

Design of a Variable-Pitch Screw Feeder for Ultrafine Calcium Carbonate Powder based on EDEM Simulation

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Abstract

Addressing the problems of insufficient powder feeding accuracy and significant flow fluctuations during the automated preparation of drilling fluids in laboratory environments, a screw feeding mechanism based on a variable-pitch screw was designed. Discrete Element Method (DEM) simulations were performed using EDEM to investigate the powder conveying characteristics under different structural parameters. A comparative analysis of the mass flow rate and flow fluctuation was conducted. Under the same operating conditions, the mass flow rate of the variable-pitch screw was 0.373 g/s with a fluctuation rate of 13.3%. In comparison, the constant-pitch screw with an outlet pitch of 9.6 mm achieved a mass flow rate of 0.357 g/s with a fluctuation rate of 18.1%. The conveying capacities of the two structures were comparable, while the variable-pitch screw significantly reduced the flow fluctuations. The results demonstrate the structural advantages of the variable-pitch screw in high-precision continuous powder feeding, providing a reference for the structural design of precision feeding devices.

Keywords

Spiral Parameters; Transport Performance; Screw Conveyance; EDEM.

1. Introduction

Drilling fluid laboratories are gradually transitioning toward automation, digitalization, and intelligent operation to improve research efficiency, enhance data accuracy, and achieve full-process traceability [1]. In automated preparation systems, powder handling is a critical factor affecting operational stability. However, ultrafine calcium carbonate powder, characterized by poor flowability and strong interparticle adhesion, is prone to blockage, stagnant flow, and intermittent discharge during conveying, which reduces dosing accuracy. Therefore, a stable and reliable automatic feeding mechanism is required to improve the continuity and stability of powder feeding.

The screw conveyor mechanism is widely used in powder quantitative conveying systems due to its advantages such as simple structure, strong adaptability, and capability of achieving continuous feeding [2]. Under constant rotational speed conditions, the conveying capacity per unit length of an equidistant screw remains consistent. However, in actual operation, the material tends to be insufficiently filled at the inlet section and prone to instantaneous concentrated discharge at the outlet section, resulting in flow pulsation and excessive conveying. Especially under micro-feeding conditions, this uneven conveying characteristic of the structure is further amplified, and it is difficult to improve the flow fluctuation problem solely by adjusting the rotational speed.

To address the uneven distribution of axial conveying capacity in screw conveying processes, a powder feeding mechanism based on a variable-pitch screw is considered in this study. By gradually varying the screw pitch along the axial direction, the conveying capacity can be regulated in a graded manner, allowing compression and buffering regions to form during material transport, thereby improving the stability of powder flow [3, 4]. However, studies on laboratory-scale micro-dosage powder feeding remain limited, particularly under conditions requiring low flow rates and high-precision control. Therefore, this study conducts the design and validation of an automatic powder feeding mechanism based on a variable-pitch screw.

This article centers on the laboratory powder automatic feeding device, taking ultrafine calcium carbonate as the research object, and proposes a design method for a variable pitch screw feeding mechanism aimed at stable conveying. By establishing a parameterized model with a linear change in pitch along the axial direction, and combining discrete element simulation to compare and analyze the powder conveying process before and after optimization, the structural performance is evaluated from two indicators: average mass flow rate and flow fluctuation rate. The research results provide a theoretical basis for the application of variable pitch screws in continuous conveying of micro-powders, and offer a reference for the structural optimization design of high-precision automatic feeding devices.

2. Variable-pitch Screw Rod Structural Design

1). Conveying capacity

The powder is transported primarily by the pushing action of the helical blade along the axial direction during screw rotation. Under ideal conditions, assuming that the particles are uniformly distributed within the screw groove and that no significant axial blockage or backflow occurs, the volume of powder conveyed per revolution can be approximated as the product of the effective volume of the screw groove and the filling ratio.

Accordingly, the theoretical conveying flow rate of the screw feeder can be expressed as:

$$Q = \frac{\pi}{240} (D^2 - d^2) S n \rho \varphi \varepsilon \quad (1)$$

2). Pitch

The pitch size directly determines the effective volume of the spiral groove and the motion characteristics of the powder during conveying. For ultrafine powder, if the pitch is too large, it is prone to uneven filling of the spiral groove, particle backflow, and instantaneous flow rate fluctuations, which affect the feeding accuracy. Reducing the pitch appropriately can enhance the axial constraint of the powder within the spiral groove, helping to form a relatively stable filling state and improve the continuity and controllability of the conveying process. At the same time, the pitch size also affects the distribution of the components of particle velocity. As the pitch increases, the axial velocity of particles during spiral conveying increases, but it is prone to improper distribution of circumferential velocity components, affecting the stable conveyance of materials. When the pitch is smaller, the distribution relationship between the components of particle velocity is relatively reasonable, which is conducive to maintaining the stability of the conveying process. However, at this time, the axial conveying velocity is relatively low, and the feeding efficiency is limited to some extent. Therefore, when determining the maximum allowable pitch of the spiral structure, in addition to meeting the basic conveying capacity requirements, it is necessary to comprehensively consider the reasonable matching relationship between the components of particle velocity. Ideally, while ensuring that the particles have a large axial conveying velocity, the axial velocity components at various positions on the spiral blade surface should always be greater than their circumferential velocity components, thereby achieving efficient and stable powder conveyance.

