SIMULATION OPTIMIZATION OF A CONVEYING AND SOIL-REMOVING DEVICE FOR A CORN STALKS PICKING AND PELLETIZING MACHINE
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秸秆捡拾制粒机输送除土装置仿真优化

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ABSTRACT
RockyDEM is used to simulate the conveying and soil-removing device to determine its optimal structural parameters in order to solve the problem of low soil removal rate and high straw loss rate of the conveying and soil-removing device of the corn stalks picking and pelletizing machinery. Single-factor and multi-factor simulation tests were conducted with soil removal rate and corn stalks loss rate as evaluation indexes, and blade shell clearance, sieve aperture and pitch as influencing factors. The experimental results show that the soil removal rate and the loss of corn stalks have better consistency with the simulation data. Therefore, the procedures of this study can be used for the design and optimisation of conveying and soil-removing device.

摘要
为解决玉米秸秆捡拾造粒机械的输送除土装置除土率低、秸秆损失率高的问题，采用 RockyDEM 对输送除土装置进行模拟，确定其最佳结构参数。 以土壤去除率和秸秆损失率为评价指标，以叶片与壳体的间隙、筛孔和间距为影响因素，进行了单因素和多因素的模拟试验，土壤去除率和秸秆损失率的试验结果与模型的模拟数据显示出良好的一致性。因此，本研究的程序可用于输送和除土装置的设计和优化。

INTRODUCTION
Pelletizing molding is one of the effective ways to improve the comprehensive utilization of corn stalks (*Huo et al, 2019; Wang et al, 2017*). Most of the domestic corn stalks pelletizing equipment is fixed, has high operating costs and low efficiency, so the development of field corn stalks picking and pelletizing technology is an important trend in the comprehensive utilization of corn stalks in the future. Therefore, it is important to design and optimize a kind of conveying and soil-removing device which is suitable for corn stalks pelletizing.

Ulantuya et al, (2016), studied the factors affecting the performance of screw conveyor, and concluded that the influence law of factors, the primary spin velocity and secondary feed into the speed factors were identified and the best combination of parameters. *Fu Qiankun et al, (2018*), designed a vibrating sieve to solve the problem of high soil content after corn stalks picking and baling, taking the soil removal rate and corn stalks loss rate as the test index, which provided a theoretical reference for the design optimization of conveying and soil-removing devices. In summary, the main research methods for screw conveying and screening at home and abroad are discrete element simulation, but there are fewer studies that combine screw conveying and screening.

This study takes the conveying and soil-removing device of corn stalks picker and pelletizer as the research object, combines the screw conveying and sieving, and conducts discrete element simulation analysis: using the blade shell clearance, sieve aperture and pitch as factors, and the soil removal rate and corn stalks loss rate as indicators, the single-factor and ternary quadratic regression orthogonal rotation combination test is designed to determine the optimal structural parameters. A test bench was built for test verification to provide a theoretical basis for the design of the cornstalks picking and pelletizing machine conveying and soil-removing device.

MATERIALS AND METHODS
Test materials and equipment
Simulation and experimental design of the conveying and soil-removing device for the self-propelled ring die granulator, and analysis of the movement pattern of corn stalks and dust in the conveying and soil-removing device by the discrete unit method were carried out.

In order to facilitate the analysis of the influence of the structural parameters of the device on the conveying and dust removal, a single-factor simulation test was conducted using RockyDEM software, and the device was reasonably modified and simplified to be divided into two parts: the casing and the screw conveying shaft. After the introduction, the material properties of the two parts were set, the casing was fixed, the motion of the screw conveyor shaft was set to rotation, and the working speed of the conveying and soil-removing device was set to 1600 r/min based on the working speed of the self-propelled ring die granulator.

The optimal solution of the structural parameters of the conveying and soil-removing device was obtained through the simulation test, and the model of the conveying and soil-removing device test bench was designed according to the optimal structural parameters, and the test bench test was conducted.

Device structure and working principle

The corn stalks picking and pelletizing machine is powered by 117 kW diesel engine, which can complete the functions of corn stalks picking and crushing, conveying and removing soil, and compressing and forming at one time to realize the function of moving dense pellets in the corn stalks field, as shown in Figure 1. The machine can produce about 1.5t of corn stalks pellets per hour, the pellet forming rate reaches 95%, and the pellet density is between 800~1200kg/m^3. In order to improve the corn stalks pellet forming rate and corn stalks pellet density, the corn stalks soil rate needs to be reduced, so the conveying and soil-removing device is optimally designed.

