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Simulation Optimization of Hopper and Agitator Parameters for Powder Feeding Device based on EDEM

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Abstract

Aiming at the problems of poor discharging performance and insufficient feeding capacity of powder quantitative feeding devices, coarse coffee granules with a diameter of 1 mm were taken as the research object. The discrete element method (EDEM) was adopted to simulate the feeding process of the screw feeder, and the effects of hopper taper angle, agitator installation and agitator rotational speed on particle velocity and outflow rate at the hopper outlet were investigated. The Hertz-Mindlin (no-slip) contact model was employed. The time step was set to 15%-20% of the Rayleigh time step. The minimum particle velocity, maximum particle velocity, mean particle velocity at the outlet section and the number of discharged particles within 0.05 s were selected as evaluation indices. The results show that the hopper taper angle imposes a remarkable influence on discharging capacity. At a taper angle of 60°, the mean outlet particle velocity reaches 199.9 mm/s and the number of discharged particles is 8 667, both being the maximum values among all schemes; the number of discharged particles increases by 3.1%-12.9% compared with other taper angles. By contrast, both indices decrease by 17%-20% at 75°. Installing an agitator mainly improves the discharging performance under poorly-flowing conditions: the mean velocity rises by 20.4% and the number of discharged particles increases by 4.2% at the taper angle of 75°, while the improvement is less than 1% for 60° and 90°. Within the investigated rotational-speed range of 3-20 r/min, the agitator speed exerts a weak effect on discharging capacity, with maximum variations of 0.3% for mean velocity and 1.1% for particle outflow count. 10 r/min is the relatively preferred value, yet higher rotational speed aggravates the dispersion of outlet particle velocity and impairs feeding uniformity. Accordingly, a feeding scheme with a 60° hopper taper angle and an agitator operating at 10 r/min is determined. Restricted by the short simulation duration and single-sphere particle model, the obtained results serve as relative comparisons under identical initial conditions, and the absolute flow rate needs to be calibrated via prototype tests.

Keywords

Powder Quantitative Feeding; Discrete Element Method; Hopper Taper Angle; Agitator Rotational Speed; Granular Flow; Screw Feeding.

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1. Introduction

In numerous industrial production processes such as chemical, food and pharmaceutical industries, high requirements are imposed on accurate conveying and quantitative feeding of powder materials. Screw conveying features simple structure, convenient maintenance and low cost[1]. At present, powder quantitative feeders are widely adopted by domestic and foreign food and pharmaceutical manufacturers for metering and packaging of powder and granular materials.Van Thien Tran[2] developed a rapid calculation tool with VBA-Excel in 2023. Meanwhile, the EDEM simulation software was used to model the behaviour of granular materials. The calculation results guided the selection of optimal technical dimensions for screw conveyors and generated comprehensive charts describing the relationship between screw rotational speed and throughput, providing a method for fine-tuning throughput with high accuracy on production lines.D. Rhymer[3] proposed an eight-shaped cylindrical barrel design, which is recognised as highly efficient for particle transportation. Compared with other barrel structures, greater interaction force exists between this barrel and the screw, which substantially shortens material throughput time.Milada Pezo et al.[4] studied the transportation and mixing mechanisms inside screw conveyors by experiments and discrete-element simulations, promoting broader application of DEM in performance optimisation of screw conveyors in various industries.Le Yusheng[5] designed a high-precision quantitative-feeding control system for ore powder based on fuzzy-PID control. It provides reference for the design of quantitative-feeding control systems for metallic, inorganic and organic powders and possesses promising application prospects.

2. Working Principle

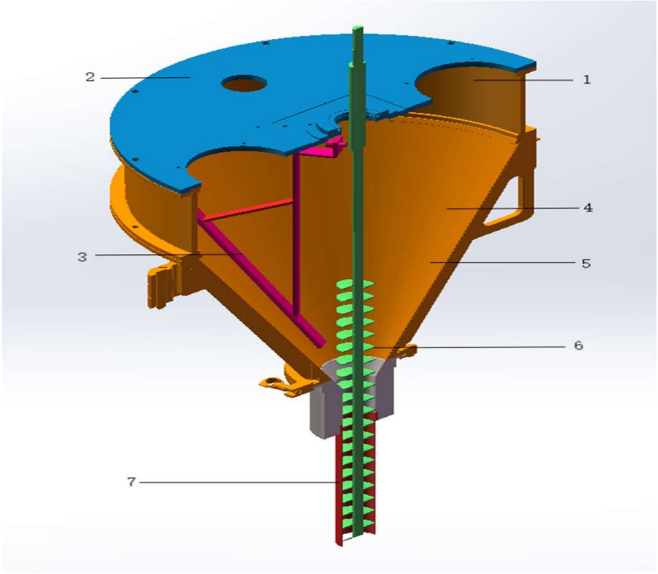
A powder quantitative feeder is a continuous conveying device driven by rotating screw blades. Its core components consist of a screw shaft, tubular housing and driving unit. During operation, materials are forced to move along the vertical direction under centrifugal force and friction generated by rotating screw blades. It is suitable for short-distance vertical conveying of powder and granular materials with moderate flowability. Characterised by compact layout and favourable sealing performance, it effectively prevents dust leakage. Widely applied in material lifting procedures for grain processing, chemical engineering and building-material industries, it features small footprint, high efficiency and strong anti-blocking capability. Nevertheless, rational matching between rotational speed and filling ratio is required to balance energy consumption and component wear. The basic structure of the powder quantitative feeder is shown in Figure 1.

