Dynamic characteristic analysis of vertical screw conveyor in variable screw section condition

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Abstract

Vertical screw conveyors are used widely in industry for elevating bulk materials over relatively short distances, but the problem of insufficient feeding and low conveying efficiency always exist in the vertical conveying process. In this paper, a vertical screw conveyor with variable screw section is presented, and the characteristics of vertical screw conveyor are investigated under the variable screw sections using discrete element method (DEM). The results show that the particle volume fraction in the inlet and the mass flow rate increase in the condition of variable screw section, and the screw rotational speed has a significant influence on mass flow rate. It is evident that the design of variable screw section provides an effective way in improving the particle feeding rate and the conveying efficiency.

Keywords

Particle conveying, DEM, variable screw section

Introduction

Bulk materials widely exists in industrial production, that is, grain, coal, metal ore. The vertical screw conveyor is a kind of continuous conveying equipment, which is used for transporting all kinds of powder, granule, and lump materials with high efficiency, small pollution and saving space. It consist of a screw flight, a screw shaft connected to a driving device, a cylindrical casing, and so on. Despite its

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structure simplicity, the mechanics of the conveying progress is very complex and
the vertical screw conveyor design relies heavily on empirical performance data.\(^1\)

Many scholars have made theoretical research on particle conveying of vertical
screw conveyor. Roberts\(^2\) analyzed the granular vortex motion of the enclosed ver-
tical screw conveyor theoretically, and an expression for volumetric efficiency was
obtained. Rademacher\(^3\) studied the effect of conveying section and inlet section on
delivery capacity by theoretical derivation. Evstratov et al.\(^4\) theoretically estab-
lished an applicable model of granular flow movement in vertical screw conveyor,
and adequate mathematical analysis of conveying process were given, but relevant
experiments was not carried out to validate the theoretical model.

With the development of computer technology, DEM simulation software
becomes one of the more effective tool to investigate particle behavior in various
engineering fields. Ono et al.\(^5\) conducted a study about the influence of elemental
shape on cutting resistance of soil in soil-machine interaction progress by compar-
ing DEM simulation and experimental results. Tsunazawa et al.\(^6\) presented a
numerical contact model for wet particles considering quantitatively the effect of
the cohesive force in contact states, and the experiments for the validation of this
model was conducted. Kobayakawa et al.\(^7\) studied the interaction force between
the inclined plate and dry granular materials, and the effect of the rake angle of the
plate on the drag force acting on the plate was investigated. Shimizu and Cundall\(^8\)
firstly used DEM to investigate particulate flow in a screw conveyor, and the
results showed that DEM was sufficiently developed to analyze the performance of
screw conveyor. Cleary et al.\(^9,10\) conducted various industrial DEM simulation to
get better understanding the dynamics of industrial particle flow, and it was con-
cluded that DEM simulation was able to give reasonable prediction for complex
industrial processes.

The research of vertical screw conveyor mainly focuses on upgrading conveying
efficiency. The capacity of vertical screw conveyor is affected by many factors, such
as feed quantity, screw rotational speed, material filling rate, screw pitch, etc.
Owen et al.\(^11,12\) studied the influence of different angles, rotational speeds and fill-
ing rates on the conveying performance using DEM, and the predictions of charac-
teristic parameters, that is, particle speeds, mass flow rate, energy dissipation and
power consumption, varied with different operating conditions were investigated.
However, the relevant research of improving conveying efficiency and blockage for
vertical screw conveyor by changing structure or operation parameters hasn’t been
proposed yet.

