade is set at 200 mm. Given a constant outer diameter and rotational speed, the material conveying velocity is related to the screw pitch and is proportional to the helix angle. With reference to established design practices and relevant theories for screw conveyors [19], the key structural parameters of the screw blade can be determined using the following formula.

$$S_a = (0.5 \sim 2.2) D_a \tag{1}$$

$$d_a = (0.2 \sim 0.35) D_a \tag{2}$$

$$\alpha_a \leq 90° \text{-} \varphi_a \tag{3}$$

In the equations, S_a is the pitch, D_a is the screw outer diameter, d_a is the screw shaft diameter, α_a is the helix angle at the inner diameter of the screw blade, and φ_a is the material friction angle (which, for edible sunflower seeds against a steel plate, ranges from 25° to 30° based on experimental measurements [3]).

Through calculations using equations (2) and (3), the following parameters were determined: screw outer diameter (D_a) of 200 mm, screw pitch (S_a) of 160 mm, screw shaft diameter (d_a) of 45 mm, and helix angle at the inner diameter of the screw blade (α_a) of 48.5°. The conveying capacity (Q_a) of the screw conveyor was obtained from equation (4).

$$Q_a = \frac{\pi}{24}[(D_a - 2\delta_a)^2 - d_a{}^2]\psi_a S_a n_a \gamma_a k_a \times 10^{-10} \tag{4}$$

In the equation, δ_a is the gap between the screw blade and the casing, ψ_a is the filling coefficient of the conveyed material, with a typical range of 0.2 to 0.4, n_a is the rotational speed of the inclined screw conveyor, γ_a is the material density, and k_a is the incline efficiency factor, taken as 1.

The density (γ_a) of the edible sunflower seeds tested was 210.4 kg/m³. As per the agricultural machinery design handbook [20], for this analysis, the gap (δ_a) between the helical blades and the housing was set to 10 mm, and the material filling coefficient (ψ_a) was taken as 0.2. Substituting these values into equation (4) shows that when the rotational speed of the screw conveyor (n_a) is$\geq$240 r/min, the conveying capacity (Q_a) reaches$\geq$0.6 kg/s. This output meets the operational requirement of the edible sunflower combine harvester.

3.2 Determination of Key Parameters for Pneumatic Conveying

3.2.1 Pneumatic Conveying Air Velocity

The air velocity required for pneumatic conveying depends on factors including the specific gravity of the material, its suspension velocity, and the pipe geometry. For materials with uniform particle size (such as seeds), the conveying air velocity is typically set at 1.5-2.5 times the material′s suspension velocity [21, 22], calculated using equation (5) to ensure reliable and stable conveyance.

$$v_{ac} = k_c v_c \tag{5}$$

In the equation, v_{ac} is the conveying air velocity, k_{ac} is the conveying air velocity coefficient, and v_c is the suspension velocity of the conveyed material, edible sunflower seeds range from 7.75 to 9.45 m/s. Due to the influence of external factors under actual operating conditions, the design air velocity is typically set 20%-35% higher than the theoretical value [23, 24]. Therefore, in this study, the pneumatic conveying air velocity (v_{ac}) is set to 32 m/s[5].

3.2.2 Solids Loading Ratio

Assuming the combine harvester operates at a constant forward speed with full-width coverage, the seed mass within the conveying pipeline is directly related to the working capacity of the screw conveyor. The solids loading ratio (μ_s), defined as the mass of seeds conveyed per unit time divided by the mass of air used, is given by equation (6). To prevent pipeline blockage by edible sunflower seeds, the value of μ_s must not exceed a certain threshold.

$$\mu_s = \frac{G_s}{G_g} \tag{6}$$

In the equation, μ_s is the solids loading ratio, *Gs* is the mass flow rate of the conveyed material through the pipeline, and G_g is the mass flow rate of air through the pipeline.

The solids loading ratio (μ_s) is typically determined from experiments and empirical data. In this study, where μ_s is determined experimentally and empirically, a value of 0.7 is adopted for the solids loading ratio of edible sunflower seeds [5].