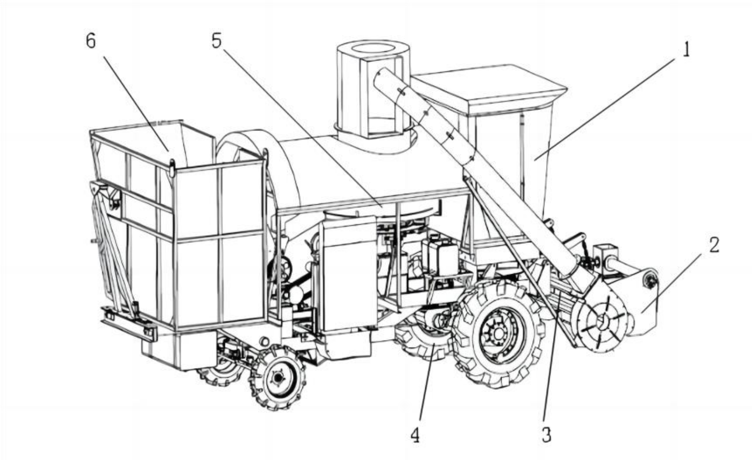


Fig. 1 - Corn stalk granulator

1. Cab 2. Picking Device 3. Conveying and De-Soiling Device 4. Walking Device 5. Molding Device 6. Stock Bin

The structure of the conveying and soil-removing device is shown in Figure 2.

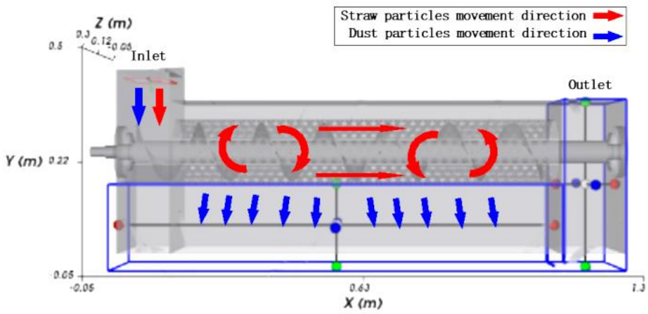


Fig. 2 - Schematic diagram of conveying dust removal device

The corn stalks scattered in the field will be picked up by the picking device with soil, and after being sent into the conveying and soil-removing device, axial movement, tumbling and throwing movement will occur due to the external force exerted by the spiral blade. In the process of movement, the corn stalks and soil are in constant contact with the screen, and the soil is screened out through the screen holes, and the corn stalks are conveyed to the paddle plate, which then throws them to the pelletizing device.

Simulation model and parameter setting

The 4th nodes and internodes of the samples were selected, and the effect of the moisture content of samples on the critical shearing strength was examined at a shearing speed of 15 mm/min.

Samples from different sections of the whole stalk were selected, and the moisture content of each sample was adjusted to 45%±2%, and the effect of the sampling location on the critical shearing strength was examined at a peeling speed of 15 mm/min. The moisture content of the sample in the 4th nodes and internodes were adjusted to 45%±2% to study the influence of the shearing speed on the critical shearing strength. The test was repeated 5 times at each test level, and the variance analysis F value tests were performed at the level of P=0.05.

There are interactions between corn stalks, soil and soil removal device, and the conditions of instantaneous contact and no significant plastic deformation after contact are met in the process of interaction, so the hard sphere contact model is chosen for corn stalks particles and soil particles (*Wang et al, 2017*).

In RockyDEM, the normal force model is set to the Hertzian spring-dashpot model. The normal force model is shown in equation (1).

$$\mathrm{F_n} = \widehat{\mathrm{K}}_\mathrm{H}\mathrm{S_n^{\frac{3}{2}}} + \hat{\mathrm{C}}_\mathrm{H}\mathrm{S_n^{\frac{1}{4}}}\dot{\mathrm{S}}_\mathrm{n} \tag{1}$$

$$\widehat{\mathrm{K}}_\mathrm{H} = \frac{4}{3}E^*\sqrt{R^*} \tag{2}$$

In Equation (1): F_n is the normal force, N. K_H is the stiffness coefficient. C_H is the damping coefficient; S_n is the contact overlap. E^* is the equivalent Young's modulus, Pa. R^* is the equivalent radius, mm.