In this paper, a vertical screw conveyor with variable screw section is presented
to improve conveying efficiency. Firstly, the DEM parameters are calibrated by the
disk experiment. Then, the conveying process of soybean in a vertical screw con-
veyor with variable screw section is numerically investigated by DEM. The particle
dynamic characteristics are compared under different variable screw section and a
traditional constant screw section. At last, in order to analyze the performance of
variable screw section, the conveying capacity and power consumption with differ-
ent screw rotational speeds are investigated.
**DEM simulation**

**DEM contact model**

The dry particles simulated in DEM are typically assumed as perfectly smooth spheres with infinite rigidity. This means there is only a single contact point between two particles when they come into contact. Also, particles are not allowed to deform but are able to overlap. The overlaps are used to determine the contact forces. The classical contact model in DEM is the Hertz-Mindlin (no slip) model which is also adopted for the contacts between particles and boundaries. It is described as follows. For two contact particles $i$ and $j$, the contact forces are typically resolved into a normal force and a tangential force, each of which has two components. The normal force is independent of the tangential force. As shown in Figure 1, the normal contact force consists of the forces resulted from a spring and a damper. Similarly, the tangential force also contains a spring force (the shear force) and a damping force.$^{13}$

![Figure 1. Hertz-Mindlin (no slip) contact model. (a) Normal force (b) Tangential force.](image)

**DEM parameters validation**

As we know, the particle DEM parameter of friction coefficient is difficult to obtain, and then the macroscopic properties of the particle angle of repose is often used to calibrate and validate these parameters which are difficult to measure. There are many researchers have focused on the use of quasi-static experiments to validate the DEM simulation parameters. However, investigations have shown that DEM parameters derived from static validation experiments are often
unsatisfactory for dynamic DEM simulations. In order to accurately acquire the dynamic characteristics of particles in the conveying process, the DEM parameters are validated using the disk experimental device, comparing the simulation results with the disk experiment results is an effective way to validate and calibrate the DEM parameters.\textsuperscript{14,15} A schematic representation of the rotating disk apparatus is shown in Figure 2, it consists of measuring rods, circular casing, central axis, horizontal disk and variable speed motor. The horizontal disk imparts circumferential motion to the particles. When the disk is adjusted at a certain rotational speed, the particles also gradually flow to the tube wall until the free surface reaches a limit equilibrium state. The measuring rods are installed perpendicularly to measure the particle free face. The diameter of the disk is 200 mm, and the disk could be regarded as a screw flight with zero pitch. The motor drives the horizontal disk to rotate through the central axis, and thus the material rotation movement in the conveyor is simulated. Under the stable operation condition, the particles will not move axially, and the material movement state can be maintained.

The validation process is mainly to compare the free surface of the disk experiment with that of the DEM simulation. The parameters of DEM simulation which free surface is similar to the disk experiment are the calibration goal. The soybean DEM parameters are given in Table 1.

The coefficient of restitution determines the post-collisional velocities and the rate of energy dissipation in direct particle impacts, and the Coulomb friction is dominated by static friction coefficient.\textsuperscript{16} Therefore, the restitution coefficient and static friction coefficient should be calibrated, the calibration parameter groups are detailed in Table 2, the other DEM simulation parameters are consistent with the Table 1. The disk rotating speed is 150 rpm and the initial filling height of soybean is 30 mm. The maximum diameter D2 of each set of variable helix is increased by 60 mm in turn, and the values are taken at equal intervals from 550 mm.
In the disk experiment, the height data of the particle surface is measured using 12 vertical rod with equal distance. 12 calculation points are selected to measure the height in the DEM simulation in accordance with the disk experiment. In Group 1, the free surface of DEM simulation is shown in Figure 3(a). The height data of the disk experiment is compared with that of the DEM simulation, and results are illustrated in Figure 3(b). The determination factor \( R^2 \) of the material height is calculated to illustrate the consistency between the simulation results and the experimental results.

The determinant coefficients \( R^2 \) of Group 1 to Group 5 are 0.973, 0.961, 0.921, 0.943 and 0.895, respectively. According to the \( R^2 \) value in the simulation analysis, it is undeniable that random error exists in the experiment and the simulation when there are some particle instabilities jumping. But, it is clear that the consistency between the free surface simulation results and experiments from the value of \( R^2 \), and the random error within 5%, it thus can be conclude that the Group 1 parameters can be used in the screw conveying simulations.

