OPTIMIZATION OF SCREW CONVEYING OF KNEADED CORN STALKS BASED ON DISCRETE ELEMENT METHOD
/
基于离散元法的揉碎玉米秸秆螺旋输送的优化

ZhiPeng FAN, Zhe MA, HongBo WANG*, ZhiHong YU
College of Mechanical and Electronic Engineering, Inner Mongolia Agricultural University, Hohhot / China
Tel: +86 13739981395; E-mail: wanghb@imau.edu.cn
DOI: https://doi.org/10.35633/inmateh-69-60

Keywords: *screw conveyor, kneading corn stalks, discrete elements, parameter optimization*

ABSTRACT
In order to explore the conveying mechanism of kneaded corn stalk in the screw conveyor and improve the conveying performance of the screw conveyor, the study of the screw conveying process of kneaded corn stalk was carried out, and the simulation model of the screw conveying process was established by using the discrete element method. The results showed that: The pitch, feed amount and screw shaft speed have significant effects on the productivity and power of screw conveying, and there are significant interactions. The optimal parameters of the multi-factor simulation optimization test were 319.428 mm pitch, feed amount of 71.062 kg/min, screw shaft speed of 117.034 r/min, corresponding productivity of 71.517 kg/min and power of 769.84 W. This study reveals the screw conveying mechanism of kneaded corn stalk, verifies the feasibility of using discrete element simulation to analyse the conveying process of kneaded corn stalk, and provides a theoretical basis for improving and optimizing the screw conveying device.

摘要
为了探究揉碎玉米秸秆在螺旋输送机中的输送机理，提高螺旋输送机的输送性能，该研究揉碎玉米秸秆螺旋输送过程中的螺距、喂入量、螺旋轴转速进行单因素、多因素试验和离散元仿真。结果表明：螺距、喂入量、螺旋轴转速对螺旋输送的生产率和功率有显著影响，且存在显著的交互作用；多因素仿真寻优试验的最优参数结果为螺距 319.428 mm、喂入量 71.062 kg/min、螺旋轴转速 117.034 r/min，对应的生产率为 71.517 kg/min，功率为 769.84 W。该研究揭示了揉碎玉米秸秆的螺旋输送机理，验证了运用离散元仿真分析揉碎玉米秸秆输送过程的可行性，同时为改进和优化螺旋输送装置提供理论依据。

INTRODUCTION
Maize is an important food crop and feed crop, with great production potential, high economic benefits, edible, feed and a variety of industrial uses, and has an important strategic position in ensuring food security. According to statistics, China's corn production in 2021 was about 270 million tons, accounting for about 23% of the world's total production, second only to the United States. As an inevitable product in the corn production process, corn stalk has a very high annual yield. Corn stalk itself is relatively tall and has high crude fibre content, and transportation and processing are relatively difficult, which leads to a low comprehensive development utilization rate of this resource *((Wang, 2022)*.

Screw conveyor is one of the important equipment in the process of crop harvesting and agricultural fibre material processing. Screw conveyor can continuously transport materials, and is widely used in the transportation of agricultural materials with the advantages of simple and compact structure, easy installation, convenient operation and maintenance *(Wu, 2022)*. However, the conveying performance of the screw conveyor directly affects the quality and productivity of material harvesting and processing, and also affects the energy consumption of the conveying equipment itself.

Emulation Discrete Element Method (EDEM) is mainly used for simulation and analysis of particle processing and manufacturing equipment production process in industrial production. Modelling by discrete element method and simulating and analysing the entire production process can intuitively display the macroscopic motion state changes and the force and energy transfer between microscopic particles, which is convenient for studying the operation of the equipment and further improving and optimizing.

ZhiPeng Fan, M.S. Stud.; Zhe Ma, M.S. Stud.; HongBo Wang, Professor, Correspondent author; ZhiHong Yu; Professor

In recent years, this method has also been widely used in agricultural fields such as agricultural tools, seeds and soil research, providing a theoretical basis for the improvement and optimization of agricultural machinery *(Hu et al., 2022; Liu et al., 2022; Li et al., 2022; Chen et al., 2023; Wang et al., 2022)*.

At present, *Youwang et al*., *(2020)*, simulated and analysed the conveying process of the horizontal screw feeder through EDEM software, and obtained the influence of the number of feed points on the productivity, filling rate and conveying speed of the feeder. *Tingzhou et al*., *(2019)*, carried out simulation test analysis on the three factors (inclination, pitch, speed) affecting the screw conveying capacity of grain, and obtained the significance relationship and the best parameter combination of the three factors. *Jiangtao et al*., *(2017)*, used EDEM software to analyse the discrete element of the conveying process of the screw conveying device under different pitches and speeds, and obtained the best parameter combination. *Yaoyu*, *(2020)*, analysed the discrete element of the internal conveyor force of the double screw conveyor, and obtained the law that the double screw conveyor was affected by the screw shaft speed, screw blade pitch, conveyor tilt angle and its own wheelbase when transporting grains, and the particle mass flow rate changed with the geometric and physical parameters of the conveyor.