The shaft end of the screw main shaft is tightly connected to the motor through a coupling, with screw blades welded on its lower section. As the core component of the feeder, the continuously rotating screw blades push materials downwards. Materials enter the hopper through the inlet port. The agitator plays an important auxiliary role: it assists feeding, mitigates material accumulation and blocking risks, accelerates material inflow and improves conveying efficiency. After being conveyed by screw blades, materials pass through the conveying barrel and are finally discharged from the outlet for filling operations.

Coarse coffee granules with a diameter of 1 mm are selected as the conveyed material in this study. It is necessary to analyse basic physical properties including density and bulk density of coarse coffee. These parameters directly influence flow behaviour and accumulation state of coffee granules inside the feeder and provide accurate material-property support for subsequent structural design.

In the EDEM simulation environment, the whole motion process of coarse coffee granules inside the feeder can be observed in detail. The motion trajectory and velocity distribution of particles from inlet to outlet are investigated. Simulations under different working conditions are carried out to identify particle-flow rules and corresponding influencing factors, laying a foundation for feeder optimisation.

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1-Inlet port, 2-Working plane, 3-Agitator, 4-Hopper, 5-Screw main shaft, 6-Screw blade, 7-Conveying barrel

Figure 1. Schematic diagram of powder quantitative feeder

3. Establishment of Simulation Model

3.1 Basic Parameter Setting

Food-grade 304 stainless steel is selected for device components. Food-grade 304 stainless steel exhibits excellent corrosion resistance, favourable mechanical and machining performance, wide service-temperature range, high cost-performance and recyclability. With stricter quality requirements than ordinary 304 stainless steel, it guarantees food safety during production, processing, storage and consumption.

The conveyed material is coarse coffee granules with a diameter of 1 mm. As dry and highly porous granular material, coarse coffee possesses low density and moderate elasticity. Its particles feature rough and irregular surfaces, leading to remarkable friction effects and tendencies of accumulation or adhesion during flow. Owing to porous and brittle characteristics, considerable energy dissipation occurs upon particle collision with low restitution capacity. Dry coarse coffee presents satisfactory flowability, yet adhesion increases significantly under damp conditions or with residual grease, which may cause caking and blocking. Special attention shall be paid to flow stability and energy control during conveying and mixing. Key physical and contact parameters are obtained from relevant references, as listed in Table 1 and Table 2.

Table 1. Physical parameters

Material	Poisson's ratio	Shear modulus	Density /(kg/m³)
Coarse coffee granule	0.2	5.0e+08 Pa	400
304 stainless steel	0.3	7.692e+09 Pa	7930

Table 2. Contact parameters

Contact pair	Restitution coefficient	Static-friction coefficient	Rolling-friction coefficient
Coarse coffee-coarse coffee	0.3	0.5	0.08
Coarse coffee-304 stainless steel	0.4	0.4	0.04

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3.2 Import of Device and Particle Model

Model complexity decreases simulation speed in EDEM. Therefore, geometric simplification is implemented for simulation optimisation. The simplified geometry is saved in STL format and imported into EDEM, as illustrated in Figure 2. Length unit is set to millimetre and velocity unit to millimetre per second. The Hertz-Mindlin (no-slip) contact model is adopted for both particle-particle and particle-wall contacts between coarse-coffee granules and 304 stainless-steel surfaces.

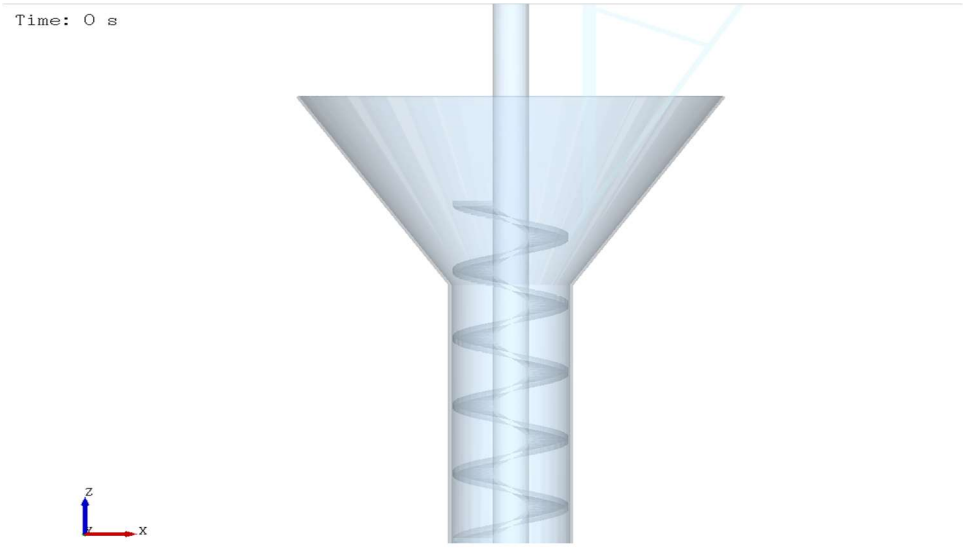


Figure 2. Simplified model of powder quantitative feeder

For particle setup, a bulk material template is created in EDEM, followed by particle definition as shown in Figure 3. Single-sphere particles with a physical radius of 0.5 mm are defined with 100 % weight fraction. Remaining particle-property parameters are calculated automatically by EDEM, as shown in Figure 4.