### Table 1. Parameters in experiment and DEM simulation.

| Parameters                                    | Experiment | Simulation |
|-----------------------------------------------|------------|------------|
| hRadius of soybean (mm)                       | 5          | 5          |
| Poisson ratio of soybean                      | -          | 0.2        |
| Poisson ratio of steel                        | -          | 0.3        |
| Shear modulus of soybean (Pa)                 | -          | \( 1 \times 10^8 \) |
| Shear modulus of steel (Pa)                   | -          | \( 7 \times 10^{10} \) |
| Density of soybean (kg/m³)                    | 1200       | 1200       |
| Density of steel (kg/m³)                      | 7850       | 7850       |
| Restitution coefficient between soybeans      | -          | 0.5 (varied 0.4–0.6) |
| Restitution coefficient between soybean and steal | -          | 0.5 (varied 0.4–0.6) |
| Static friction coefficient between particles  | -          | 0.5 (varied 0.4–0.6) |
| Static friction coefficient between soybean and steal | -          | 0.5 (varied 0.4–0.6) |
| Rolling friction coefficient between soybeans  | -          | 0.01       |
| Rolling friction coefficient between soybean and steal | -          | 0.02       |

In Table 1, \( \varepsilon \) is restitution coefficient; \( \mu_s \) is static friction coefficient; \( p \rightarrow p \) means simulation value between soybeans, \( p \rightarrow g \) means simulation value between soybean and geometry.

### Table 2. Simulation setting for calibration parameters.

| Group | \( \varepsilon(p \rightarrow p) \) | \( \varepsilon(p \rightarrow g) \) | \( \mu_s(p \rightarrow p) \) | \( \mu_s(p \rightarrow g) \) |
|-------|----------------------------------|----------------------------------|--------------------------|--------------------------|
| 1     | 0.6                              | 0.5                              | 0.4                      | 0.5                      |
| 2     | 0.5                              | 0.5                              | 0.5                      | 0.5                      |
| 3     | 0.5                              | 0.6                              | 0.5                      | 0.4                      |
| 4     | 0.4                              | 0.5                              | 0.4                      | 0.6                      |
| 5     | 0.6                              | 0.4                              | 0.6                      | 0.6                      |

Note: \( \varepsilon \) is restitution coefficient; \( \mu_s \) is static friction coefficient; \( p \rightarrow p \) means simulation value between soybeans, \( p \rightarrow g \) means simulation value between soybean and geometry.
Vertical screw conveyor model with feeding funnel

The DEM simulation model is shown in Figure 4. The parameters of geometry model are as follows: diameter of the screw shaft $d$ 140 mm, the diameter of the upper equal screw flight $D_1$ 550 mm, the maximum diameter of the lower screw flight $D_2$, the thickness of the screw flight $t_s$ 4 mm, the clearance between the screw flight and the casing wall $C$ 5 mm, and the thickness of the casing $t$ 8 mm.

Figure 3. The material free surface morphology of Group 1 (a) simulated material surface diagram (b) comparisons between simulation and disc experiment results of material surface.

Figure 4. DEM model of screw conveyor with variable screw section.
The maximum diameter of screw flight $D_2$ is set according to certain rules. As shown in Table 3, four groups simulation are set up, and a series of different screw rotational speeds are set up to investigate the particle dynamic characteristics for each group. The constant screw section is used in geometry model of Group 1, and the variable screw section is used in the other three groups.