The equivalent Young's modulus and equivalent radius are shown in equations (3) and (4).

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \tag{3}$$

$$\frac{1}{R^*} = \begin{cases} \frac{2}{L_1} + \frac{2}{L_2} \\ \frac{2}{L} \end{cases} \tag{4}$$

In the Equation (3) and Equation (4): E_1, E_2 is the Young's modulus of the particle-particle or particle-boundary contact; v_1, v_2 is Poisson's ratio; L_1, L_2 is the size of the two particles when the particle is in contact with the particle; L is the size of the particle when the particle is in contact with the boundary.

The damping factor can be found as shown in equation (5).

$$\hat{C}_H = 2\eta_H\sqrt{m^*K_H} \tag{5}$$

In Equation (5): m^* is the effective mass. η_H is the damping ratio of the Hertzian spring-dashpot model.

The effective mass m can be found as shown in equation (6).

$$\frac{1}{R^*} = \begin{cases} \frac{2}{L_1} + \frac{2}{L_2} \\ \frac{2}{L} \end{cases} \tag{6}$$

In Equation (6): L_1, L_2 is the size of the two particles when the particle is in contact with the particle; L is the size of the particle when the particle is in contact with the boundary.

According to the analysis of Antypov and Elliott's study, the damping ratio η is shown by equation (7).

$$\varepsilon = \begin{cases} exp\left[-\frac{\eta}{\sqrt{1-\eta^2}}\left(\pi - arctan\frac{2\eta\sqrt{1-\eta^2}}{1-2\eta^2}\right)\right] & \left(0 \le \eta \le \frac{1}{\sqrt{2}}\right) \\ exp\left(-\frac{\eta}{\sqrt{1-\eta^2}}arctan\frac{2\eta\sqrt{1-\eta^2}}{2\eta^2-1}\right) & \left(\frac{1}{\sqrt{2}} \le \eta \le 1\right) \\ exp\left(-\frac{\eta}{\sqrt{\eta^2-1}}ln\frac{\eta+\sqrt{\eta^2-1}}{\eta-\sqrt{\eta^2-1}}\right) & (\eta > 1) \end{cases} \tag{7}$$

In the Equation (7): ε is the recovery factor.

In RockyDEM, the tangential force model is set to the Coulomb limit model as shown in equation (8).

$$\mathrm{F_\tau} = -\mu\mathrm{F_n}\frac{\dot{\mathrm{S}}_\tau}{|\dot{\mathrm{S}}_\tau|} \tag{8}$$

In the Equation (8): F_τ is the tangential force; μ is the friction coefficient; and S_T is the tangential component of the relative velocity.

SolidWorks software is used to simplify and model the conveying and soil-removing device.

The simplified device mainly consists of two parts: the casing consists of screen and baffle plate, the screen is 1915 mm long and wrapped around the spiral conveying shaft in a positive octagonal shape, and the round hole screen is arranged in a T-shaped arrangement; the baffle plate is divided into front and rear baffle plate, support plate and upper baffle plate; the outer diameter of the spiral blade is 304 mm, the spiral shaft is 114 mm in diameter and the shaft length is 2400 mm. The diameter of the spiral blade is 304 mm, the diameter of the spiral shaft is 114 mm, and the length of the shaft is 2400 mm. The speed of the screw conveyor shaft is set to 1600 r/min by reviewing the literature (*Tian et al, 2018*) and combining with the actual situation.

The material model settings are shown in Table 1 (*Schulz et al, 2019; Kovacs A et al, 2017*).