The thread pitch can usually be calculated according to the following formula:

$$S = K_1 D \quad (2)$$

In the equation, K_1 denotes the ratio of the pitch to the blade diameter.

The value of the pitch in the conveying section is closely related to the diameter of the helical blade. For standard helical conveying, it is generally recommended to take $K_1=0.8\sim 1.2$. When arranged at an angle or conveying powders with poor fluidity, $K_1 \leq 0.8$ [5].

3).Screw shaft diameter

The diameter of the screw shaft determines the effective volume of the screw groove and the filling state of the powder during the conveying process. The selection of the screw shaft diameter is closely related to the pitch, and together they determine the helix angle of the screw blades. Variations in the helix angle affect the tendency of the material to slip along both the axial and circumferential directions. When determining the combination of screw shaft diameter and pitch, the friction characteristics between the screw surface and the material, as well as the proper matching of the velocity components of the particles, should be taken into account, so as to identify a shaft diameter and pitch configuration that is conducive to stable conveying.

According to relevant design literature and design manuals, the screw shaft diameter can be calculated as follows:

$$d = K_2 D \quad (3)$$

In the equation, K_2 is the ratio coefficient between the screw shaft diameter and the blade diameter, which is generally taken as $0.2\sim 0.4$.

4).Screw rotational speed

The rotational speed of the screw directly determines the mass of powder conveyed per unit time and the stability of the feeding process. However, a higher screw rotational speed is not always beneficial. At relatively low speeds, the powder remains in a stable pushing state within the screw groove, with a high filling rate, resulting in a smooth conveying process that is favorable for precise metering. As the rotational speed increases, the powder may deviate from the screw wall, leading to slipping and centrifugal stratification, which reduces the effective filling rate and increases instantaneous flow fluctuations, thereby impairing high-precision feeding. Moreover, for powders with poor flowability or a tendency to agglomerate, excessively high speeds may cause intensified disturbance in the feeding section, increasing the risk of clogging and bridging. According to the literature [6], the calculation of the critical screw rotational speed can be expressed as:

$$n_{\max} = \frac{30}{\pi} \sqrt{\frac{\tan(\alpha + \beta) g}{f_1 R_1}} \quad (4)$$

5).Screw blade diameter

The diameter of the screw blade directly affects the mass of material fed per unit time as well as the continuity and stability of the conveying process. For a vertically downward powder feeding structure in drilling fluid applications, the blade diameter must not only satisfy the target conveying capacity and the 0.01 g-level weighing accuracy requirement, but also accommodate the powder flow characteristics and structural matching. If the diameter is too small, the effective volume of the screw groove will be insufficient, requiring a higher filling rate at a given rotational speed to meet the conveying requirement, which may cause flow fluctuations. Conversely, if the diameter is too large, the powder may become overly compacted, increasing contact pressure on the inner wall and raising the risk of clogging or bridging.

Based on the previously determined target conveying capacity Q , pitch S , inner shaft diameter d , and Screw rotational speed n , the calculation formula for the screw blade diameter can be expressed as follows:

$$D = \sqrt[3]{\frac{240Q}{\pi K_1(1 - K_2^2)n\rho\phi\varepsilon}} \tag{5}$$

The system control core adopts a Programmable Logic Controller (PLC) to realize sequential control of equipment operation, speed regulation, and data acquisition management. The PLC’s sampling period and control response time directly influence the selection of screw operation parameters. Since the feeding process uses periodic weight-feedback control, in order to ensure that the mass variation within a single sampling period meets the 0.01 g precision requirement, the screw rotational speed and structural dimensions must be compatible with the PLC’s sampling frequency. In this study, a Delta PLC, model DVP60ES200T, was selected, with a data reading time of 20 ms. To achieve the 0.01 g feeding accuracy, factors such as powder tailing, weighing signal filtering, and actuator response delay were considered. Furthermore, a safety margin was introduced, and the target feeding rate was controlled within a 0.004 g range, ensuring that the system can reliably maintain 0.01 g-level metering precision under actual operation conditions.

$$QT \leq 0.004g$$

Accordingly, the maximum permissible stable feeding rate is:

$$Q = \frac{\pi}{240} (D^2 - d^2)Sn\rho\phi\varepsilon \leq 0.25g/s$$

After completing the calculation of conveying capacity and the analysis of structural parameter matching, the operating speed of the screw has been limited to a reasonable medium-to-low speed range. This range can simultaneously meet the requirements of the target conveying volume and the constraints of weighing control accuracy. Since the purpose of this chapter is to construct a benchmark design model for equal pitch screws, rather than to optimize the speed to an extreme value, a representative operating speed within the feasible range needs to be selected as the design parameter. Considering that under the given structural dimensions, the mass increment per unit sampling period at this speed is within a controllable range, 20r/min is selected as the benchmark design speed. Combining conventional helical structure design experience and the requirements for stable powder conveying, the proportional coefficient K_1 between the pitch and blade diameter is taken as 0.96, and the proportional coefficient K_2 between the shaft diameter and blade diameter is taken as 0.4. Substituting the above proportional coefficients into the blade diameter back-calculation formula, and combining with the determined target conveying volume and speed, the helical blade diameter and corresponding structural dimensions are calculated. The calculation results are rounded appropriately, and the main structural parameters of the equal pitch screw are determined as shown in Table 1.