### Table 3. Four different simulation cases.

| No.   | Maximum diameter of screw flight $D_2$ (mm) | Screw rotation speed n (rpm) |
|-------|-------------------------------------------|-------------------------------|
| Case.1| 550                                       | 150, 200, 250, 300            |
| Case.2| 610                                       | 150, 200, 250, 300            |
| Case.3| 670                                       | 150, 200, 250, 300            |
| Case.4| 730                                       | 150, 200, 250, 300            |

![Figure 5. Distribution of particle axial velocity of different cases.](image)

The maximum diameter of screw flight $D_2$ is set according to certain rules. As shown in Table 3, four groups simulation are set up, and a series of different screw rotational speeds are set up to investigate the particle dynamic characteristics for each group. The constant screw section is used in geometry model of Group 1, and the variable screw section is used in the other three groups.

### Numerical analysis and discussion of simulation results

**Particle velocity distribution in variable screw section condition**

To get a better understanding of the particle flow in the inlet, the particle velocity distribution is investigated. Figure 5 shows the particles axial velocity distribution in the variable screw section for four cases with the screw rotational speed 150 rpm. The particles are colored according to their speed grade. The faster moving
particles are marked red 3m/s, the slower moving particles are marked blue 0m/s, and the intermediate velocity particles are marked cyan.

From Figure 5, it can be seen that from Case 1 to Case 4, with the increase of the maximum diameter $D_2$, the number of red particles gradually increase, which indicates the particles with high axial velocity have increased. The above results show that the variable screw section is beneficial to particles accelerating process.

The main view and the top view of the transverse section at the variable section of DEM simulation are shown in Figures 6 and 7. Figures 6 and 7 are consistent with Figure 5 in coloring. Figures 6 and 7 clearly show the particle axial velocity distribution at different screw sections of vertical screw conveyor.

Figure 7 shows that the quantity of high velocity particles (marked red) in the inlet increases gradually with the increase of diameter $D_2$. This is due to the fact that the increasing contact area between screw flight and particles in the inlet, thus particles contact with screw flight directly, and then particles move to the edge of screw as the centrifugal force.

**Particle number statistics at the bottom of screw**

In the feeding process, the high rotational speed of screw flight influences particles movements strongly. In order to investigate the influence of different screw diameters on feeding process, the particle number is counted at variable screw section region with different cases. As shown in Figure 8, the region with variable screw section is divided into $8 \times 8 \times 8$ on average (512 small volume). The number of particles is counted with simulation time increasing. The results are expressed by the volume fraction of particles in the statistical region. Figure 9 shows the relationship
between the volume fraction of particles in the statistical region and the simulation time under the screw rotational speed 150 rpm.

From the volume fraction curve of different cases in Figure 9, it can be seen that the material volume fraction in the variable screw section region has the maximum value. The results show that the maximum volume fraction of different cases appear at about 1.25 s of simulation time. The maximum volume fraction of Case 3 increased by 4% compared with Case 1. It is concluded that the feed efficiency is improved with the increase of diameter $D_2$. However, when $D_2$ increases

**Figure 7.** Top view of particle velocity distribution in transverse section of different cases.

**Figure 8.** Statistical region.
continuously, the volume fraction of material in the variable screw section region decreases. This is due to the insufficient feed quantity in gravity drive mode.

**Mass flow rate result of variable section screw conveyor**

The particle mass flow rate is an important operating parameter for ensuring overall conveying stability in a screw conveyor. The flow capacity of material in vertical screw conveyor can be quantitatively expressed by measuring the material mass flow rate along the axis. To ensure the accuracy and the stability of particle mass flow rate, the mass flow monitor is set at the height of 2000 mm. The four simulations are conducted under the screw rotational speed 150 rpm. The DEM simulation monitoring results of the different cases are shown in Figure 10.