Table 1

Material model settings

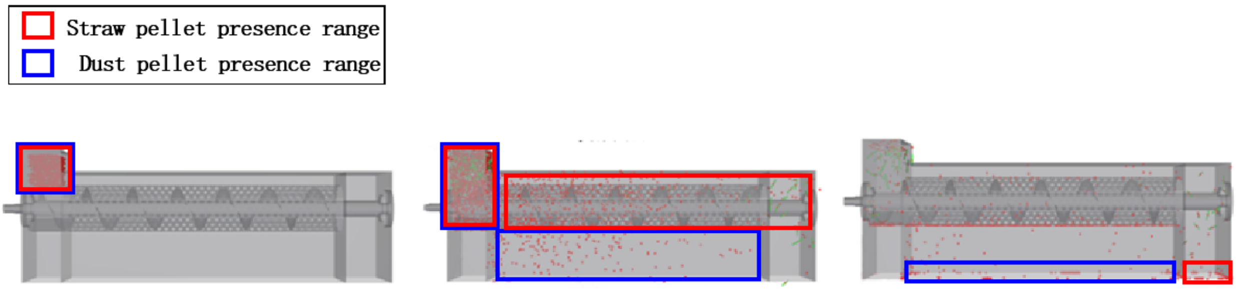
Project Name	Model Type	Vertical Aspect Ratio	Horizontal Aspect Ratio	Number of surfaces	Length range
Soil	Irregular Polyhedra	1.5	1	24	1~2 mm
Corn stalks	Cylindrical	10	1	-	50~100 mm

Referring to the relevant literature, the material property parameters and material contact parameters between the conveying soil removal device casing, soil particles and corn stalks particles were determined as shown in Table 2 (*Li et al, 2019*).

Table 2

Material contact parameters

Interaction	Recovery factor / e	Static friction coefficient / s	Rolling friction coefficient / k
Corn stalks-corn stalks	0.3	0.3	0.01
Corn stalks-soil	0.5	0.5	0.05
Corn stalks-casing	0.3	0.45	0.01
Soil-casing	0.6	0.6	0.05
Soil-soil	0.5	0.4	0.4



Simulation time 0.13s *Simulation time 0.3s* *Simulation time 3s*

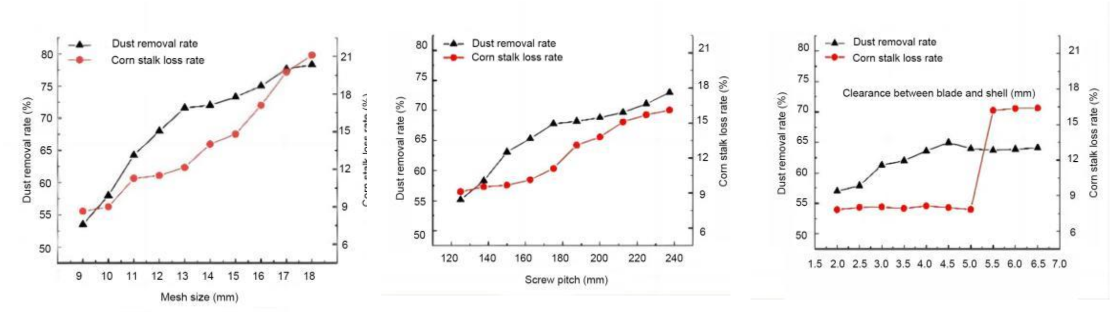
Fig. 3 - Simulation situation under different time steps

The corn stalks-soil mixture feeding time is set to 2 s, and the data collection frequency is 100 points per second. It is known that the machine to be optimized can pick up 1.5~2 t of corn stalks per hour, and the weight ratio of soil to corn stalks is about 1:4. Assuming that the machine picks up 1.8 t of corn stalks per hour, the feeding amount of soil particles is 0.36 t/h, and the feeding amount of corn stalks particles is 1.44 t/h. Figure 4 shows the simulation situation under different time steps, and it can be seen from Figure 3 that the mixture is delivered completely when the total simulation time is 3 s.

Simulation test factors and indicators

In order to study the working performance of the conveying and de-soiling device under different structural parameters, after reviewing the literature, the aperture diameter of the sieve, the pitch and the gap between the blade and the casing were used as the test factors, and the corn stalks loss rate and the de-soiling rate were used as the evaluation indexes of the working performance (*Fu Qiankun et al, 2018*).