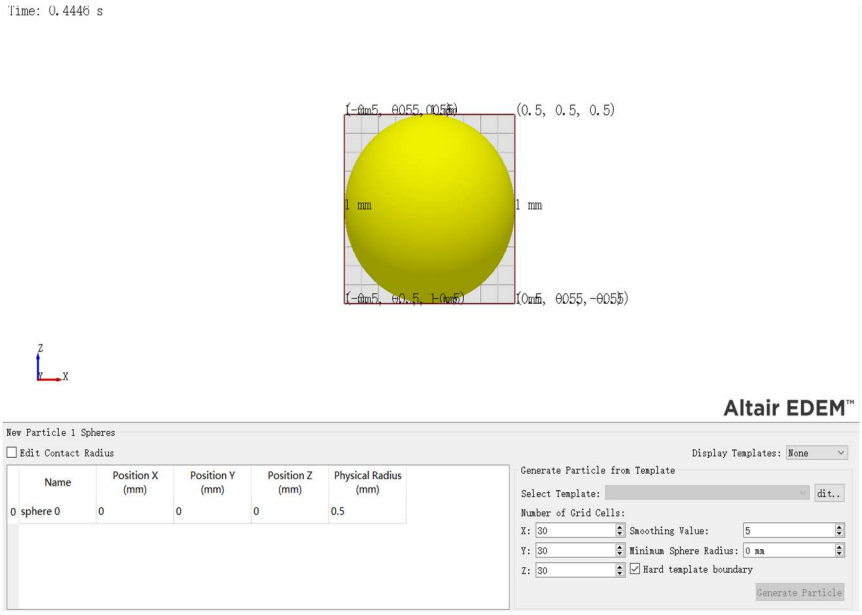


Figure 3. Particle generation setup

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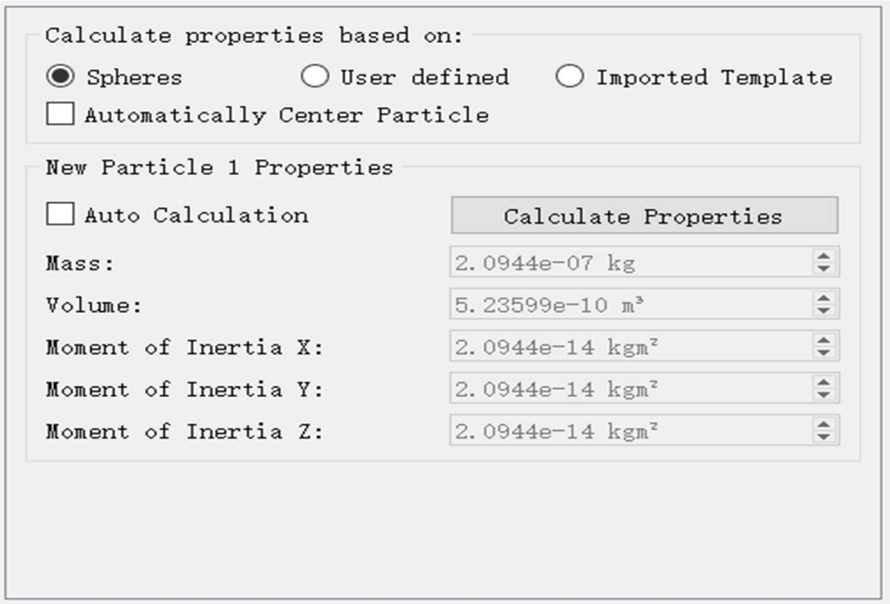


Figure 4. Property configuration of single particle

4. Simulation Result Analysis

4.1 Simulation Scheme and Statistical Criteria

Taking 1 mm coarse coffee granules as conveying material, discrete-element simulations are performed focusing on two factors: hopper taper angle and agitator rotational speed. To ensure comparability among cases, identical geometric model (Figure 2), particle physical parameters, contact parameters (Table 1, Table 2) and the Hertz-Mindlin (no-slip) contact model are applied for all simulation cases. Only structural or kinematic parameters under investigation are modified while other conditions remain unchanged.

The GPU CUDA solver is utilised. The time step is set to 20 % of the Rayleigh time step for cases without agitators; for agitator-equipped cases, the time step is reduced to 15 % to guarantee computational stability for additional particle-agitator contacts. Data-saving interval is 0.01 s and total simulation duration for each case is 0.3 s.