Table 1. Structural parameters of equal pitch screw

Screw blade diameter/D(mm)	Pitch/S(mm)	Screw shaft diameter/d(mm)	Screw rotational speed/n(r/min)
10	9.6	4	20

It should be noted that the purpose of this chapter is to construct a benchmark model for equal pitch screws, rather than to perform extreme optimization on rotational speed or structural parameters. Therefore, within the determined reasonable parameter range, representative structural dimensions and operating conditions are selected as the design benchmark. This parameter combination meets the requirements of target feed rate and control accuracy, while exhibiting stable conveying characteristics and good structural compatibility.

2.1. Linear Fitting of Variable Pitch Screw

Given the characteristics of ultrafine calcium carbonate powder, such as low apparent density, poor fluidity, and a certain degree of adhesiveness, the use of a constant pitch screw may lead to issues such as excessive instantaneous feeding volume or unstable truncation during the low-speed fine feeding stage, making it difficult to achieve feeding accuracy on the order of 0.01g. Therefore, a two-stage variable pitch screw structure has been designed to achieve graded conveying control through zoned regulation of structural parameters, thereby improving feeding accuracy.

The geometric characteristics of a variable pitch screw can be described by the curve form of the helical line after axial unfolding, as shown in Figure 1. When the pitch changes, the slope of the unfolding curve also changes, reflecting the variation law of the helical propulsion speed and axial conveying capacity. If a segmented constant pitch design is adopted, discontinuities in slope will occur at the boundaries between adjacent segments, corresponding to abrupt changes in the axial velocity and propulsion acceleration of the material. Such discontinuous changes will lead to sharp adjustments in the local material stress state, potentially causing issues such as particle accumulation, flow field fluctuations, or unstable impact loads, thereby affecting the continuity and feeding accuracy of the conveying process. Therefore, in the design of a variable pitch screw, the pitch of each segment should be treated continuously, through function fitting or smooth transition methods, so that the pitch varies continuously along the axial direction, ensuring a smooth transition in the slope of the unfolding curve. This method can effectively reduce abrupt changes in material velocity gradients, reduce local pressure fluctuations, and improve the stability and controllability of the conveying process.

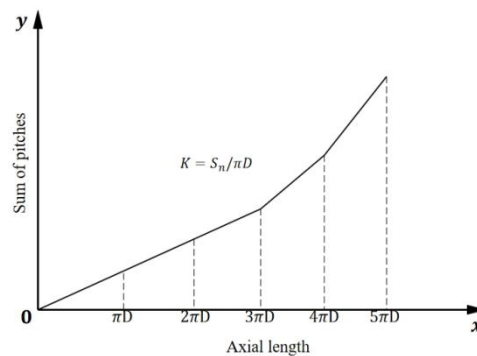


Fig 1. Spiral unfolding diagram

In the design of variable pitch screws, the pitch distribution along the axial direction is considered as a continuously changing function and is fitted using a quadratic function. The quadratic function has a continuous first-order derivative, and its pitch change rate varies linearly along the axial direction. This approach ensures a gradual transition of the pitch while avoiding drastic fluctuations and transient impacts in the powder filling rate caused by abrupt gradients, thereby enhancing the stability of the conveying process. Additionally, the quadratic function is simple in form, has few parameters, and has clear physical interpretations, making it easy to mathematically couple with design conditions such as target conveying capacity, length constraints, and pitch limitations [7].

In this paper, a quadratic function with an upward opening and tangent to equal pitch line segments is employed for linear fitting of the pitch expansion. To simplify the fitting process, the fitted quadratic function curve is made to pass through the origin and tangent to two equal pitch line segments, as shown in the spiral line fitting curve in Figure 2. Let the quadratic function be defined as follows:

$$y = Ax^2 + Bx \tag{6}$$

where y is the cumulative pitch of the variable-pitch screw, and x is the cumulative axial length. Differentiating Eq. (6) with respect to x yields:

$$\dot{y} = 2Ax + B \tag{7}$$

When $x=0$, since $\dot{y} = \frac{1.5S}{\pi D}$, it follows that:

$$B = \frac{S}{\pi D} \tag{8}$$

When $x = m\pi D (m > 0)$, $\dot{y} = \frac{1.5S}{\pi D}$, it follows that:

$$\frac{1.5S}{\pi D} = 2Am\pi D + B \tag{9}$$

By combining the above equations, the following expressions can be obtained:

$$\begin{cases} A = \frac{1}{4m} \cdot \frac{S}{\pi^2 D^2} \\ B = \frac{S}{\pi D} \end{cases} \tag{10}$$