3.2.3 Air Flow Rate

The required conveying air flow rate depends on both the target material throughput (harvester productivity) and the designed solids loading ratio (μ_s). It is determined by equation (7).

$$Q = \frac{Q_s}{\mu_s \rho_a} \tag{7}$$

In the equation, Q is the required air flow rate, Q_s is the combine harvester′s material throughput or productivity, and ρ_a is the air density, taken as 1.29 kg/m³.

Based on the maximum working efficiency of the 4KHZ-330 edible sunflower combine harvester and the yield per unit area, the required material throughput (Q_s) is estimated as 2250 kg/h. Substituting all parameters into equation (7) yields a required air flow rate (Q) of 2492 m³/h. Given the inclined pipeline and high flow rate, a high-pressure centrifugal fan was selected. Preliminary tests indicated that a fan speed of 3000 r/min is both safe and economical, achieving the target pneumatic conveying air velocity of 32 m/s.

3.3 Structural Design and Analysis of the Conveying Pipeline

The cross-sectional area of the pneumatic conveying pipeline directly affects both energy consumption and conveying smoothness. Its equivalent diameter (D_s) is calculated using equation (8).

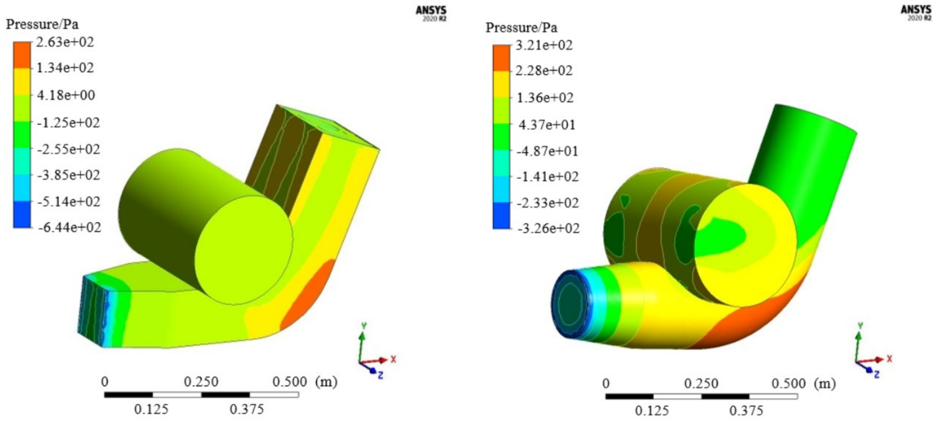
$$D_s = \sqrt{\frac{4Q}{3600\pi N v_{ac}}} \tag{8}$$

In the equation, D_s is the equivalent diameter of the conveying pipeline, and N is the number of conveying pipelines.

Substituting the air flow rate (Q) and the conveying air velocity (v_{ac}) into equation (8), the equivalent diameter of the conveying pipeline is calculated to be 166 mm.

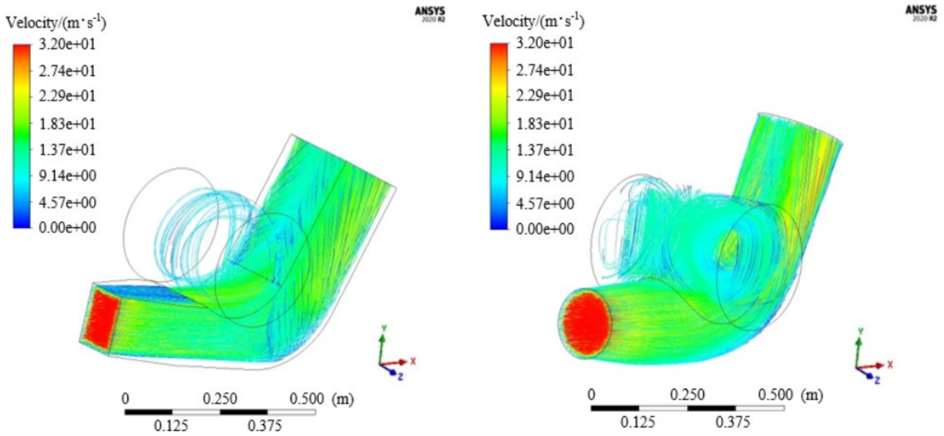
The pneumatic conveying pipeline comprises three segments: upper, middle, and lower. The lower segment, which interfaces directly with both the screw conveyor and the fan outlet, is critical to the system′s overall performance. Consequently, its design must ensure smooth material flow, stable airflow, and minimal pressure loss. Numerical simulations of the airflow field were performed using ANSYS FLUENT for both circular and rectangular pipeline geometries.