Discharging performance is characterised by particle kinematics at the hopper outlet section. A cross-section selection zone is established at the hopper outlet to acquire the minimum, maximum and mean particle velocity. A Grid Bin Group is configured to count particles passing through the outlet cross-section. The statistical time window is set from 0.25 s to 0.30 s (time duration: 0.05 s), and the number of outflow particles *N* within this window serves as an equivalent indicator of outflow rate. Since uniform 1-mm particle size is adopted for all cases, *N* corresponds proportionally to mass flow rate and supports horizontal comparison among different schemes.

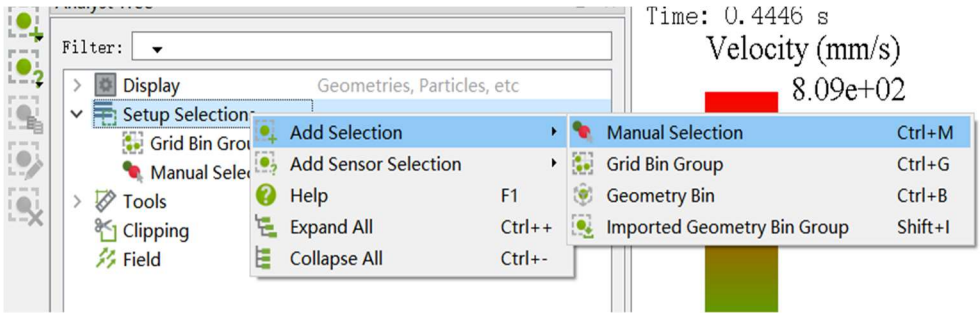


Figure 5. Enable manual particle-selection function

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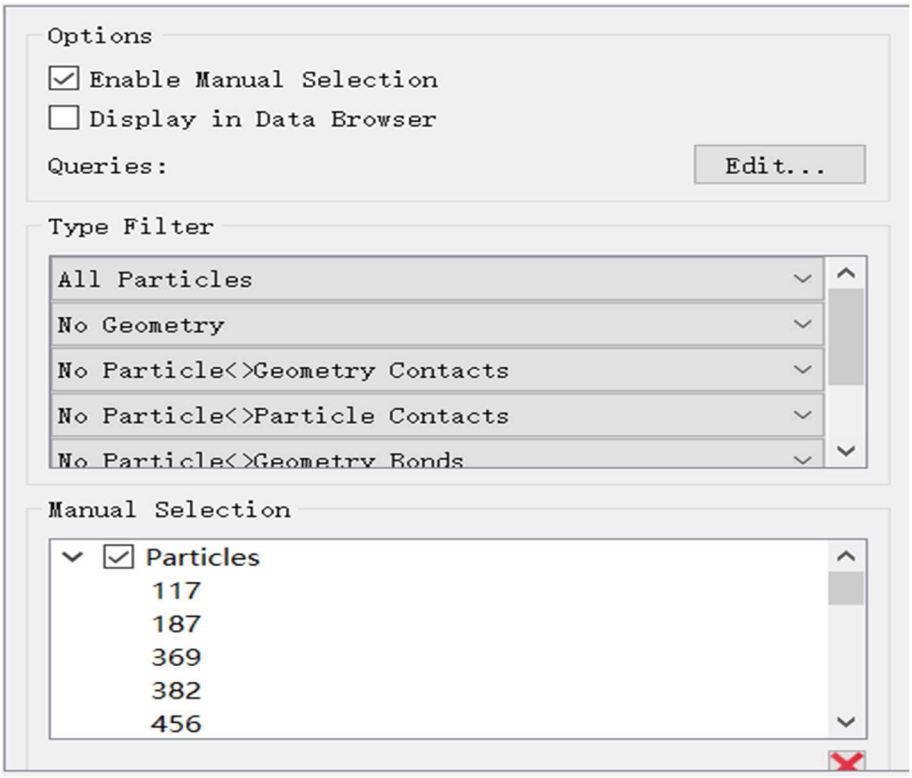