According to DB21T 2786-2017 "Technical conditions of biomass solid forming fuels", the corn stalks loss rate of the conveying and soil-removing device should be less than 15% and the soil removal rate should be more than 60%, and the single-factor simulation test was conducted based on this standard. The test results are shown in Figure 4.



a. Effect of sieve aperture size on soil removal rate and corn stalks loss rate
b. Effect of pitch on the rate of soil removal and corn stalks loss
c. Effect of blade and casing clearance on soil removal rate and corn stalks loss rate

Fig. 4 - Single factor simulation test result

When the simulation is completed, calculate the soil removal rate according to Equation (9).

$$y_1 = \left(1 - \frac{M_y}{M_t}\right) \times 100\% \tag{9}$$

In the Equation (9): M_y is the mass of remaining soil particles, kg; M_t is the total mass of input soil particles, kg.

When the simulation is completed, calculate the corn stalks loss rate according to Equation (10).

$$y_2 = \frac{M_s}{M_j} \times 100\% \tag{10}$$

In the Equation (10): M_s is the lost corn stalks mass, kg; M_j is the total input corn stalks mass, kg.
The simulation analysis of the conveying and soil-removing device shows that: the soil removal rate and corn stalks loss rate increase gradually when the sieve aperture increases; the soil removal rate and corn stalks loss rate increase gradually.

When the pitch increases; the blade shell clearance and the casing increases, and the soil removal takes the lead in increasing and then decreasing. According to DB21T 2786-2017 "Biomass solid forming fuel technical conditions", the range of values is 12~16 mm for the sieve aperture, 150~200 mm for the pitch, and 3~5 mm for the clearance between the blade and the casing.

RESULTS

Results and analysis of single factor test

According to the single-factor simulation test results, the ternary quadratic orthogonal rotating combination test method was used for the characteristic analysis and parameter optimization of the conveying and soil-removing device, and the factor level coding table is shown in the table, and the sieve aperture X_1, pitch X_2, and blade shell clearance X_3 are the actual values of the factors.

Table 3

Coding table of factor level

Code	Sieve aperture / x_1 mm	Pitch / x_2 mm	Blade shell clearance / x_3 mm
+1.682	12	150	3
+1	12.8	160	3.4
0	14	175	4
-1	15.2	190	4.6
-1.682	16	200	5

Experimental results and analysis

The results of the ternary quadratic regression orthogonal rotated combination test are shown in Table 5, with X_1, X_2, and X_3 as factor coded values.

Significance test and regression equation building

The significance test and ANOVA were performed at α=0.05 significance level using Design-Expert data analysis software, and the corn stalks loss rate ANOVA is shown in Table 4 and the soil removal rate ANOVA is shown in Table 5.

Table 4

Analysis of variance

Source	Variance	Degree of freedom	Mean Square	F-value	P-value
Models	392.32	9	43.59	10.91	<0.0001
X_1	78.92	1	78.92	19.76	0.0007
X_2	71.32	1	71.32	17.86	0.0010
X_3	137.82	1	137.82	34.50	<0.0001
$X_1 X_2$	19.03	1	19.03	4.77	0.0480
$X_1 X_3$	0.13	1	0.13	0.031	0.8623
$X_2 X_3$	31.60	1	31.60	7.91	0.0147
X_1^2	3.62	1	3.62	0.91	0.3584
X_2^2	30.13	1	30.13	7.54	0.0166
X_3^2	20.34	1	20.34	5.09	0.0419
Residuals	51.93	13	3.99		
miss drafting	10.77	5	2.15	0.42	0.8236
Error term	41.15	8	5.14		
Total error	444.25	22			

Table 5

Analysis of variance

Source	Variance	Degree of freedom	Mean Square	F-value	P-value
Models	910.30	9	101.14	14.94	<0.0001
X_1	632.95	1	632.95	93.50	<0.0001
X_2	39.40	1	39.40	5.82	0.0313
X_3	144.05	1	144.05	21.28	0.0005
$X_1 X_2$	3.08	1	3.08	0.45	0.5121
$X_1 X_3$	35.28	1	35.28	5.21	0.0399
$X_2 X_3$	6.02	1	6.02	0.89	0.3628
X_1^2	31.77	1	31.77	4.69	0.0494
X_2^2	1.78	1	1.78	0.26	0.6172
X_3^2	15.63	1	15.63	2.31	0.1526
Residuals	88.00	13	6.77		
miss drafting	6.20	5	1.24	0.12	0.9837
Error term	81.80	8	10.23		
Total error	998.30	22			

As can be seen from Table 4, P<0.0001 and F=10.91> F 0.01(9,13)=4.19 for the corn stalks loss rate model indicate that this model is suitable; F=0.42< F 0.05(5,8)=3.69 and P=0.8236>0.05 for the misfit term of this regression equation model, so the model fits well The correlation was high. Among the terms of the model, all of them were significant except for the interaction term X_1X_3 of the sieve aperture and the blade and blade shell clearance and the quadratic term X_1^2 of the sieve aperture. The order of the factors affecting the corn stalks loss rate was blade shell clearance > sieve aperture > pitch.