Based on the above derivation, the fitted quadratic curve is given by:

$$y = \frac{1}{4m} \cdot \frac{S}{\pi^2 D^2} x^2 + \frac{S}{\pi D} x \tag{11}$$

Given that the pitch S_n is defined as the increment of the cumulative function, namely,

$$S_n = y_n - y_{n-1} \tag{12}$$

the following expression can be obtained:

$$S_n = \frac{(4m + 2n - 1)}{4m} \cdot S \tag{13}$$

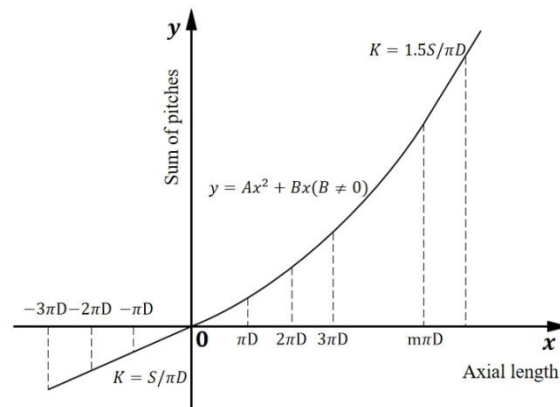


Fig 2. fitted spiral curve

Set the pitch of the maximum pitch segment to 1.5S.

When $m = 3, S_1 = 0.08, S_2 = 0.25, S_3 = 0.42$;

When $m = 4, S_1 = 0.06, S_2 = 0.19, S_3 = 0.31, S_4 = 0.44$;

When $m = 5, S_1 = 0.05, S_2 = 0.15, S_3 = 0.25, S_4 = 0.35, S_5 = 0.35, S_4 = 0.45$.

When $m \geq 4$, The first segment of the variable pitch section has a pitch ratio less than 0.08, indicating that the variable pitch is too small. Additionally, there are too many variable pitch sections. Due to structural size constraints, the variable pitch result with $m=4$ is selected for the design of the variable pitch section.

Based on the varying pitch patterns and specific parameter values determined in the previous sections, the structural design of the variable pitch spiral feeding screw is shown in Figure 3. The designed screw adopts a "two-segment variable pitch" configuration along the axial

direction: the upper segment is a region with a larger pitch, primarily used for the initial conveyance and loosening of the powder.

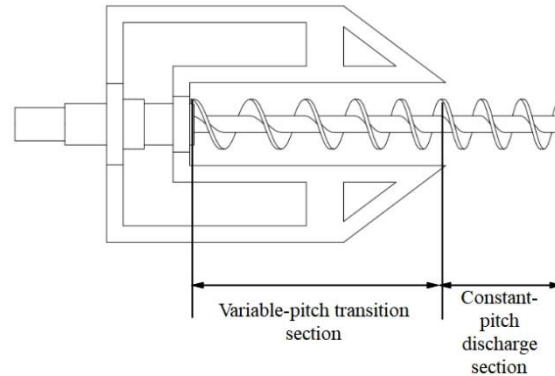


Fig 3. Structural diagram of variable pitch helical rod

Through the larger pitch and higher groove capacity, the powder entering the spiral groove achieves a higher axial propulsion speed, while mitigating powder accumulation and local congestion at the feeding end. The screw discharge end is designed as a constant pitch segment with a smaller pitch, where the pitch decreases and remains constant, allowing the powder to gradually form a higher and stable filling rate in this segment. This effectively reduces particle backflow and slippage, enhances the continuity of conveying flow, and achieves uniform control over the powder discharge process. To further improve the force state and flow uniformity of the powder in the spiral groove, two auxiliary push plate structures symmetrically arranged along the axial direction are added on the outside of the spiral blade. This structure can provide additional guidance and squeezing effects on the powder during the spiral rotation process, inhibiting the occurrence of bias flow and retention phenomena in the spiral groove. Thus, the spiral feeding screw structure based on the variable pitch design concept is formed.

2.2. Structural Design of Powder Spiral Feeding Device

Based on the determined two-segment variable pitch structure and operating speed parameters, the structural design of the powder spiral feeding mechanism is carried out. In the automatic drilling fluid preparation system, the powder feeding unit not only needs to meet the requirements of stable conveyance and high-precision metering, but also needs to adapt to the frequent switching of various powder materials. Based on this, this paper designs the spiral feeding mechanism as a movable structure that integrates storage and feeding, and can be quickly loaded and unloaded.