In the previous research, our research group made a theoretical analysis of the screw conveying process of kneaded corn stalks. The influence mechanism of structural parameters and motion parameters on productivity and power consumption was analysed. The significance analysis and optimization analysis of three factors (pitch, screw shaft speed, and feed amount) that significantly affect the specific power consumption were carried out through experiments results, and the optimal combination of parameters were found. The eigen parameters and contact parameters of kneaded corn stalks were calibrated by discrete element calibration method, and an accurate discrete element model of screw conveying of kneaded corn stalks was established *Zhao et al., 2019; Liu et al., 2022; Wulan et al., 2015,2016,2019; Li, 2015)*.

In this study, a combination of experiment and simulation was used to study the screw conveying process of kneaded corn stalks. A discrete element model was established, and single-factor tests of pitch, feed amount and screw shaft speed were carried out with productivity and power as indicators. On this basis, the Box-Behnken response surface method was used to do the experiments, and the mathematical model between each index and the three factors was found. Through the analysis of variance (ANOVA) of its significance and optimization verification, the whole screw conveying process of kneaded corn stalks was optimized, which provided a theoretical basis for the design and improvement of the actual screw conveying device.

MATERIALS AND METHODS

SELECTION OF MATERIALS

The test materials were taken from the surrounding farmland of Wuchuan County, Hohhot, Inner Mongolia Autonomous Region, China, in October 2021, and the variety was Bian 31. The 9R-40 type kneading machine was used for kneading, and the filament body with a length of less than 100 mm and a width of 2~8 mm was obtained, with an average moisture content of 60%. The moisture content of materials was done with reference to the determination method of moisture in food according to the national food safety standard. The calculation formula is as follows.

$$\textit{Material moisture content}=[(\textit{fresh matter quality}-\textit{dry matter mass})/\textit{fresh matter quality}]\times 100\% \tag{1}$$

TEST BENCH CONSTRUCTION AND MODELING

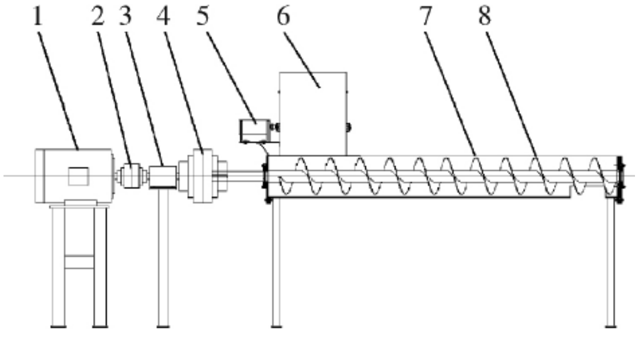
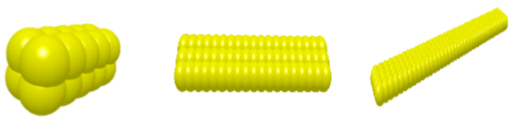


Fig. 1 - Screw conveyor test bench

1 – Electric motor; 2 – Coupling; 3 – Speed torque measuring instrument; 4 – Coupling; 5 – Single-phase DC speed regulating motor; 6 – Feed box; 7 – Shell; 8 – Screw shaft

The screw conveying test bench built in this study is mainly composed of motor, speed torque measuring instrument, feeder, casing and screw shaft (Figure 1). The feed inlet size is 260 mm×400 mm, the outer diameter of the screw blade is 250 mm, the diameter of the centre shaft is 60 mm, the gap between the screw blade and the shell is 5~8 mm, the conveying length is 2500 mm, and the pitch, screw shaft speed and feeder speed are adjustable.