From Figure 10, it can be seen that the maximum mass flow rate of Case 1 to Case 3 increases gradually. The maximum mass flow rate of Case 1 is approximately 250 t/h, while that of Case 4 is about 180 t/h. Case 1 is a traditional vertical screw conveyor with constant screw section, and the others are in variable screw section condition. The decreasing mass flow rate of Case 4 is resulted from the reducing filling rate in the conveyor. When the bottom of screw flight in Case 4 becomes oversize, the feed quantity by gravity drive is not adequate for conveying. The results show that Case 3 has the highest conveying efficiency.
Power draw of screw shaft in conveying process

Power draw is an important index in screw conveyor design procedure, and it is related to torque which determines from DEM predictions of the forces exerted by the particles on the rotating screw. Figure 11 shows the relationship between the power draw and the conveying time under the screw rotational speed 150 rpm. The results show that the power draw of screw shaft varying with simulation time has the same trend for different cases. From the results of Case 1 to Case 4, it can be seen that the screw shaft consumes more power with the increase of diameter $D_2$. On the one hand, it reflects that the vertical screw conveyor with variable screw section feeds more materials, which leads to more power consumption. On the other hand, combined with Figure 9, it is concluded that the rate of feed for particles in Case 4 is not able to catch up with conveying rate. In addition, the granular vortex motion is intensified due to the larger diameter $D_2$. It consumes more power to keep the particles rotating at high vortex$^2$ speed, which means that the lateral centrifugal pressure exerted on particles is greater than the vertical, gravitational induced pressure. Therefore, the oversize diameter $D_2$ is not beneficial for particle conveying.

Effect of screw rotational speed on conveying process

The conveying capacity of a screw conveyor is proportional to the screw rotational speed.$^{21,22}$ Thus, the conveying characteristics of the above four cases at different rotational speeds are investigated, such as: volume fraction, mass flow rate, power.
Figure 11. The power draw results under the different cases.

Figure 12. Maximum volume fraction in statistical region variation with rotational speed.

draw of screw shaft. The relationship between above conveying characteristics and rotational speeds are shown in Figures 12–14 respectively.
Figure 12 shows that the volume fraction in the statistical area decreases with the increase of the screw rotational speed. This is caused by intensified particle movement in the statistical region. The faster movement reduces the residence time of particles in the statistical region, thus the maximum volume fraction decreases.

Figure 13 shows that the maximum mass flow rate of the four cases increases significantly with the increase of screw rotational speed. Compared with the traditional constant screw section in Case 1, the variable screw section in Case 2 and
Case 3 get better conveying performance. As the restricted feeding and oversize diameter $D_2$ reduce the filling rate, the variable screw section in Case 4 has the opposite effect on particles conveying.

For all cases, Figure 14 shows that the screw shaft consumes more power with the increase of screw rotational speed. Besides, the above curves show that the power draw increasing rate of four cases has a downtrend. At low rotational speeds, the maximum difference of power draw between four cases is 1300 W. With the screw rotational speed increasing, the difference between four cases becomes more obvious. Both Case 2 and Case 3 have more power consumption than Case 1, and the conveying quantity increases accordingly. The screw shaft of Case 4 consumes more power, but the mass flow rate of the Case 4 is ranked second, which indicates that the oversize screw section is not appropriate to elevate materials.

**Conclusion**

In this paper, DEM simulation is used to analyze the conveying process of a traditional vertical screw model with constant screw section and three kinds of variable screw section. The DEM parameters are calibrated through experiment. The effects of variable screw section on particles feeding process are studied. The dynamic characteristic, that is, particle velocity distribution, volume fraction, mass flow rate and power draw of screw shaft, are investigated. It can be seen from the results and discussion above that:

1. The volume fraction in the inlet in the condition of variable screw section is higher, and the mass flow rate also increases in the condition of variable screw section. It is obvious that the variable screw section design may effectively upgrade feed quantity and conveying efficiency comparing to constant screw section.

2. The particle vortex motion may intensify when the diameter $D_2$ is oversize, which reduces the axial conveying velocity. The positive effect of variable screw section on particles conveying only happens under sufficient feeding.

3. The variable screw section design increases power consumption of the conveyor accordingly, thus the specific energy consumption should be an index to judge whether the design is reasonable.

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