The powder feeding structure consists of six components, as shown in Figure. 4. The screw shaft 1 is connected to the one-way coupling 4 through a coupling 2 that passes through the cover plate 5 and the spacer plate 3. The cover plate 5 and spacer plate 3 are fixed to the powder tank body 6 using bolts. A positioning block for the robotic gripper is designed on the powder tank 6 to facilitate grasping of the powder feeding unit by the robotic arm. To reduce the influence of screw rotation on the overall actuator, a bearing is installed inside the spacer plate 3. The bearing is interference-fitted with both the spacer plate 3 and the mating structure 5, ensuring that the rotation of the screw shaft only occurs within the actuator and preventing misalignment or jamming. Standard components are used for the coupling and bearings, while the remaining parts are manufactured by 3D printing. The variable-pitch screw 1 inside the powder tank is vertically arranged, allowing powder storage and metered conveying to be completed within the same enclosed structure. This design avoids issues associated with traditional external conveying systems, such as material exposure, environmental dust contamination, and secondary transfer errors. The powder tank achieves axial powder conveying and continuous feeding through the rotational motion of the screw blade.

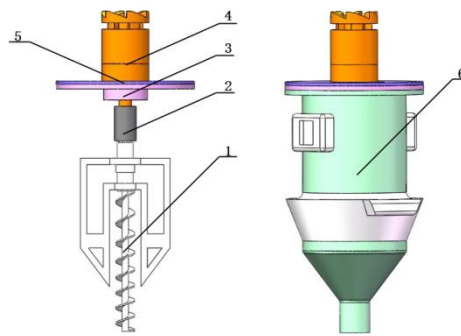


Fig 4. powder can structure

- 1. Screw shaft 2. Coupling 3. Spacer plate
- 4. One-way coupling 5. Cover plate 6. Powder tank

The one-way coupling 4 realizes unidirectional transmission based on a dynamic locking mechanism using wedge-shaped grooves, as illustrated in Fig. 5. After the robotic arm completes positioning and grasping, an external motor can be quickly connected to the coupling at the top of the powder tank to transmit power. This enables the screw shaft to obtain rotational driving force and initiate the feeding process. When the motor is removed, the powder tank remains in a closed and stationary state, without affecting its function as an independent storage container. Structurally, a wave spring is arranged inside the coupling on the side connected to the powder tank to provide axial preload and compensate for assembly tolerances, thereby improving transmission stability. On the motor connection side, a conical protrusion–recess self-guiding structure is designed, which enables automatic centering and angular correction during the docking process. Even if positioning errors occur during robotic grasping or placement of the powder tank, reliable coupling engagement can still be achieved.

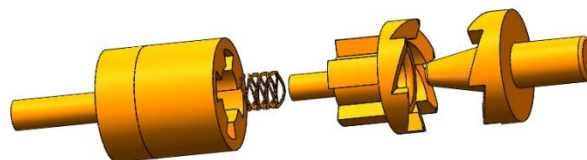


Fig 5. one-way clutch

The designed powder feeding mechanism consists of a support frame 12, a powder tank-type feeding actuator 10, a drive module 9, and a weighing unit 7, which are arranged on the support frame in a modular manner, as shown in Figure 6. The powder tank, as an integrated unit for storage and feeding, is vertically placed in the positioning area of the support frame. Its shape and support interface adopt a conical guiding structure, which enables automatic centering and stable support during placement, reducing the impact of assembly deviations on feeding accuracy. An independent stepper motor module is set up on the drive side, and the exterior of the module is designed with a clamping structure that facilitates grasping by a robotic arm. The motor output end is quickly docked with the spiral feeding actuator inside the powder tank through a one-way clutch. When powder feeding is required, the robotic arm places the stepper motor module and completes centering and coordination with the powder tank. The motor drives the vertical spiral rod to rotate, achieving continuous and controllable powder feeding. A receiving tray 8 and an electronic scale are set up below for real-time weighing and feedback control of the feeding quality. The overall structure ensures high-precision feeding performance while also considering engineering applicability for module replacement, robotic arm operation, and system integration.

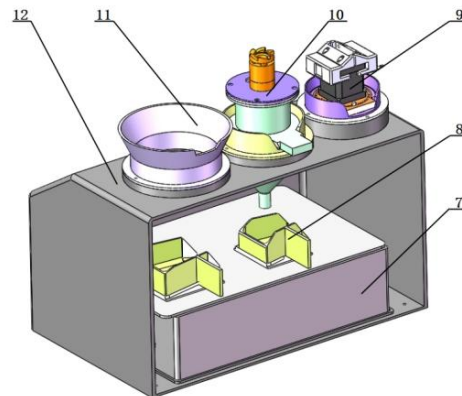


Fig 6. Powder feeding mechanism

7. Weighing platform 8. Material receiving tray 9. Integrated module of stepper motor
10. Powder tank 11. Large-sized powder tank limit slot 12. Support frame

In summary, the movable, integrated storage-discharging structural design significantly outperforms the fixed structural form in terms of powder adaptability, operational stability, maintenance friendliness, and system flexibility, and is more in line with the engineering requirements of high reliability and high precision for intelligent drilling fluid preparation equipment.