Kneaded corn stalks have complex and diverse shapes. Due to the different materials of each part of the corn stalk itself (core, leaves, husks, nodules, etc.), this paper divides the kneaded corn stalks into straw core, straw husks and straw leaves, and other parts are ignored because they account for less. In order to reduce the complexity of simulation calculation without affecting the accuracy of simulation, the shape and size of straw core, husks and leaves are simplified to a certain extent, and the results are: core: 12 mm×6 mm×6 mm, husks: 20 mm×4 mm×2 mm, leaves: 20 mm×2.5 mm×1 mm. Their discrete element models are shown in Figure 2. The screw conveyor model is established for 1:1 with the test bench screw conveyor housing and screw shaft, as shown in Figure 3.



a. Straw core *b. husks* *c. Leaves*

Fig. 2 - Discrete element model of straw core, husks and leaves

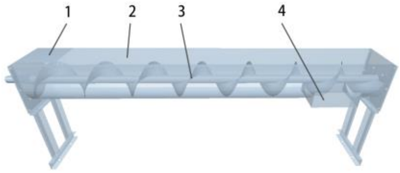


Fig. 3 - Discrete element model of screw conveying device

1 – Pellet factory; 2 – Screw conveyor shell; 3 – Screw shaft; 4 – Discharge outlet

Table 1

Eigen parameters of the parts of kneaded corn stalks and 45-steel

Parameters	Values	Parameters	Values
Density of straw core	62 kg/m^3	Density of husks	798 kg/m^3
Shear modulus of straw core	1.52×10^8 Pa	Shear modulus of husks	8.88×10^8 Pa
Poisson's ratio of straw core	0.032	Poisson's ratio of husks	0.317
Density of leaves	152 kg/m^3	Density of 45	7.85×10^3 kg/m^3
Shear modulus of leaves	5.842×10^8 Pa	Shear modulus of 45	8×10^7 Pa
Poisson's ratio of leaves	0.284	Poisson's ratio of 45	0.31

Table 2

Contact parameters between the parts of the kneaded corn stalks and 45-steel

Contact Parameters	Values	Contact Parameters	Values
Static friction coefficient of straw core-straw core	2.705	Collision restitution coefficient of husks-husks	0.380
Rolling friction coefficient of straw core-straw core	0.350	Static friction coefficient of husks-leaves	0.380
Collision restitution coefficient of straw core-straw core	0.390	Rolling friction coefficient of husks-leaves	0.377
Static friction coefficient of straw core-husks	0.900	Collision restitution coefficient of husks-leaves	0.385
Rolling friction coefficient of straw core-husks	0.345	Static friction coefficient of husks-45-steel	0.325
Collision restitution coefficient of straw core-husks	0.400	Rolling friction coefficient of husks-45-steel	0.270
Static friction coefficient of straw core-leaves	0.930	Collision restitution coefficient of husks-45 steel	0.425
Rolling friction coefficient of straw core-leaves	0.325	Static friction coefficient of leaves-leaves	0.411
Collision restitution coefficient of straw core-leaves	0.395	Rolling friction coefficient of leaves-leaves	0.335
Static friction coefficient of straw core-45-steel	1.030	Collision restitution coefficient of leaves-leaves	0.335
Rolling friction coefficient of straw core-45-steel	0.365	Static friction coefficient of leaves-45-steel	0.380
Collision restitution coefficient of straw core-45-steel	0.415	Rolling friction coefficient of leaves-45-steel	0.215
Static friction coefficient of husks-husks	0.665	Collision restitution coefficient of leaves-45-steel	0.395
Rolling friction coefficient of husks-husks	0.295		

When setting the Eigen parameters and contact parameters of the kneaded corn stalks model, directly use the data obtained from the previous test and calibration. In the pre-processing section of EDEM software, the volumes V-N (0.05,1) of the straw core, husks and leaves are set in Bulk Material, and other parameters are set according to Table 1 and Table 2.

The parameters set to 45-steel in Equipment Material are shown in Table 1. In Geometries, three pellet plants are set up at the screw conveyor inlet to produce straw core, husks, and leaves respectively, and the total production ratio is 3:4:16; the particle contact model in Physics is set up as Hertz-Mindlin (no slip) and Standard Rolling Friction. In the simulation section of EDEM software, set the time step to 2.214×10^{-7} s and total time to 5 s. The interval between storing data is 0.01 s. The grid size is $3xR_{min}$, where R_{min} means the minimum particle radius.

SCREW CONVEYING TEST OF KNEADED CORN STALKS

Since it is necessary to study the screw conveying performance of kneaded corn stalks, the efficiency and power consumption of kneaded corn stalks screw conveying are selected as the indicators.

Through the review of paper *(Wulan et al., 2016)* and the analysis of the screw conveying process of kneaded corn stalks, these factors are selected for this test: pitch, speed and feed amount. It can be seen that when the pitch of the screw blade of the screw conveyor is 160~300 mm, the feed amount is 10~70 kg/min, and the screw shaft speed is 50~148 r/min. The screw conveyor can meet the stable conveying requirements of kneaded corn stalks. And the factor levels are shown in Table 3.