The airflow field simulation employed the standard k-ε turbulence model in ANSYS FLUENT. The inlet boundary condition was set to a velocity of 32 m/s, with a turbulence intensity of 3.5% and a hydraulic diameter of 110 mm. The outlet was defined as a pressure outlet with the same turbulence intensity (3.5%) but a larger hydraulic diameter of 166 mm. The pressure contour (Fig. 2) reveals that the circular pipeline exhibits higher pressure and greater pressure loss at its bottom section. In contrast, the rectangular pipeline demonstrates lower bottom pressure, reduced pressure loss, and consequently, better conveying performance. Similarly, the velocity contour (Fig. 3) shows a more stable airflow distribution in the rectangular pipeline. The circular pipeline, however, contains large vortices, leading to poor flow uniformity, which is detrimental to the smooth conveyance of seeds.



a. Rectangular Pipe b. Circular Pipe

Fig. 2 Pressure contour in the downward conveying pipeline



a. Rectangular Pipe b. Circular Pipe

Fig. 3 Velocity contour in the downward conveying pipeline

In summary, the simulation results for the lower pneumatic conveying segment demonstrate that a rectangular pipeline is more suitable for seed conveying. Compared to a circular design, it exhibits lower pressure loss and, consequently, lower energy consumption. Drawing on the equivalent diameter of pipelines used in existing edible sunflower combine harvesters [24], the rectangular cross-section for this study is designed with side lengths of 185 mm and 155 mm. Furthermore, to promote smooth seed flow and minimize impact forces between the seeds and the pipe wall, all internal corners of the pipeline are designed with circular arc transitions.

4 Motion Characteristic Analysis of Confectionery Sunflower Seeds in a Conveying Pipeline

Pneumatic conveying in this context is a pressure-feed system operating at medium-low pressure. The motion of seeds within the pipeline is relatively complex. This paper employs gas-solid two-phase flow theory for analysis [25]. The gas in the pipeline is assumed to be incompressible. Furthermore, the material conveyed consists solely of edible sunflower seeds after the cleaning process, and these seeds are assumed to be uniformly distributed within the pneumatic conveying pipeline.

4.1 Seed Motion Analysis in Inclined Pneumatic Conveying Pipelines

As shown in Fig. 4, the conveying pipeline is inclined at an angle θ_m to the horizontal. A micro-segment of length ΔL is selected for force analysis on the seed group within it. Here, v_a is the air velocity, v_s is the motion velocity of seed group. The main forces acting on the cluster include the air drag force (F_R), the wall resistance (F_M) and the gravity (G_W) of the seeds contained in the segment ΔL.

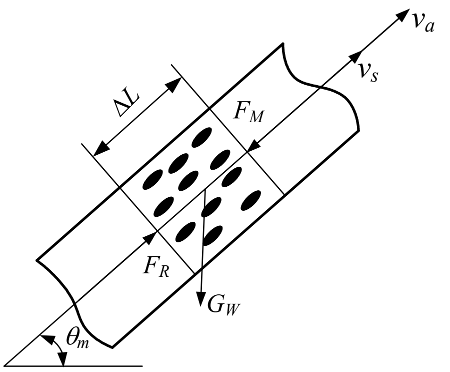


Fig. 4 Force Analysis of a Seed Group in an Inclined Conveying Pipeline

Based on the theory of pneumatic conveying [25, 26], the following can be derived:

$$F_R = C_s a_s \rho_a \frac{(v_a - v_s)^2}{2} \tag{9}$$

$$F_M = \lambda_s \rho_n \frac{\Delta L {v_s}^2}{2D_s} ab \tag{10}$$

$$G_W = g\Delta L \frac{G_s}{v_s} \tag{11}$$

Applying Newton′s Second Law of Motion to the seed group yields：

$$\frac{G_s}{v_s} \Delta L \frac{dv_s}{dt} = F_R - F_M - G_W \sin\theta_m \tag{12}$$