The regression model of corn stalks loss rate Y obtained after excluding the insignificant term 1 is shown in equation (11).

$$\hat{Y}_1 = 9.52 + 2.4X_1 + 2.29X_2 + 3.18X_3 + 1.54X_1X_2 + 1.99X_2X_3 + 1.38X_2^2 + 1.13X_3^2 \quad (11)$$

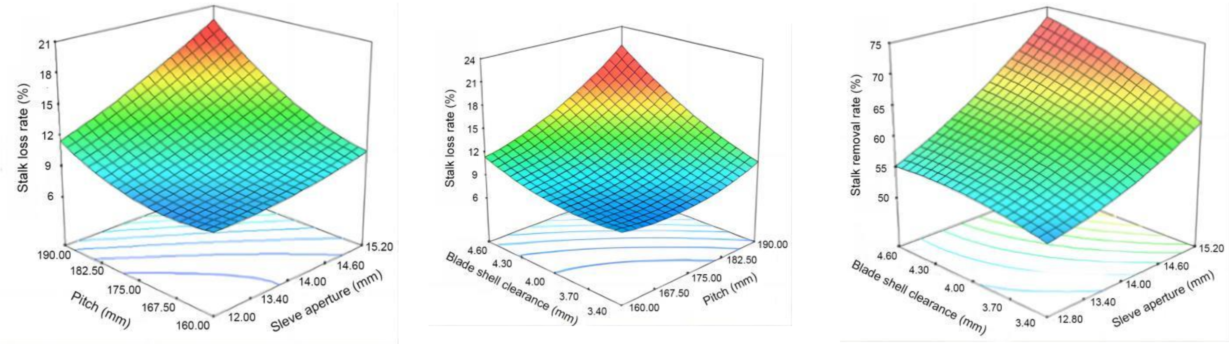
As can be seen from Table 5, P < 0.0001 and F = 14.94 > F 0.01(9,13) = 4.19 for the soil removal rate model indicate that the regression is highly significant; F = 0.12 < F0.05 (5,8) = 3.69 and P = 0.9837 > 0.05 for the misfit term indicate that the misfit term is not significant and the model is a good fit.

Since the P-values of sieve aperture (X_1), pitch (X_2), and blade shell clearance (X_3), interaction term of sieve aperture and blade shell clearance (X_1X_3), and quadratic term of sieve aperture (X_1^2) all satisfy P<0.05, it is obtained that X_1,X_2,X_3,X_1X_3,X_1^2 has a significant effect on soil removal rate. According to the F-value analysis, the influence on the soil removal rate from the largest to the smallest is the sieve aperture, blade shell clearance and pitch.

The regression model of soil removal rate Y obtained after excluding the insignificant term 2 is shown in equation (12).

$$\hat{Y}_2 = 60.63 + 6.81X_1 + 1.7X_2 + 3.25X_3 + 2.1X_1X_3 + 1.41X_1^2 \quad (12)$$

Response Surface Analysis



a. The effect of X_1 and X_2 interactions on Y_1 *b. The effect of the interaction of X_2 and X_3 on Y_1* *c. The effect of X_1 and X_3 interactions on Y_2*

Fig. 5 - Response surface of corn stalk loss rate

As can be seen from Figure 5. When the sieve aperture was fixed, the corn stalks loss rate *Y* shows a gradually increasing trend with the increase of pitch. When the pitch was fixed, the corn stalks loss rate *Y* shows a gradually increasing trend with the increase of sieve aperture. When the blade shell clearance was fixed, the corn stalks loss rate *Y* shows a gradually increasing trend with the increase of pitch. When the pitch was fixed, the corn stalks loss rate *Y* shows a gradually increasing trend with the increase of blade shell clearance. When the pitch was fixed, the corn stalks loss rate *Y* shows a gradually increasing trend with the increase of blade shell clearance. When the clearance between the blade and the casing was fixed, the soil removal rate *Y* gradually increases with the increase of the sieve aperture. When the sieve aperture was fixed, the soil removal rate *Y* gradually increases with the increase of the blade shell clearance and sieve aperture, and the results are consistent with the single-factor test, and the interaction effect of the two factors is obvious. The response surface diagram shows that the corn stalks loss rate is small and the removal rate is high in the range of sieve aperture 12.8~15.2 mm, pitch 160~190 mm, and blade shell clearance 3.4~4.6 mm..