Table 3

Test factors' levels

Level	1	2	3	4	5	6
Pitch [mm]	160	220	250	300	335	355
Feed amount [kg/min]	10	25	40	55	70	85
Screw shaft speed [r/min]	50	73	94	117	132	148

During single factor test of pitch, the feed amount is 40 kg/min, the speed is 94 r/min. The screw conveying test of kneaded corn stalks is carried out with the pitch as the variable. The results are shown in Figure 4. It can be seen from the figure that the productivity shows an upward trend with the increase of the pitch; and when the pitch reaches 335 mm, the inflection point occurs, and the productivity begins to decline; the power continues to rise with the increase of the pitch.

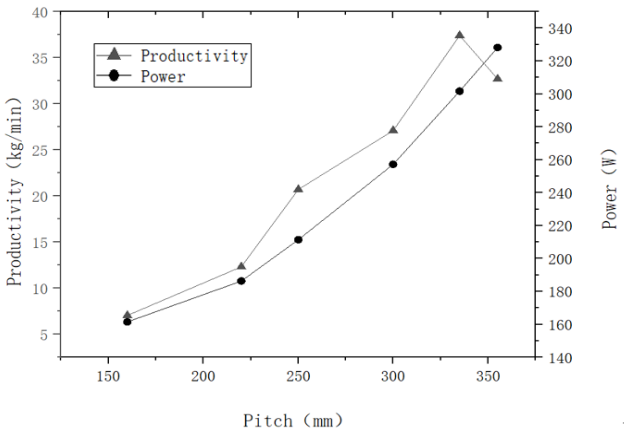
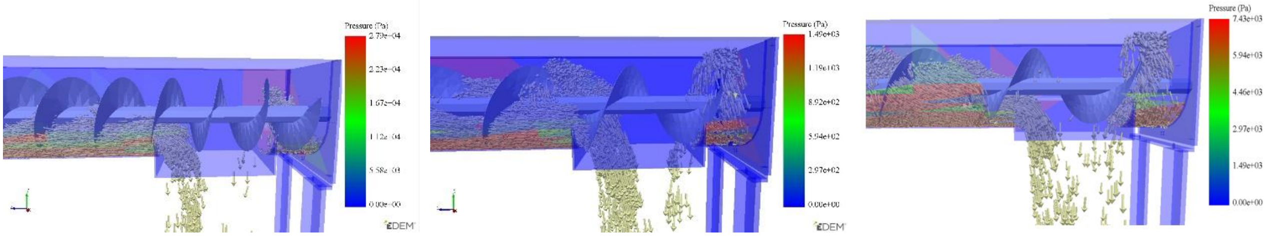


Fig. 4 - Relationship between pitch, productivity and power

Figure 5 are simulations of single factor screw conveying process of different pitches. In order to observe its motion law more intuitively, the particles of the three types of kneaded corn stalks in the figure are replaced by arrows in their own movement direction, and the blue, green and red areas in the figures represent the area of pressure on the shell of the body (the same below). It can be seen from the figures that with the increase of the pitch (Fig. 5a to 5b), the screw rising angle increases at the same time, and the movement space of the particles is also increasing, so the fluidity is enhanced and the productivity is improved; while the red area is significantly increased, representing that the friction area and friction between the particles and the body are increasing, so the power is also increasing; as the pitch continues to increase (Fig. 5b to 5c), the screw rising angle increases at the same time, and the circular motion of the particles increases significantly, so the productivity tends to decrease, and the friction area and friction between the particles and the body are also increasing, so the power continues to increase.



a. Pitch as 160 mm b. Pitch as 335 mm c. Pitch as 355 mm

Fig. 5 - Screw conveying simulation of different pitches

During single factor test of feed volume, the pitch is 355 mm, the speed is 94 r/min, and the screw conveying test of kneaded corn stalks is carried out with the feed amount as the variable. The results are shown in Figure 6, and it can be seen from the figure that the productivity shows an upward trend with the increase of the feed volume; the power tends to increase with the increase of feed.