Simultaneously solving equations (9)-(12) yields：

$$\frac{G_s}{v_s} \Delta L \frac{dv_s}{dt} = C_s a_s \rho_a \frac{(v_a - v_s)^2}{2} - \lambda_s \rho_f \frac{\Delta L {v_s}^2}{2D_s} ab - g\Delta L \frac{G_s}{v_s} \sin\theta_m \tag{13}$$

In the equations, C_s is the damping coefficient of the seed group, a_s is the total frontal area of the seed group against the airflow, λ_s is the friction coefficient of seeds during movement inside the conveying pipeline, ρ_f is the bulk density of seeds in the suspended state, a and b are the length and width of the cross-section of the rectangular conveying pipeline, and g is the gravitational acceleration.

For simplicity, in this analytical model, the damping coefficient C_s of the seed group during conveying is assumed to be equal to its damping coefficient C_{fs} in the suspended settling state. Thus, we have:

$$C_s = \frac{\Delta x}{Re^k} = \frac{\Delta x}{\left(\frac{(v_a - v_s) d_s \rho_a}{\mu_a}\right)^k} \tag{14}$$

In the equation, d_s is the equivalent spherical diameter of edible sunflower seeds, Re is the Reynolds number, μ_a is the kinematic viscosity of the fluid, Δx and k are dimensionless exponents varying with the Reynolds number.

$$C_{fs} = \frac{\Delta x'}{Re^{k'}} = \frac{\Delta x'}{\left(\frac{v_f d_s \rho_a}{\mu_s}\right)^{k'}} \tag{15}$$

In the equation, v_f is the suspension velocity of edible sunflower seeds.

If the seed conveying state and the seed settling state are in the same resistance region, then $\Delta x = \Delta x'$, $k = k'$, and the following equation can be derived:

$$\frac{C_s}{C_{fs}} = \left(\frac{v_f}{v_a - v_s}\right)^k \tag{16}$$

When the seed group is in a suspended state inside the conveying pipeline, the air drag force (F_R) equals its self-weight (G_W). Combining equations (9), (11), and (16) under this condition yields:

$$F_R = \frac{G_s}{v_s} g \Delta L \left(\frac{v_a - v_s}{v_f}\right)^{2-k} \tag{17}$$

Given that the rotational speed of the fan is constant, the air velocity can be regarded as fixed, resulting in a steady flow field. For simplicity in modeling, the accelerated motion of the seeds is assumed to be uniformly accelerated.

$$\frac{dv_s}{dt} = v_s \frac{dv_s}{\Delta L} \tag{18}$$

The exponent k varies between 0 and 1 with the Reynolds number (Re). To simplify the model while adhering to the physical framework governed by Newton's Laws of Motion, this study adopts k=1. By substituting k=1 into and simultaneously solving equations (13), (17), and (18), we obtain the differential equation for the motion velocity of the edible sunflower seed group as a function of displacement in the acceleration section of the inclined conveying pipeline:

$$\frac{dv_s}{dL}=\frac{g^2(v_a-v_s)^2}{{v_f}^2{v_s}^2}-\frac{(a+b)\lambda_s v_s}{4ab}-\frac{v_s\sin\theta_m}{g} \tag{19}$$

4.2 Seed Motion Analysis in Arc-Shaped Conveying Pipes

As shown in Fig. 5, a segment of angular range $\Delta\theta$ is randomly selected from the curved conveying pipeline with radius R_C. The seed group within this segment is subjected to force analysis, F_C is the centrifugal force. Thus:

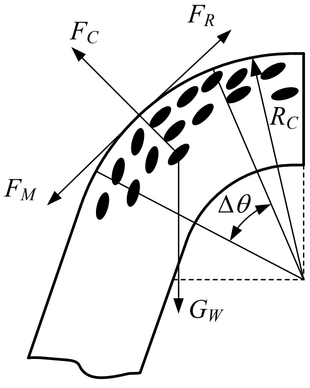


Fig.5 Force Analysis of a Seed Group in an Arc-Shaped Pipeline

$$F_R=\frac{G_s}{v_s}g\Delta\theta\frac{v_a-v_s}{v_f} \tag{20}$$

$$G_W=\frac{G_s}{v_s}gR_C\Delta\theta \tag{21}$$

$$F_M=\left(\frac{G_s}{v_s}gR_C\Delta\theta\frac{{v_s}^2}{R_C}-\frac{G_s}{v_s}gR_C\Delta\theta\cos\theta_m\right)\mu_f \tag{22}$$

In the equation, μ_f is the friction coefficient between edible sunflower seeds and the conveying pipeline.