The model is solved optimally using the Optimization-Numerical module in the optimization design software Design-Expert, and the target actual variables are optimized with the constraints as shown in equation (13).

$$\begin{cases} minY_1 \\ maxY_2 \\ 12.8 \le x_1 \le 15.2 \\ 160 \le x_2 \le 190 \\ 3.4 \le x_3 \le 4.6 \end{cases} \tag{13}$$

Applying Design-Expert software to optimize the optimal working parameters: sieve aperture was 15.2 mm, pitch 160 mm, blade shell clearance was 4.6 mm, at this time the corn stalks loss rate is 12.4%, the soil removal rate is 72.8%. Combined with the actual situation to take the sieve aperture was 15 mm, pitch 160 mm, blade and blade shell clearance was 4.5 mm for simulation test verification, simulation results corn stalks loss rate is 13.8%, soil removal rate is 70.3%.

Test bench test verification

The test was carried out with Danyu-311 corn stalks from Heihe County, Jinzhou City, Liaoning Province, with a length of 50-200 mm and a width of 3-15 mm. Portions of corn stalks were randomly selected from the materials to be tested, each with 500±2 g. The corn stalks were weighed after full burning, and the soil content was calculated according to equation (14), and the average soil content was 38%.

According to agricultural machinery test conditions, the average moisture content was measured as 19%.

$$T = \frac{M}{500} \times 100\% \tag{14}$$

Where:

T is the soil content of corn stalks, %; M is the total mass of corn stalks ash and soil after burning, g.

The test apparatus includes: conveying and soil-removing device test bench, optical type tachometer, moisture content measuring instrument, electronic balance (accuracy of 0.01 g), vernier calliper, and timer. The test bench developed by combining the simulation model parameters and simulation optimization results is shown in Figure 6, and its power is provided by a diesel engine.

Fig. 1- Conveying dust removal test device

In order to reduce the error, three repetitive tests were conducted and the test results were averaged. The results are shown in Table 6.

Table 6

Experimental value of evaluation indices at optimal condition

Projects	Corn stalks loss rate/%	Soil removal rate/%
Average value of simulation test	13.8	70.3
Test bench test average	13.2	69.7
Relative Error	4.5	0.8

As can be seen from the table, the error between the test bench verification test results and the simulation test results is small, which proves that the structural parameters optimized by using the discrete element method are reliable and meet the working requirements of actual production.

CONCLUSIONS

(1) Using RockyDEM to establish a discrete element model for simulation tests, the test results show that: screen aperture diameter, pitch and blade and casing clearance have a significant effect on the corn stalks loss rate; the main order of corn stalks loss rate is blade shell clearance > sieve aperture > pitch.

(2) Apply Design-Expert software to optimize the model solution, and get the optimal working parameters: when the sieve aperture was 15.2 mm, the pitch was 160 mm, and the blade shell clearance was 4.6 mm, the corn stalks loss rate was 12.4%, and the soil removal rate was 72.8%.Combine with the actual situation to select the appropriate parameters for simulation verification test: When the screen aperture was 15 mm, the pitch was 160 mm, and the blade shell clearance was 4.5 mm, the corn stalks loss rate is 13.8%, and the soil removal rate is 70.3%.

(3) Based on the simulation and optimization results, a test bench of a conveying and soil-removing device was developed for test verification, and the results showed that when the sieve aperture was 15 mm, the pitch was 160 mm, and blade shell clearance was 4.5 mm, the corn stalks loss rate was 13.2%,and the soil removal rate was 69.7%, which were similar to the simulation test results and the simulation results were reliable. The results of this paper provide a theoretical basis for the selection of structural parameters of the conveying and soil-removing device on the corn stover picking and pelletizing machine.

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