3. Simulation Experiment of EDEM

The Discrete Element Method (DEM) is a numerical method used to simulate the motion behavior of granular materials, first proposed by Cundall in 1971. In this method, bulk materials are represented as a large number of interacting particles. By calculating the contact interactions and motion between particles and boundaries, the overall motion characteristics of granular materials can be numerically simulated [8]. Numerical simulation software such as EDEM, LIGGGHTS, and YADE are particle simulation tools developed based on the Discrete Element Method [9]. These platforms enable efficient construction of parameterized particle system models and integrate material properties, mechanical characteristics, and other physical parameters of particles, thereby facilitating numerical analysis of granular system behavior.

The target angle of repose was obtained through a static powder stacking experiment [10]. Meanwhile, the measured bulk density, particle density, and particle size distribution of the powder were used as the fundamental physical input parameters. By adjusting the Poisson's ratio, shear modulus, restitution coefficient between ultrafine calcium carbonate particles, restitution coefficient between particles and stainless steel, static friction coefficient between particles, rolling friction coefficient between particles, static friction coefficient between particles and stainless steel, rolling friction coefficient between particles and stainless steel, and surface energy, multiple parameter combinations were tested within reasonable ranges. The parameter calibration process continued until a simulated stacking geometry consistent with the experimental results was obtained.

The discrete element simulation model is shown in Figure 7. The funnel cone angle used for powder repose angle calibration was 60° , the inner diameter of the funnel outlet was 10 mm, and the distance between the outlet plane and the inner plate surface of the receiving tray was 100 mm. The simulation calibration model was consistent with the actual repose angle measurement device.

In the numerical simulation, particle scaling was applied to improve computational efficiency while ensuring that the scaled particles could still represent the physical characteristics of the real particles [11]. The particles were modeled as spherical particles with a diameter of 1 mm. A total of 150,000 particles were generated during the simulation with a generation rate of 15,000 particles per second, and the generation mode was set to Dynamic. The total simulation time was 15 s. The computational boundary adopted the default minimum bounding space of the software to cover the entire structure. After completing the relevant parameter settings, the simulation was carried out.

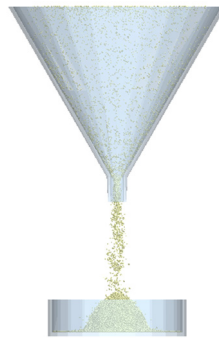


Fig 7. EDEM parameter calibration model

The DEM parameters obtained after calibration can effectively describe the macroscopic accumulation behavior and flow trend of drilling fluid powder, providing a reliable material parameter basis for the subsequent simulation of the spiral feeding process. The specific simulation parameters are shown in Table 2.

Table 2. EDEM simulation parameters

Simulation parameters	Numerical values	Simulation parameters	Numerical values
Density of ultrafine calcium carbonate/(kg/m ³)	2800	Particle–particle static friction coefficient	0.6
Poisson's ratio of ultrafine calcium carbonate	0.28	Particle–particle rolling friction coefficient	0.31
Shear modulus of ultrafine calcium carbonate/P _a	5 × 10 ⁷	Particle–wall restitution coefficient	0.1
Restitution coefficient of ultrafine calcium carbonate particles	0.1	Particle–wall static friction coefficient	0.6
Density of stainless steel/(kg/m ³)	7800	Particle–wall rolling friction coefficient	0.2
Poisson's ratio of stainless steel	0.3	JKR surface energy/(J/m ²)	0.06
Shear modulus of stainless steel/P _a	7 × 10 ⁷		

Utilizing Solidworks software, a feeding mechanism model was established. After exporting the model in igs file format, it was imported into EDEM software. The particle size of ultrafine calcium carbonate was enlarged to 1mm, and the shape was set to spherical. Meanwhile, the particle distribution size was set to normal distribution. A particle factory was established, with the particle generation method set to Dynamic, the total number of particles set to 200,000, and

the particle generation speed set to 15,000/s. Considering that the propagation of stress waves in particles is influenced by simulation parameters, the Rayleigh time step varies in different simulations. Therefore, 1/5 of the Rayleigh time step was selected as the calculation time step for the simulation model, and the size of the simulation grid was set to three times the minimum sphere diameter. Too many grid cell divisions can lead to insufficient memory on the computing platform, while a larger grid can result in greater errors in the simulation. Choosing reasonable grid cells can improve simulation efficiency and accuracy. The simulation process is shown in Figure 8. The powder first falls freely in the silo and completes initial filling, and then enters the screw conveying zone.



Fig 8. Simulation process diagram

4. Simulation Results and Analysis

Based on the simulation results outputted by the EDEM Analyst module, the performance of spiral feeding is evaluated from two aspects: mass flow characteristics and feeding stability. During the feeding process, the powder is continuously discharged from the outlet after being conveyed by the spiral blade, and its feeding capacity can be characterized by the mass change per unit time. In the simulation, a mass statistics area is set at the spiral outlet to record the real-time relationship between cumulative mass and time. On this basis, the mass flow fluctuation rate is introduced as an important indicator to measure feeding stability.