Figure 6. Manual selection of particles within target region

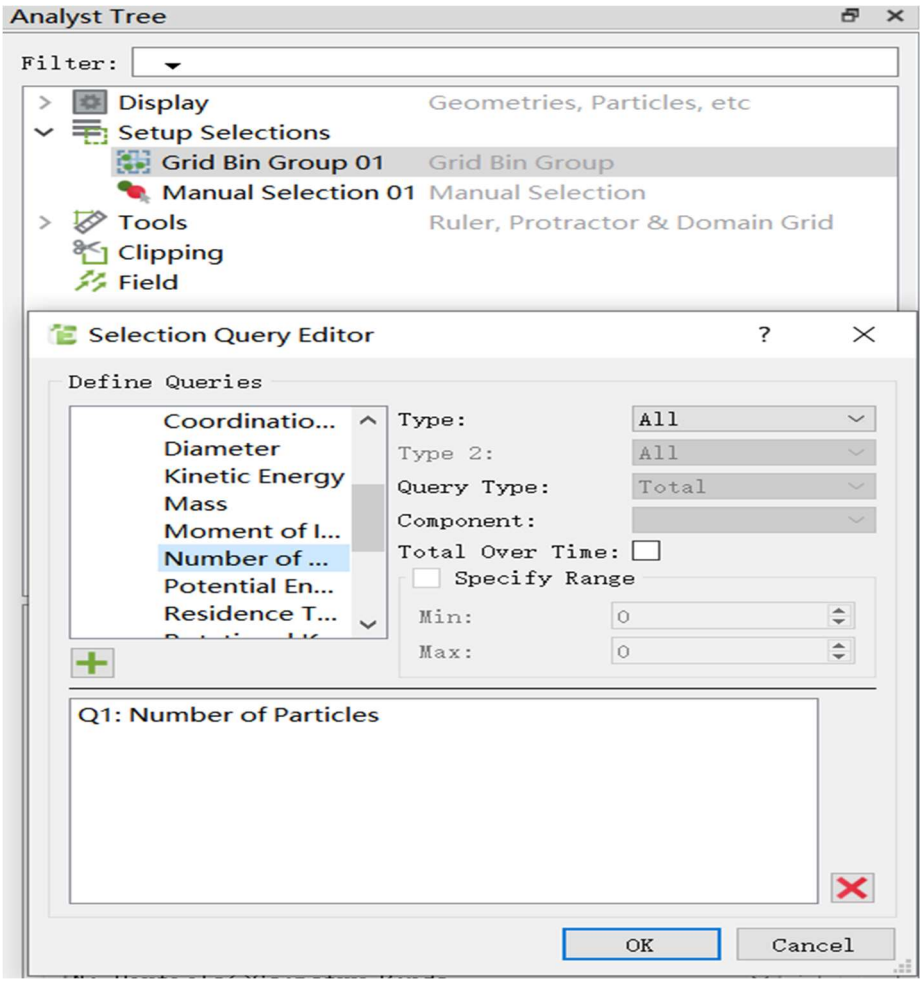


Figure 7. Add Grid Bin Group filter

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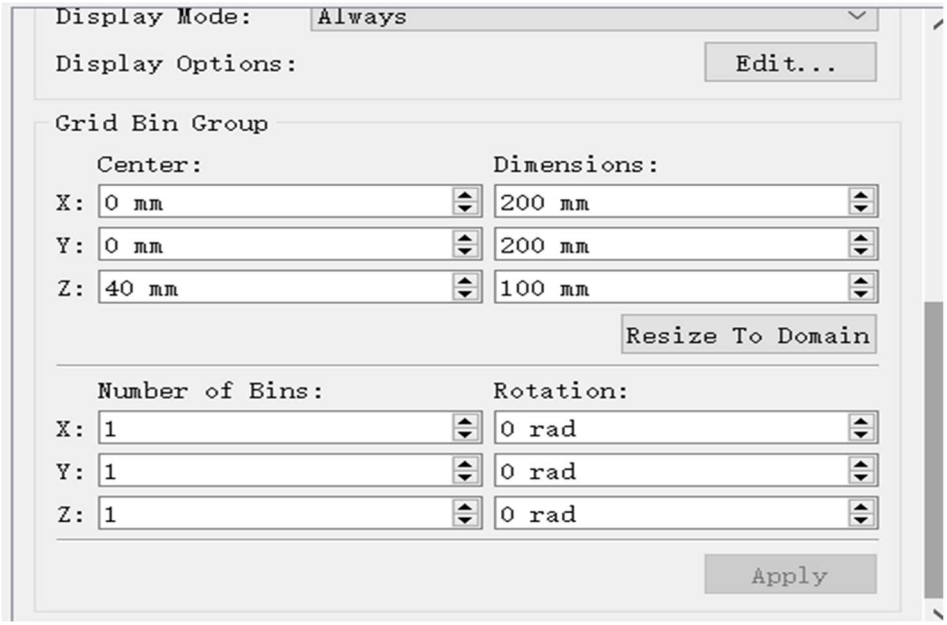


Figure 8. Dimension configuration of filter region

4.2 Influence of Hopper Taper Angle on Discharging Performance

No agitator is installed inside the hopper. Four hopper-taper-angle levels (45°,60°,75°,90°) are investigated with other conditions consistent with Section 4.1. Simulation results of outlet-section particle velocity and outflow-particle count are summarised in Table 3. Particle-velocity contours for each scheme are presented in Figure 9-Figure 12.

Table 3. Simulation results under different hopper taper angles without agitator

Hopper taper angle/(°)	Minimum velocity/(mm/s)	Maximum velocity/(mm/s)	Mean velocity/(mm/s)	Number of outflow particles *N* within 0.05 s
45	39.74	430.72	194.50	7 973
60	46.69	438.97	199.90	8 667
75	25.43	284.46	165.99	7 678
90	10.08	431.79	199.23	8 406

As listed in Table 3, the mean outlet-section particle velocity for four taper-angle schemes is 194.5 mm/s, 199.9 mm/s, 166.0 mm/s and 199.2 mm/s respectively, and the corresponding outflow-particle count is 7 973, 8 667, 7 678 and 8 406. Both indicators reach their maximum values at 60°. Compared with 45°, 75° and 90°, the number of outflow particles increases by 8.7 %, 12.9 % and 3.1 % respectively; the mean velocity rises by 2.8 % and 20.4 % relative to 45° and 75°, and differs merely by 0.3 % from that at 90°.