According to Newton's Second Law of Motion:

$$\frac{G_s}{v_s}\Delta\theta\frac{dv_s}{dt}=F_R-F_M-G_W\sin\theta_m \tag{23}$$

Simultaneously solving equations (20) to (23) yields the differential equation for the motion velocity of the edible sunflower seed group as a function of the angle in the acceleration section of the curved conveying pipeline:

$$\frac{dv_s}{d\theta} = gR_C\left[\frac{v_a - v_s}{v_f v_s} - \frac{\left(v_s^{2} - R_C\cos\theta_m\right)\mu_f}{v_s} - \frac{R_C\sin\theta_m}{v_s}\right] \tag{24}$$

In summary, the motion velocity of seeds in the pneumatic conveying pipeline is related to factors such as the inclination angle θ_m of the pipeline, the arc radius R_C, the air velocity v_a, the seed suspension velocity v_f, and the seed friction coefficient μ_f.

5 CFD-EDEM Coupled Simulation of Pneumatic Conveying for Edible Sunflower Seeds

The pneumatic conveying system for edible sunflower seeds designed in this study involves a coupled gas-solid flow, where the airflow field and seed motion interact. Therefore, a CFD-EDEM coupled simulation of this two-phase flow is performed to: (1) verify the structural design rationality of the conveying system, (2) elucidate the seed motion patterns within the pipeline, and (3) provide a theoretical basis for selecting key components and parameters in subsequent research.

5.1 Calibration of Simulation Parameters

To enhance simulation accuracy by creating a realistic virtual model, edible sunflower seeds were scanned and modeled using an EinScan-Pro handheld 3D scanner. The scanning setup is shown in Fig. 6, while Fig. 7 presents the resulting seed models at key stages of the reconstruction process.

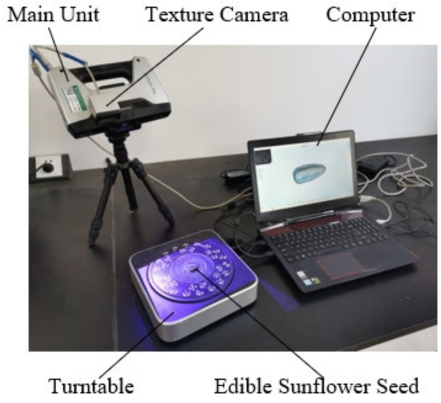
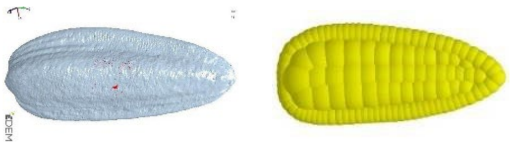


Fig. 6 Scanning Process of Edible Sunflower Seeds

a. Physical seed b. Scanning Model



c. Particle Template d. Particle Model

Fig.7 Edible Sunflower Seeds Model

The discharge port of the screw conveyor was defined as the particle generation zone. The interaction between the particles and the fluid was modeled in Fluent using the *Dense Discrete Phase Model*, while the standard *k*-*ε* turbulence model was employed for the airflow field simulation [26]. For the inlet boundary, the velocity was set to 32 m/s, with a turbulence intensity of 3.5% and a hydraulic diameter of 110 mm. For the outlet boundary, a pressure-outlet condition was applied, with a turbulence intensity of 3.5% and a hydraulic diameter of 166 mm. In the EDEM simulation, the *Hertz-Mindlin* (no-slip) contact model was adopted. The seed generation rate was set to 0.6 kg/s, and the conveyor wall material was defined as ordinary steel (Q235). The contact parameters and mechanical properties between the edible sunflower seeds and the Q235 steel were assigned based on values listed in Table 1 [27-29]. The time steps for EDEM and Fluent were set to 2×10^{-6} s and 1×10^{-3} s, respectively. The simulation of 5,000 iterations (5.0 s physical time) allowed the system to reach a quasi-steady state, given that the seeds completed a full conveying cycle approximately 1.25 s.