Simulation comparisons were conducted using a variable pitch screw with an exit pitch of 9.6mm, an isometric screw with a pitch of 9.6mm, and an isometric screw with a pitch of 14.4mm. The simulation results showed that in the initial feeding stage, due to the unstable powder filling, the cumulative mass curve at the screw exit exhibited a certain nonlinear growth characteristic, and the mass flow fluctuation was relatively obvious. As the screw continued to rotate, the powder gradually formed a relatively stable filling state in the screw groove, and the cumulative mass curve tended to increase linearly, indicating that the system entered a stable feeding stage. In subsequent analysis, only data within the stable operating range was selected as the basis for evaluation to avoid interference from start-up transients.

The simulation results for mass flow rate are shown in Figure 9. The mass flow rate of the variable pitch screw designed is 0.373g/s, with a fluctuation of 13.3%. For the equal pitch screw with a pitch of 9.6mm, the mass flow rate is 0.357g/s, with a fluctuation of 18.1%. Comparing the two, the variable pitch screw also adopts a small pitch of 9.6mm at the outlet section, and its conveying capacity has not decreased due to the variable pitch design. However, the equal pitch screw designed with the maximum pitch of 14.4mm using the variable pitch screw has a mass flow rate of 0.591g/s, with a fluctuation of 25.83%, and the curve exhibits severe oscillation. This indicates that although the large pitch design improves the conveying capacity, it exacerbates the irregular sliding and collapsing behavior of the powder in the screw channel, leading to severe deterioration in the stability of the feeding process. The above results show that the variable pitch structure achieves efficient feeding through large pitch at the inlet

section and stable flow suppression through small pitch at the outlet section, effectively suppressing the intermittent bridging and collapsing phenomena that are prone to occur in low-flowability powders while maintaining conveying capacity, ensuring the accuracy of feeding. The variable pitch screw can significantly improve the smoothness of the feeding process without sacrificing conveying efficiency, verifying its feasibility as a core actuator for high-precision powder feeding.

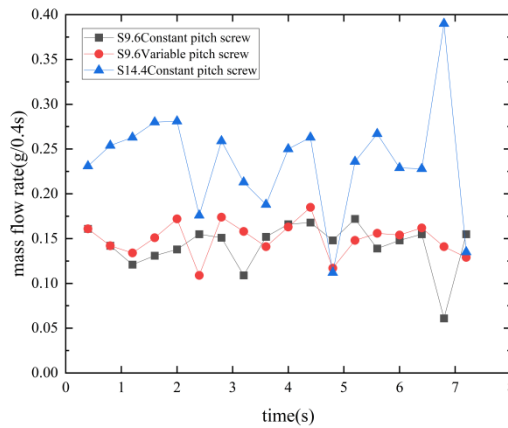


Fig 9. Mass flow comparison

As shown in Figure 10, by comparing the discrete element simulation results of the axial velocity distribution of powder particles inside variable pitch screws and constant pitch screws, the differences in flow characteristics between the two can be observed. In the constant pitch screw (a), the axial velocity of particles exhibits a relatively obvious stratified feature, with a large proportion of low-velocity regions and locally continuous blue stripes, indicating that particles are stagnant at some locations.

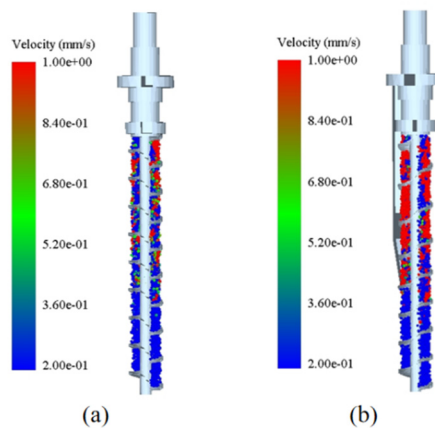


Fig 10. Comparison of particle axial velocity distribution

- a. Axial velocity distribution of a constant pitch screw; b. Axial velocity distribution of a variable pitch screw

At the same time, the distribution of high-velocity particles is relatively discrete, indicating that the axial propulsion effect is spatially unevenly distributed, and there is a certain degree of fluctuation in the conveying process. In contrast, the overall level of axial velocity of particles inside the variable pitch screw (b) is significantly improved, the proportion of high-velocity particles is significantly increased, the velocity distribution is more continuous and uniform, and the range of low-velocity regions is significantly reduced. This indicates that the variable pitch structure can effectively improve the axial momentum transfer path and enhance the axial conveying ability of particles. This shows that by adjusting the pitch distribution, the variable

pitch structure effectively improves the force and motion coordination of powder particles during conveying, and enhances the axial conveying efficiency. Therefore, under the same operating conditions, the variable pitch screw exhibits superior flow uniformity and conveying stability.