At 75°, both mean velocity and outflow-particle count decrease simultaneously and drop by 17 %-20 % compared with other schemes. Its maximum particle velocity is only 284.5 mm/s, distinctly lower than approximately 430 mm/s of other cases, indicating significant deterioration of particle-flow behaviour at the hopper outlet. The difference in mean velocity and outflow-particle count between 45° and 90° is 0.3 % and 1.0 % respectively, falling within the fluctuation range of simulation batches. Their discharging capacities can be regarded as equivalent.

Judging merely by discharging velocity and flow rate, 60° represents the preferable value among the four alternatives. Nevertheless, hopper-taper-angle selection shall also consider arching and bridging

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risks inside the hopper. A small taper angle leads to sharp contraction of the cross-section at the lower hopper, where stable particle arches may form above the outlet and interrupt discharging. This paper adopts outlet-section velocity and flow rate as evaluation criteria without quantifying particle contact force and arch-evolution inside the hopper. Therefore, this conclusion needs further validation combined with internal hopper-flow analysis.

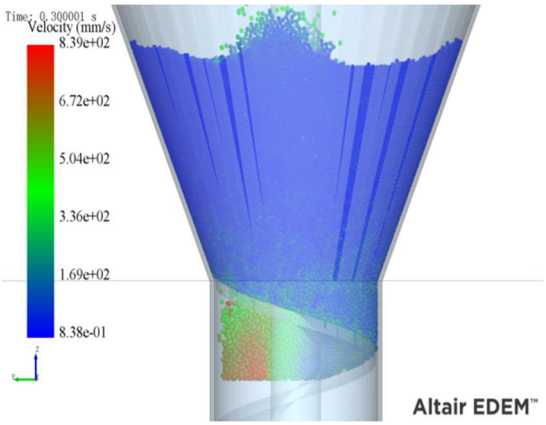


Figure 9. Velocity contour at hopper taper angle of 45°

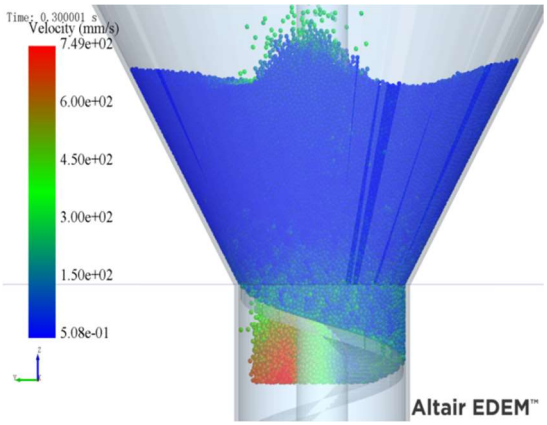


Figure 10. Velocity contour at hopper taper angle of 60°

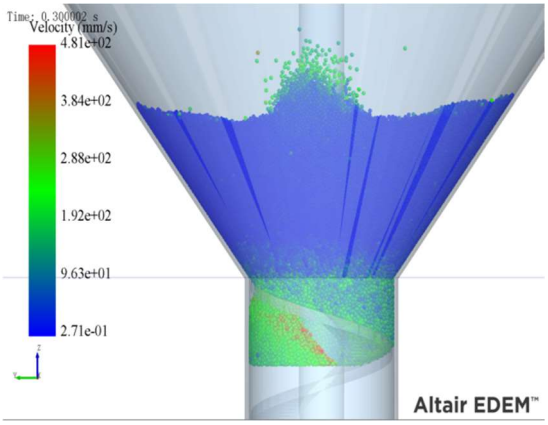


Figure 11. Velocity contour at hopper taper angle of 75°

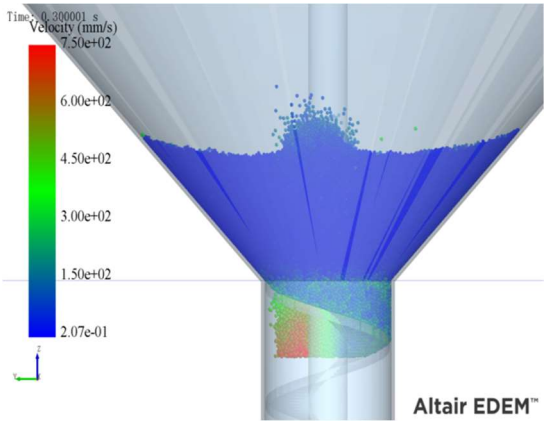


Figure 12. Velocity contour at hopper taper angle of 90°

4.3 Influence of Agitator on Discharging Performance

An agitator is installed inside the hopper with identical taper angles. The agitator rotational speed is set to −10 r/min (negative sign denotes opposite rotation direction relative to the screw main shaft). Other conditions follow Section 4.1, and results are shown in Table 4. Outlet-section particle-velocity contours are displayed in Figure 13-Figure 16. For strict comparison with Table 3, the number of outflow particles in Table 4. is also counted within the time window of 0.25-0.30 s.