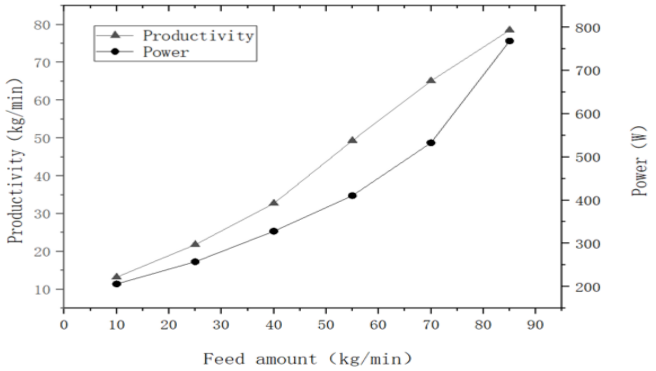
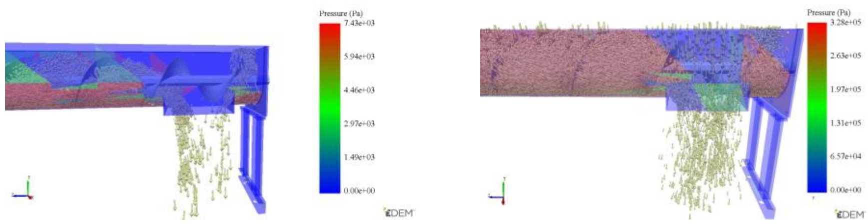


Fig. 6 - Relationship between pitch, productivity and power



a. Feed amount as 40 kg/min b. Feed amount as 85 kg/min

Fig. 7 - Screw conveying simulation of different feed volumes

As can be seen in Figure 7, with the increase of feed volume (Fig. 7a to 7b), the productivity is increasing, and the red area is significantly increased, which means that the friction area and friction between particles and the body, particles and blades are increasing, so the power is also increasing.

During single factor test of screw shaft speed, the pitch is 355 mm, the feed amount is 40 kg/min, and the screw conveying test of kneaded corn stalks is carried out with the screw shaft speed as the variable. The results are shown in Figure 8, it can be seen from the figure that the productivity increases with the increase of the screw shaft speed, and when the screw shaft speed reaches 117 r/min, the inflection point occurs, and the productivity begins to decline; the power always shows an upward trend with the increase of the speed of the screw shaft.

It can be seen from Figure 9 that with the increase of the speed of the screw shaft (Fig. 9a to 9b), the fluidity of particles is enhanced, the productivity is constantly increasing, and the red area is also increasing, which means that the friction area and friction between the particles and the body are increasing, so the power is also increasing; as the speed of the screw shaft continues to increase (Fig. 9b to 9c), due to the action of centrifugal force, the circular motion of particles increases significantly, and the axial movement decreases, so the productivity tends to decrease, and the friction area and friction between particles and the body are still increasing, so the power continues to increase.

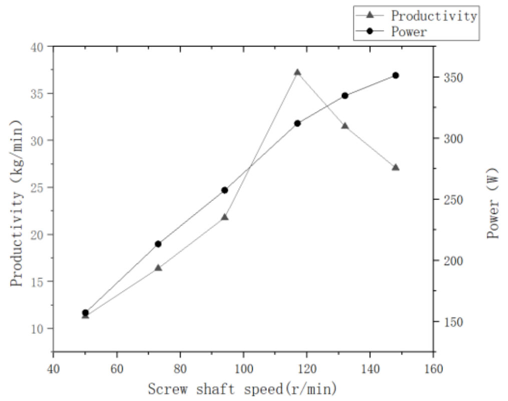
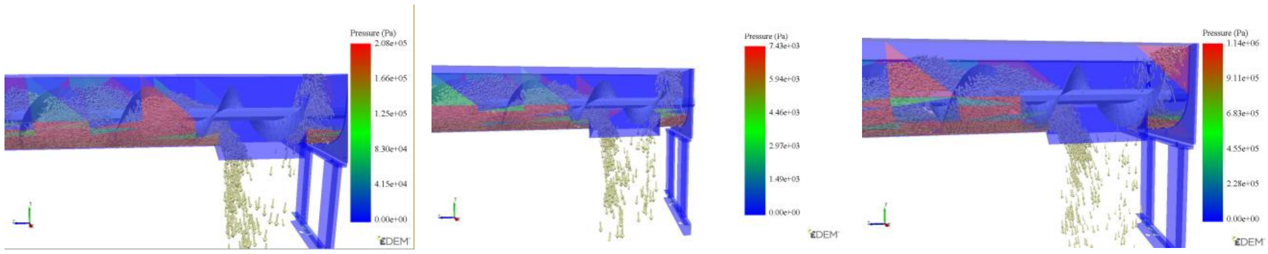


Fig. 8 - Relationship between screw shaft speed, productivity and power



a. Screw shaft speed as 50 r/min b. Screw shaft speed as 94 r/min c. Screw shaft speed as 148 r/min

Fig. 9 - Screw conveying simulation of different screw shaft speeds

BOX-BEHNKEN TEST AND ANALYSIS

In order to obtain the influence of multiple factors on productivity and power evaluation indicators, the last three levels of each factor are taken at a high level (+1) and a low level (-1), and the factors and their levels are shown in Table 4, and the Box-Behnken experiments are designed by using Design Expert software. Other non-significant parameters are averaged from physical tests. The Box-Behnken experimental design and results of significant contact parameters are shown in Table 5.