The particle velocity distribution within the variable pitch screw is illustrated in Figure 11. The velocity distribution reveals a notable decreasing trend in the overall particle motion intensity along the axial direction. The particle velocity is relatively high in the inlet region and significantly decreases in the outlet section. This suggests that the overall kinetic energy of the particles gradually diminishes as they pass through the variable pitch screw structure. In conjunction with the overall simulation process, it can be observed that this velocity attenuation phenomenon is closely related to changes in structural constraints. In the upper region of the screw, the powder is not completely enclosed by the tank, allowing particles greater spatial freedom. Consequently, the degree of compaction between particles is lower, and friction dissipation is limited, enabling the maintenance of a high motion intensity. As particles move downward and enter the fully enclosed region of the tank, their radial and circumferential degrees of freedom are significantly restricted. Simultaneously, the variable pitch structure results in stronger geometric compression effects on particles within a unit axial length, leading to an increased particle filling rate and higher contact frequency and normal force between particles and between particles and the wall. Under these multiple constraints, energy dissipation during particle motion intensifies, resulting in a continuous decline in overall kinetic energy. This is reflected in the velocity distribution, where the particle motion intensity significantly decreases in the outlet section, achieving a stable and controlled powder feeding process.

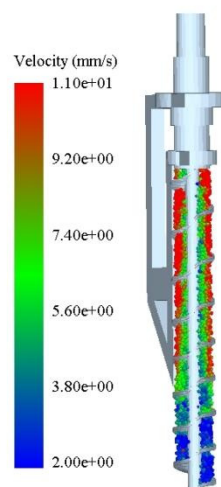


Fig 11. Particle velocity distribution inside a variable pitch screw

From the perspective of powder flow morphology, the variable pitch screw adopts a larger pitch structure in the feeding section, which facilitates the smooth entry of powder into the screw groove and reduces the risk of local accumulation and bridging at the inlet. As the pitch gradually decreases along the axial direction, the powder experiences stronger axial confinement in the middle and rear sections of the screw groove, forming a relatively stable contact network between particles, and effectively suppressing backflow and slippage phenomena. In the small pitch and equal pitch sections at the discharge end, the powder discharge process is more continuous and stable in speed, playing a good role in stabilizing flow and buffering.

The comprehensive simulation results indicate that the variable pitch helical structure outperforms the equal pitch helical structure in terms of powder conveying continuity, mass

flow stability, and metering controllability. Its advantage lies in the rational distribution of pitch along the axial direction, which enables different functional sections of the helix to play their respective roles during the conveying and discharging stages, thereby achieving structural regulation of the powder flow state.

5. Conclusion

the variable pitch structure enhances feeding through a large pitch at the inlet section and forms a stable flow zone with a small pitch at the outlet section, achieving a gradient distribution of axial conveying capacity. This effectively suppresses intermittent bridging and transient emptying phenomena without sacrificing conveying efficiency, significantly improving the continuity and smoothness of the feeding process. The research results verify the structural advantages of the variable pitch screw in high-precision continuous powder feeding, providing a feasible path for the structural design of precision feeding devices. Subsequent optimization through experimental verification and control strategies can further enhance the quantitative control accuracy under micro-flow conditions.

References

- [1] Murch, D. K., White, et al. Integrated Automation for a Mud System[C]//Proceedings of the Drilling Conference. 1994.
- [2] Chen, SuifanCAa, Zhang, et al. The vertical screw conveying characteristics of cohesive particle and optimization of design parameters[J]. *Eksploatacja i Niezawodnosc*, 2023, Vol. 25(1): 134-144.
- [3] Xu, X., Li, et al. Design and Experiment of Quantitative Variable Pitch Screw (Article)[J]. *Nongye Jixie Xuebao/Transactions of the Chinese Society for Agricultural Machinery*, 2019, Vol. 50(12): 89-97.
- [4] XIANG D. Z., XU Y. W. Design parameter selection of spiral conveyor[J]. *Cement Technology*, 2010, (1): 29-33.
- [5] MEI X., KE Z. J., WANG W., et al. Correction of productivity calculation model of vertical screw conveyor[J]. *China Powder Science and Technology*, 2018, 24(4): 37-43.
- [6] Cleary, P.W, Fernandez, et al. Effect of screw design on hopper drawdown of spherical particles in a horizontal screw feeder[J]. *Chemical Engineering Science*, 2011, Vol.66(22): 5585-5601.
- [7] Li, Fei-Xiang, Zong, et al. Pitch design and simulation analysis of variable pitch spiral structure[J]. *Food and Machinery*, 2020, Vol.36(9): 122-126,169.
- [8] Cundall P A, Strack O D L. A discrete numerical model for granular assemblies[J]. *geotechnique*, 1979, 29(1): 47-65.
- [9] Pan C, Li X, He L, et al. Study on the effect of micro-geometric heterogeneity on mechanical properties of brittle rock using a grain-based discrete element method coupling with the cohesive zone model[J]. *International Journal of Rock Mechanics and Mining Sciences*, 2021, 140: 104680.
- [10] CAI Wenyuan, WANG Liqiang, XU Limin. Discrete elemental parameter calibration of ultrafine calcium carbonate based on static and dynamic angle of repose[J]. *China Powder Science and Technology*, 2024, 30(4):81-93.
- [11] FENG Y T, LOUGHRAN J. On upscaling of discrete element models: similarity principles[J/OL]. *Engineering Computations*, 2009, 26(6): 599-609. DOI:10.1108/ 02644 400910975405.