Compared with Table 3, after installing the agitator, the mean outlet-section particle velocity for four taper-angle schemes becomes 194.8 mm/s, 206.5 mm/s, 199.9 mm/s and 201.4 mm/s, and the corresponding outflow-particle count is 8 065, 8 677, 8 004 and 8 371. The most remarkable improvement occurs for the 75° case: the mean velocity increases from 166.0 mm/s to 199.9 mm/s (20.4 % increment), and the outflow-particle count rises from 7 678 to 8 004 (4.2 % increment). For 45°, the mean velocity and outflow-particle count increase by 0.2 % and 1.2 % respectively. For 60°, the mean velocity grows by 3.3 %, yet the outflow-particle count only increases by 10 (0.1 % increment). For 90°, the mean velocity rises by 0.9 %, while the outflow-particle count decreases slightly by 0.3 %.

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Table 4. Simulation results under different hopper taper angles with agitator (agitator speed −10 r/min)

Hopper taper angle/(°)	Minimum velocity/(mm/s)	Maximum velocity/(mm/s)	Mean velocity/(mm/s)	Number of outflow particles *N* within 0.05 s
45	54.66	446.43	194.80	8 065
60	55.47	441.22	206.50	8 677
75	40.27	371.11	199.90	8 004
90	10.52	448.12	201.40	8 371

The above results indicate that the improvement brought by the agitator varies with hopper taper angle. For the 75° case with poor inherent flowability and low outflow rate, the disturbance of the agitator breaks particle arches at the lower hopper and recovers discharging capacity obviously. For 60° and 90° with favourable original flow status, the improvement induced by the agitator stays within the range of statistical fluctuation. Hence, it cannot be generalised that installing an agitator yields better performance under all taper-angle conditions. More precisely, the agitator mainly enhances discharging performance under poorly-flowing working conditions and exerts limited influence under smooth-flow conditions.

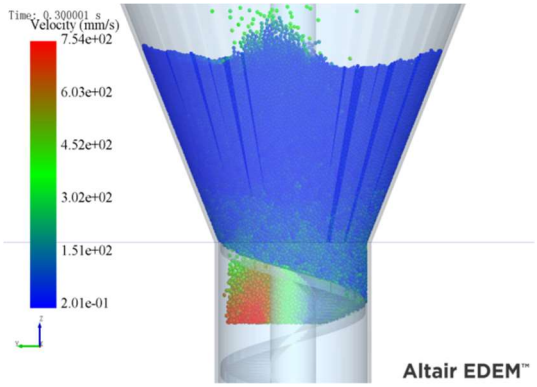


Figure 13. Velocity contour for hopper taper angle of 45° with agitator

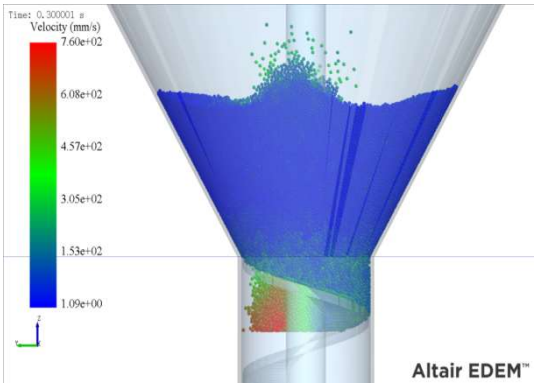


Figure 14. Velocity contour for hopper taper angle of 60° with agitator

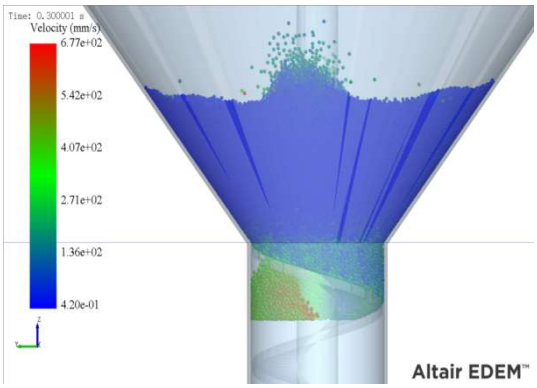


Figure 15. Velocity contour for hopper taper angle of 75° with agitator

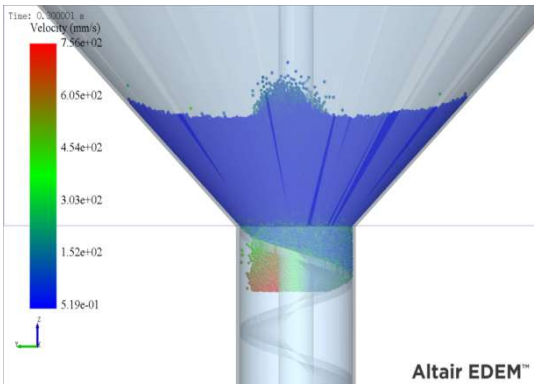


Figure 16. Velocity contour for hopper taper angle of 90° with agitator

4.4 Influence of Agitator Rotational Speed on Discharging Performance

The hopper geometry and agitator mounting position are fixed. Only agitator rotational speed is adjusted: six speed levels of 3 r/min, 5 r/min, 10 r/min, 13 r/min, 15 r/min and 20 r/min (rotating

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opposite to the screw main shaft) are adopted. Other conditions keep consistent with Section 4.1. The rotational-speed configuration interface is shown in Figure 17, and simulation results are listed in Table 5.