Table 4

Box-Behnken test parameter level table

Level	Pitch – A [mm]	Feed amount – B [kg/min]	Screw shaft speed - C [r/min]
-1	300	55	117
0	335	70	132
+1	355	85	148

Box-Behnken experiment design and results

Table 5

Experimental group	A	B	C	Productivity [kg/min]	Power [W]
1	-1	-1	0	41.3	457.3
2	1	-1	0	43.4	482.7
3	-1	1	0	65.5	712.4
4	1	1	0	67.2	747.5
5	-1	0	-1	69.3	694.2
6	1	0	-1	71.4	735.4
7	-1	0	+1	65.5	835.7
8	1	0	+1	63.8	874.1
9	0	-1	-1	47.5	513.2
10	0	1	-1	82.8	895.8
11	0	-1	+1	38.7	574.3
12	0	1	+1	73.2	958.4
13	0	0	0	55.4	654.3
14	0	0	0	63.5	738.5
15	0	0	0	65.6	764.5
16	0	0	0	63.1	749.8
17	0	0	0	58.2	671.1

The multiple regression analysis of the experimental results in Table 5 is carried out by Design-Expert software, and the quadratic polynomial regression model of screw conveying productivity (Y_1) and power (Y_2) of kneaded corn stalks are established.

$$Y_1 = 222.6561 + 0.28854A + 5.36956B - 6.33944C - 0.001455AB + 0.000117AC - 0.00086BC - 0.000238A^2 - 0.027244B^2 + 0.022976C^2 \quad (2)$$

$$Y_2 = 386.26531 + 29.12865A + 59.94399B - 109.18962C + 0.005879AB - 0.001642AC + 0.001613BC - 0.043795A^2 - 0.366867B^2 + 0.425931C^2 \quad (3)$$

ANOVA of the Box-Behnken experiment results of productivity as indicator **Table 6**

Source of variation	Sum of Squares	df	nagMean Square	F-value	P-value	
Model	2106.09	9	234.01	11.45	0.0020	significant
A	13.01	1	13.01	0.6363	0.4513	
B	1676.20	1	1676.20	82.01	< 0.0001	
C	142.80	1	142.80	6.99	0.0333	
AB	1.44	1	1.44	0.0705	0.7983	
AC	0.0100	1	0.0100	0.0005	0.9830	
BC	0.1600	1	0.1600	0.0078	0.9320	
A^2	0.1364	1	0.1364	0.0067	0.9372	
B^2	158.22	1	158.22	7.74	0.0272	
C^2	128.30	1	128.30	6.28	0.0407	
Residual	143.07	7	20.44			
Lack of Fit	72.18	3	24.06	1.36	0.3754	not significant
Pure Error	70.89	4	17.72			
Cor Total	2249.16	16				
R^2	0.9364	C.V.%	7.44	Adeq Precision	11.8102	

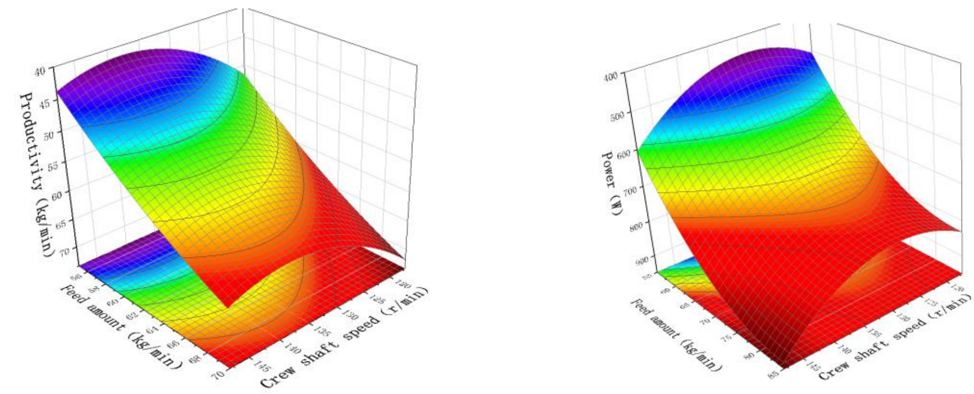
ANOVA of the Box-Behnken experiment results of power as indicator **Table 7**