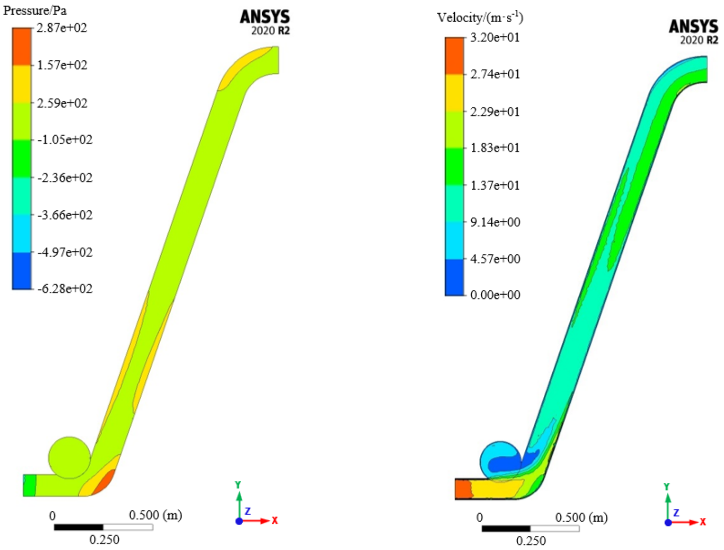
Table 1

Simulation parameters

Parameters	Value
Edible sunflower density/(kg·m^{-3})	297.5
Poisson′s ratio	0.35
Shear modulus/MPa	56.3
Sunflower seeds-Sunflower seeds collision recovery coefficient	0.57
Sunflower seeds-Sunflower seeds coefficient of static friction	0.42
Sunflower seeds-Sunflower seeds coefficient of rolling friction	0.01
Sunflower seeds-Q235 material collision recovery coefficient	0.33
Sunflower seeds- Q235 material coefficient of static friction	0.42
Sunflower seeds- Q235 material coefficient of rolling friction	0.15

5.2 Analysis of Simulation Results

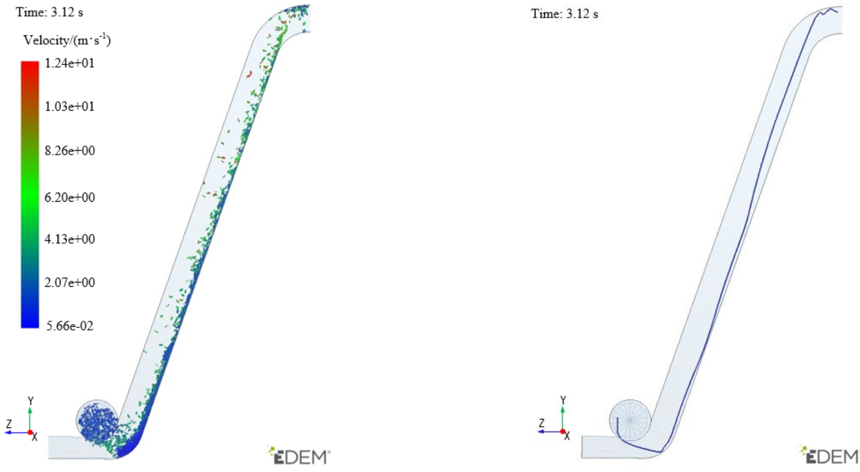
As shown in the pressure and velocity contour of the seed conveying pipeline in Fig. 8, pressure loss occurs first at the open material feeding port. Subsequently, as the airflow passes through the feeding port and is deflected at the curved section, additional pressure loss is generated. Within the inclined pipeline section, the air pressure stabilizes at approximately 250 Pa, then decreases slightly at the outlet of the curved elbow. Similarly, the airflow velocity peaks at the material feeding port, decreases thereafter, stabilizes at around 13.5 m/s in the inclined section, and finally experiences a slight decrease at the outlet.



a. Pressure contour plot b. Velocity contour plot

Fig. 8 Contour Plots of Pressure and Velocity in the Seed Conveying Pipeline

As shown in Fig. 9, the velocity contour and trajectory of seeds in the conveying pipeline were generated with the EDEM post-processor.