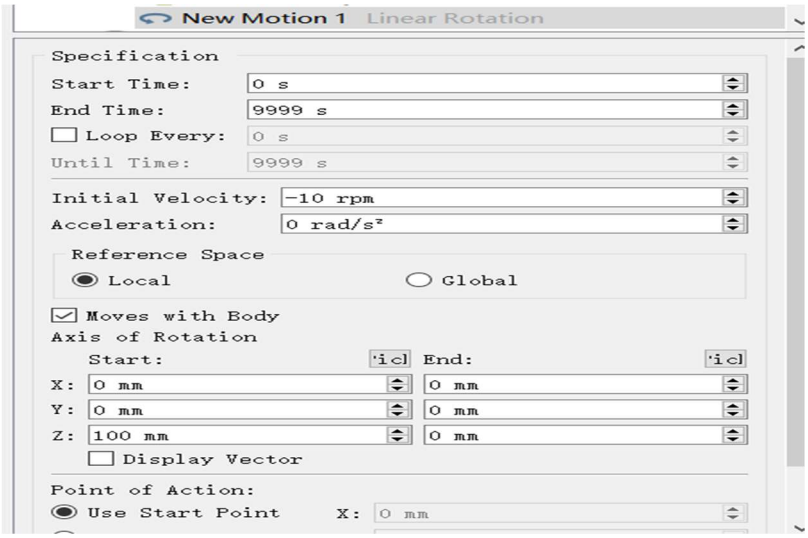


Figure 17. Setup of agitator rotational speed

Table 5. Simulation results under different agitator rotational speeds

Agitator rotational speed/(r/min)	Minimum velocity/(mm/s)	Maximum velocity/(mm/s)	Mean velocity/(mm/s)	Number of outflow particles *N* within 0.05 s
3	508.61	690.02	634.94	43 697
5	507.72	688.13	636.02	43 816
10	517.69	688.54	636.87	43 946
13	490.09	700.44	634.79	43 751
15	442.47	718.32	635.19	43 467
20	497.98	688.09	634.92	43 475

As presented in Table 5, when rotational speed increases from 3 r/min to 20 r/min, the mean outlet-section particle velocity varies between 634.8 mm/s and 636.9 mm/s with a maximum variation of 0.3 %; the number of outflow-particles ranges from 43 467 to 43 946 with a maximum variation of 1.1 %. Both indicators reach their peak values at 10 r/min and decline slightly with further speed growth, showing an overall unimodal trend of first increasing and then decreasing.

On the other hand, the difference between maximum and minimum outlet-particle velocity generally enlarges with rising rotational speed: it is 171-181 mm/s within 3-10 r/min, increases to 210 mm/s at 13 r/min and reaches the maximum value of 275.8 mm/s at 15 r/min. Larger velocity difference implies higher dispersion of outlet-particle velocity and intensified fluctuation of instantaneous outflow rate, which impairs feeding uniformity and accuracy. Therefore, for devices targeting high feeding accuracy, excessively high agitator speed should be avoided. The speed around 10 r/min balances discharging capacity and flow stability.

5. Conclusion

In this paper, coarse coffee granules are selected as conveyed material. The discharging process of a powder quantitative feeder is simulated by the discrete element method, and parametric analysis is

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carried out for hopper taper angle and agitator rotational speed. The main conclusions are summarised as follows:

(1) The hopper taper angle exerts a significant influence on discharging capacity. Without an agitator, both the mean outlet-particle velocity (199.9 mm/s) and the number of outflow particles (8 667) reach maximum values at the taper angle of 60°, and the outflow-particle count increases by 3.1 %-12.9 % compared with other schemes. Both indicators decrease by 17 %-20 % at 75°, which corresponds to the least favourable condition. Considering discharging velocity and flow rate comprehensively, the hopper taper angle is recommended to be 60°.

(2) Installing an agitator mainly improves discharging performance under poorly-flowing conditions. At 75°, the mean velocity rises by 20.4 % and the number of outflow particles increases by 4.2 %, achieving the most prominent improvement. Variations are less than 1 % for 60° and 90°, and approximately 1 % for 45°. Taking structural complexity, cleaning-maintenance requirements and particle-breakage risk for brittle materials into consideration, the agitator should be adopted as an auxiliary arch-breaking component rather than a universal efficiency-enhancing measure.

(3) Within the investigated rotational-speed range of 3-20 r/min, agitator speed imposes weak influence on discharging capacity. The maximum variations of mean velocity and outflow-particle count are 0.3 % and 1.1 % respectively. 10 r/min is the relatively-preferred value in this batch of simulation cases. Higher rotational speed aggravates the dispersion of outlet-particle velocity and reduces feeding uniformity; accordingly, excessive agitator speed shall be avoided.

(4) Restricted by short total simulation duration (0.3 s) and the single-sphere particle model, the results in this paper serve as relative comparisons under identical initial conditions and support structural-parameter selection. Absolute flow-rate values can only be adopted for engineering quantitative design after particle-parameter calibration and prototype tests. Future work will extend simulation duration until stable flow rate is obtained, supplement repose-angle calibration and quantitative analysis of hopper internal arching behaviour, and carry out prototype tests to verify simulation conclusions.

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