Source of variation	Sum of Squares	df	nagMean Square	F-value	P-value	
Model	3.034E+05	9	33706.54	11.48	0.0020	significant
A	2453.50	1	2453.50	0.8360	0.3910	
B	2.069E+05	1	2.069E+05	70.50	< 0.0001	
C	20391.90	1	20391.90	6.95	0.0336	
AB	23.52	1	23.52	0.0080	0.9312	
AC	1.96	1	1.96	0.0007	0.9801	
BC	0.5625	1	0.5625	0.0002	0.9893	
A^2	4618.67	1	4618.67	1.57	0.2499	
B^2	28689.17	1	28689.17	9.78	0.0167	
C^2	44090.23	1	44090.23	15.02	0.0061	
Residual	20544.10	7	2934.87			
Lack of Fit	10720.91	3	3573.64	1.46	0.3526	not significant
Pure Error	9823.19	4	2455.80			
Cor Total	3.239E+05	16				
R^2	0.9366	C.V.%	7.64	Adeq Precision	12.5885	

Table 6 and Table 7 are regression ANOVA results for models Y_1 and Y_2, respectively. From Table 6, it can be seen that the P-value of regression model is 0.002 which is less than 0.05, indicating that the model is significant; The coefficient of determination R^2 is 0.9364, indicating that the model Y_1 can accurately reflect the influence of factors on productivity. The misfit value is 0.3754, which is more than 0.05, indicating that the factors not considered in the test have little impact on the test results. The coefficient of variation is 7.44%, which is less than 10%, indicating that the obtained model fits well with the actual experiment. The signal-to-noise ratio is 11.8102, indicating that the model has good precision and strong response signal. Table 7 shows that the model Y_2 is also successfully established.

In summary, both models can be used as predictive models for the screw conveying of kneaded corn stalks. From the ANOVA results of the models, it can be seen that the feed amount (B) and the screw shaft speed (C) have a significant impact on productivity and power.

In order to obtain the relationship between the influencing significant factors and the response value more intuitively, the stereoscopic atlas of the response surface of the model is got by using Design-Expert software, as shown in Figure 8.



a. The influence surface of feed volume and screw shaft speed on productivity

b. The influence surface of feed amount and screw shaft speed on power

Fig. 10 - The response surface atlas of interaction effects

As can be seen from Figure 8, the impact of feed volume increasing on productivity continues to grow. The effect of increased screw shaft on productivity shows a trend of increasing first and then decreasing. The influence of screw shaft speed increasing on productivity and power continues to increase.

RESULTS

After comprehensive analysis and optimization by Design-Expert software, the best process parameters of screw conveying are finally obtained as pitch of 319.428 mm, feeding amount of 71.062 kg/min, and screw shaft speed of 117.034 r/min. The corresponding production rate is 71.517 kg/min and the power is 769.84 W. Through EDEM software simulation and t-test explanation, the optimization results are reliable.

CONCLUSIONS

In this study, the kneaded corn stalks and screw conveying device are modelled by discrete element method, the screw conveying process of kneaded corn stalks was simulated, and the law affecting productivity and power consumption is revealed by changing the pitch, feed amount and screw shaft speed. And then the discrete-element simulation software is used to analyse the significance of three factors and obtain the optimal solution, namely the pitch of 319.428 mm, the feed amount of 71.062 kg/min, and the screw shaft speed of 117.034 r/min. The simulation verification by EDEM software shows that there is no significant difference, indicating the reliability of the optimization results.

This study also verifies the scientific rationality of the simulation of the screw conveying process of kneaded corn stalks by discrete element method, reveals the screw conveying mechanism of kneaded corn stalks, and the research results can provide a scientific and reasonable basis for the improvement and optimization of screw conveying device. On this basis, the discrete element method can be used to further reveal the wear and tear mechanism of the screw conveying device, which provides a theoretical basis for the design optimization of related conveying machinery and equipment.

REFERENCES

[1] Chen C., Ma X. D., Liu F. Y., Du Y. L., Zang F. (2023). Discrete element simulation study on grain separation in dustpan under eccentric pendulum（偏心摆振下圆簸箕中谷物分离的离散元模拟研究）, *Journal of Agricultural Mechanization Research*, vol. 45, issue 05, pp. 13-19.

[2] Hu W. H., Yang F. Z., Zhao G. D., Lin Y. L., Huang K. (2022). Analysis and optimization of working parameters of vertical rotary tillage knife based on discrete element method（基于离散元法的立式旋耕刀工作参数分析与优化）, *Journal of Chinese Agricultural Mechanization*, vol. 43, issue 10, pp. 25-32, 41.