a. Velocity Contour Plot of Edible Sunflower Seeds b. Trajectory of Edible Sunflower Seeds

Fig. 9 Current Motion State of Edible Sunflower Seeds within the Conveying Pipeline

After being fed into the conveying pipeline by the screw conveyor, the seeds are driven by the airflow, collide with the curved elbow section, and are deflected into the inclined pipeline. Within the inclined section, they distribute uniformly along the pipe wall and accelerate upward. Finally, at the curved discharge port, they change direction again and fall into the seed collection bin. Throughout this process, the motion state of the seeds remains relatively stable.

As shown in Fig. 10, the motion state of the seeds in the pneumatic conveying pipeline is dynamic. Consequently, the resultant force acting on them also varies continuously. The maximum force recorded is 20.5 N, which is smaller than the critical damage force 54 N for the seeds [30, 31].

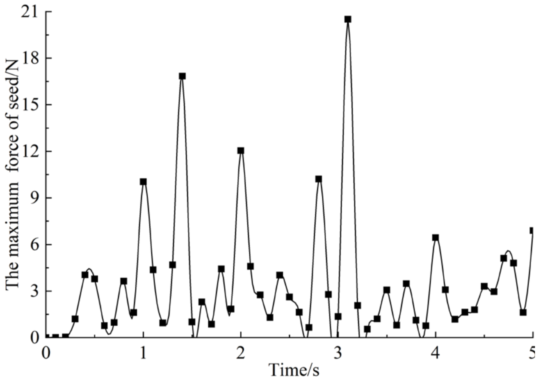


Fig.10 Variation of the Maximum Resultant Force on Seeds during Conveying

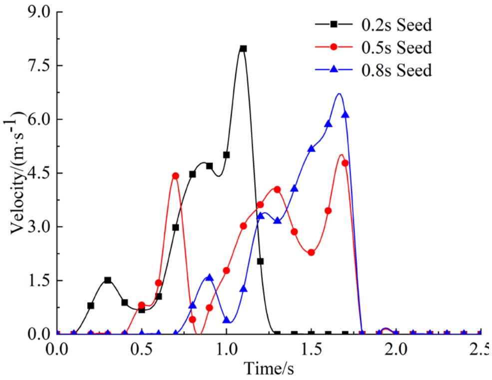


Fig. 11 Velocity Variation of a Single Seed at Different Time Instants

During the simulation, a single seed within the pneumatic conveying pipeline was randomly selected, and its velocity variation is plotted in Fig. 11. Upon entry, the seed accelerated under airflow. After colliding with the first curved elbow section, its trajectory was changed, causing a velocity drop followed by recovery. The seed then re-accelerated within the inclined pipeline section. A second collision at the outlet elbow again changed its motion, resulting in another cycle of velocity decrease and increase. Finally, the seed decelerated to rest upon entering the collection bin. The peak seed velocity during the entire process is 8 m/s. This observed motion pattern demonstrates that the structural design of the rectangular pneumatic conveying pipeline is effective and meets the conveying requirements for the 4KHZ-330 edible sunflower combine harvester.

6 Field Test

6.1 Test conditions

The 4KHZ-330 combine harvester for edible sunflower has a rated power of 110 kW and overall dimensions of 7.98 m (Length)×3.36 m (Width)×3.52 m (Height). For the seed conveying system, the inlet air velocity was set to 32 m/s, corresponding to a fan speed of 3000 r/min, as shown in Fig. 12.

Fig. 12 Field test

The field experiment was conducted from September 25 to 29, 2025, in an edible sunflower field located in Wuchuan County, Hohhot City, Inner Mongolia Autonomous Region. The field was planted with cut-and-insert-disk type edible sunflower variety, characterized by uniform plant height and flat terrain. A rectangular plot measuring 20 m in length was selected. Prior to the test, key biological parameters of the sunflower plants were measured, as summarized in table 2.