[3] Li X. Y., Wang C. G. (2015). Experimental study on the performance of corn stover on LS screw conveyor（玉米秸秆在 LS 型螺旋输送机上的性能试验研究）, *Agricultural Mechanization Research*, vol. 37, issue 02, pp. 161-165.

[4] Li X. Y., Liao M., Yang J., Zheng R. K. (2022). Discrete element parameter calibration and seeding verification of Qiang live grains and perlite（羌活籽粒和珍珠岩的离散元参数标定及排种验证）, *Chinese Journal of Agricultural Mechanization*, vol. 43, issue 08, pp. 40-46.

[5] Liu Y. Y., Yu S. J., Xu B., Wang X. L., Song F. C. (2022). Research and experiment of in-situ ploughing in facility agriculture based on discrete element（基于离散元的设施农业就地翻土犁的研究与试验）, *Journal of Jilin University*, vol. 1, issue 11.

[6] Ning T. Z., Li Y., Gu Y. N. (2019). Research on conveying capacity of inclined screw conveyor based on EDEM（基于 EDEM 的倾斜螺旋输送机输送能力研究）, *Journal of Mudanjiang Normal University*, issue 04, pp. 38-41.

[7] Qi J. T., Meng J. W., Kan Z., Li C. S., Li Y. P. (2017). Analysis and test of feed performance of double helix cow feed device based on EDEM（基于 EDEM 的双螺旋奶牛饲喂装置给料性能分析与试验）, *Transactions of the Chinese Society of Agricultural Engineering*, vol. 33, issue 24, pp. 65-71.

[8] Wang P. F., Li J. P., Liu H. J., Zhang J. L. (2022). Application and practice of EDEM software in agricultural machinery teaching（基于 EDEM 软件在农业机械教学中的应用与实践）, *Agriculture and Technology*, vol. 42, issue 06, pp. 54-57.

[9] Wang Z. G. (2021). Exploration on comprehensive utilization pathways of maize straw（玉米秸秆综合利用途径探究）, *China Animal Health*, vol. 23, issue 05, pp. 102+104.

[10] Wu Y. L., Hou S. L., Zhao L. X., Tian T. S., Meng H. B. (2013). Development status and prospect of straw conveying technology and equipment（秸秆输送技术与设备发展现状及展望）, *Research on Agricultural Mechanization*, vol. 35, issue 09, pp. 11-15+29.

[11] Wulan T. Y., Wang C. G., Qi X. H., Yan J. G., Wang J. L. (2015). Analysis and optimization of working parameters of vertical rotary tillage knife based on discrete element method（揉碎玉米秸秆螺旋输送性能试验分析）, *Journal of Chinese Agricultural Mechanization*, vol. 31, issue 21, pp. 51-59.

[12] Wulan T. Y., Wang C. G., Zhao F. C., Wang X. R. (2019). Parameter test optimization of screw conveying device for kneading corn stalk（揉碎玉米秸秆螺旋输送装置参数试验优化）, *Journal of China Agricultural University*, vol. 24, issue 02, pp. 115-122.

[13] Wulan T. Y., Wang C. G., Xie S. S., Zhao Y. Y. (2015). Research on power consumption of corn stover transported by screw conveying device（螺旋输送装置输送玉米秸秆功耗研究）, *Research on Agricultural Mechanization*, vol. 30, issue 10, pp. 45-49.

[14] Wulan T. Y., Wang C. G., Qi X. H., Wang X. R., Wang H. C. (2016). Theoretical model analysis and experiment of spiral transport of crushed corn stalk（揉碎玉米秸秆螺旋输送理论模型分析与试验）, *Transactions of the Chinese Society of Agricultural Engineering*, vol. 32, issue 33, pp. 18-26.

[15] Wulan T. Y. (2016). Research on screw conveying mechanism of kneaded corn stalk（揉碎玉米秸秆螺旋输送机理研究）, *Inner Mongolia Agricultural University*.

[16] Xin Y. Y. (2020). Material conveying characteristics and wear mechanism of double screw conveyor based on discrete element method（基于离散元法双螺旋输送机物料输送特性及磨损机理）, *Liaoning Petrochemical University*.

[17] Zhao F. C., Wang C. G., Wulan T. Y. (2019). Research on parameter optimization of spiral conveying device（螺旋式输送装置参数优化研究）, *China Agricultural Science and Technology Review*, vol. 21, issue 06, pp. 70-78.

[18] Zhang Y. W., Wang W., Liu H. Y., Zhang W. G., Lu J. C. (2020). Simulation analysis of multi-point feed horizontal screw feeder based on EDEM（基于 EDEM 的多点进料水平螺旋给料机仿真分析）, *Port Loading and Unloading*, issue 06, pp. 10-13+51.