Table 2

Key biological parameters of the sunflower plants

Item	Parameter
Crop Variety	SH363
Planting Density/$\times 10^4$ plants·ha^{-1}	Approximately 3.0
Planting Pattern	On film flat planting with wide-narrow rows of 800 mm+400 mm.
$\times 10^3$ Seed Weight/g	169.8
Yield/kg·ha^{-1}	2500～5000
Plant Height/mm	980.3～1104.5
Plant Spacing/mm	450
Sunflower Capitulum Diameter/mm	169.5～316.7
Sunflower Capitulum Thickness/mm	38.5～72.6
Seed Moisture Content/%	14.9～23.4
Sunflower Capitulum Moisture Content/%	21.4～31.3

6.2 Test Method

The field experiment was conducted in compliance with the national standards GB/T 8097-2008 (*Testing Methods for Combine Harvesters*) and DG/T 182-2019 (*Self-propelled Edible Sunflower Combine Harvesters*). Three key performance indicators—operating speed, productivity, and seed damage rate—were evaluated. Tests were performed at 6 different operating speeds, categorized into three regimes: low, medium, and high speed. Under each regime, two replicate runs were carried out over a 20 m test section, yielding 6 complete sets of measurement data. The operating speed was determined by recording the time required for the harvester to traverse the 20 m section and calculated using equation (25).

$$v = 3.6 \cdot \frac{L}{t} \tag{25}$$

In the equation, v is the working speed of the harvester, L is the length of the measurement section, t is the time taken by the harvester to pass through the measurement section.

Upon completion of each operational run, a seed sample (≥1000 g) was randomly collected from the grain tank. Each sample was then reduced using the quartering method to obtain a representative subsample. From this subsample, the total mass and the mass of damaged seeds were measured separately to calculate the damage rate for that run. This procedure was repeated for all 6 runs, and the final seed damage rate was reported as the average of the 6 individual measurements. The formulas for calculating seed impurity rate and damage rate are as follows:

$$Z_P = \frac{W_P}{W_Y - W_E} \times 100\% \tag{26}$$

In the equation, W_E is the mass of impurities in each subsample, W_Y is the mass of each subsample, Z_P is the seeds damage rate, W_P is the mass of damaged seeds (including broken seeds and those with surface scratches) in each subsample.

6.3 Test Results and Analysis

The field harvesting performance is shown in Fig.13, and the corresponding performance indicators are summarized in table 3. At low, medium, and high operating speeds, the seed damage rate remained below 2.0%, while productivity ranged from 0.42 to 0.87 hm²/h. All measured indicators met the relevant standard requirements.

a. Stubble Cutting Quality

b. Cleaning Performance

c. Threshing Performance

d. Damaged Seeds

Fig. 13. Field Harvesting Performance of the Edible Sunflower Combine Harvester

Table 3

Field Performance Measurement Results

Gear	Operating Speed/($km \cdot h^{-1}$)	Damage Rate/%	Productivity/($hm^2 \cdot h^{-1}$)
Low	3.68	1.32	0.42
	3.56	1.08	
	3.48	1.22	
Medium	5.56	1.51	0.66
	5.64	1.27	
	5.71	1.18	
High	7.31	1.62	0.87
	7.23	1.49	
	7.15	1.71	

Field tests demonstrated that the harvester operated stably. The design of the seed conveying system proved effective, ensuring smooth material flow without blockage. Both the seed damage rate and productivity complied with the standards for mechanized harvesting. Consequently, this combine harvester reduces harvesting costs and improves economic returns for edible sunflower growers.

7. Conclusions

Gas-solid two-phase flow numerical simulation results show that: the maximum edible sunflower seeds velocity is 8 m/s, and the maximum force on the seeds is 20.5 N, which is smaller than the critical damage force 54 N. Thus, the rationality of the structural design was verified.

Finally, a field test is conducted to measure three key performance indicators of the 4KHZ-330 edible sunflower combine harvester: operating speed, productivity, and seed damage rate. The results show that the seed conveying process is smooth and clog-free. The maximum operating speed was 7.15 km/h, productivity ranged from 0.42 to 0.87 ha/h, and the seed damage rate was below 2.0%. All performance indicators meet the design requirements.

Future research will pursue two key objectives: firstly, modeling the effects of airflow velocity and pipeline geometry on seed damage and conveying efficiency to optimize system parameters. Secondly, developing a machine vision-based real-time monitoring system for blockage and damage detection, integrated with adaptive control of operational parameters.

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