DISCRETE ELEMENT SIMULATION AND EXPERIMENT OF OPPOSED DOUBLE HELIX OUTER SHEAVE FERTILIZER DISCHARGER
/
对置双螺旋外槽轮排肥器离散元仿真与试验

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***Keywords:** outer grooved wheel fertilizer distributor, opposed double helix, fertilizer discharge uniformity, discrete element simulation, bench test*

ABSTRACT
Aiming at the pulsation problem of traditional external grooved wheel fertilizer distributor, an opposed double spiral external grooved wheel fertilizer distributor is designed, and the design and analysis of opposed double spiral grooved wheel parameters are carried out. In order to obtain the parameters of the grooved wheel with the best fertilizer discharge effect, the movement process of fertilizer particles in the opposite double spiral external grooved wheel fertilizer distributor was analyzed through discrete element simulation. Using the combination of discrete element simulation and bench test, a simulation orthogonal experiment was carried out on the influence of the rotational speed of the opposed double spiral sheave, the radius of the groove section, the working length of the sheave and the spiral angle of the sheave on the variation coefficient of fertilizer discharge uniformity. The result shows that the factors affecting the uniformity of fertilizer discharge are: trough wheel working length > trough wheel rotational speed > trough wheel helix angle > trough wheel groove radius, and the groove wheel working length of 50 mm, trough wheel rotational speed of 30 r/min, trough wheel spiral lift angle of 45° and groove radius of 10 mm are the optimal combination of structural parameters for fertilizer discharge effect, and the coefficient of variation of uniformity of fertilizer discharge under this combination of parameters is 3.08%. The actual fertilizer discharge performance was verified by bench test. The results show that the variation coefficient of fertilizer discharge uniformity under the parameter combination is 3.99%, and the deviation from the simulation test is 0.91%. The reliability of the discrete element simulation of the fertilizer discharge performance of the opposed double spiral external grooved wheel fertilizer discharger is verified.

摘要
针对传统外槽轮排肥器的脉动性问题，设计了一种对置双螺旋外槽轮排肥器，进行了对置双螺旋槽轮参数设计分析。为获取排肥效果最佳的槽轮参数，通过离散元仿真分析了肥料颗粒在对置双螺旋外槽轮排肥器中的运动过程，运用离散元仿真和台架试验相结合的方式，开展了对置双螺旋槽轮转速、凹槽截面半径、槽轮工作长度和槽轮螺旋升角对排肥均匀度变异系数的影响仿真正交试验，试验结果表明，影响排肥均匀度的因素主次为：槽轮工作长度>槽轮转速>槽轮螺旋升角>槽轮凹槽半径，排肥效果最优的结构参数组合为：槽轮转速30r/min，凹槽半径10mm，槽轮工作长度50mm，槽轮螺旋升角45°，该参数组合下排肥均匀度变异系数为3.08%。通过台架试验来验证其实际排肥性能，结果表明，该参数组合下的排肥均匀度变异系数为3.99%，与仿真试验偏差为0.91%，验证了离散元仿真研究对置双螺旋外槽轮排肥器排肥性能的可靠性。

INTRODUCTION
At present, there are many types of fertilizer dischargers available for fertilizer application operations in China (*Lv., 2014*), and the outer groove wheel dischargers are widely used in fertilizer strip application because of their simple structure and good versatility (*Pan., 2016*).

Most of the common external groove wheel fertilizer eliminators open a certain number of grooves in the cylindrical surface. With the rotation of the groove wheel, the fertilizer is discharged. There is pulsation in the process of fertilizer discharge from adjacent grooves, which affects the uniformity of fertilizer discharge (*Zhang X.C., 2019*).

Through discrete element simulation and bench test, domestic and foreign scholars establish the relationship between the geometric parameters of the outer sheave (sheave diameter, number of grooves, groove radius and groove shape), motion parameters (sheave speed) and the amount and uniformity of fertilizer discharge, so as to optimize the sheave parameters.

Zhu Qingzhen et al. studied the effects of the number of grooves, the radius of the grooves, the effective working length of the grooves and the shape of the groove section on the uniformity of fertilizer discharge by using the combination of simulation and bench for the traditional outer grooved fertilizer discharger (*Zhu et al., 2018*). *Dun Guoqiang et al.* optimized the structure parameters of the fertilizer tongue of the outer groove wheel fertilizer discharger through the discrete element method, and improved the uniformity of the fertilizer discharge flow of the fertilizer discharge tongue (*Dun et al., 2018*). *Wang Botao et al.* used discrete element simulation and bench test to study the influence of the working length of the outer sheave, the speed of the fertilizer discharge shaft, and the opening angle of the fertilizer discharge tongue on the fertilizer discharge amount (*Wang et al., 2017*).

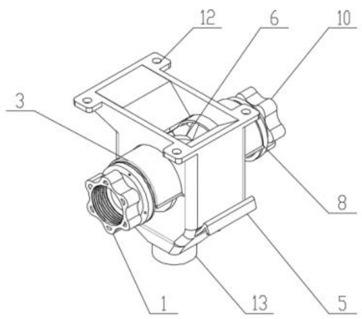
In order to reduce the pulsation of fertilizer discharge, related scholars replaced the traditional straight sheave with oblique sheave and spiral sheave, and optimized its structural parameters (*Gao G.B., 2019*). *Yang Zhou et al.* studied the effects of sheave speed, groove radius and sheave helix angle on fertilizer discharge through discrete element simulation and bench test (*Yang et al., 2018*). *Qi Xingyuan et al.* designed a fertilizer discharger with two rows of fertilizer discharge teeth arranged alternately, which can effectively reduce the fluctuation of fertilizer discharge (*Qi et al., 2016*). *Liu Dezhu and others* designed a staggered inclined groove adjustable outer groove wheel fertilizer discharge device, which has better stability and uniformity than the straight groove wheel (*Liu et al., 2021*).

Spiral outer sheave can reduce the pulsation of fertilizer discharge (*Zhang et al., 2020*). However, due to the action of screw conveying, the fertilizer is transported to one end, and the fertilizer falling belt is not centered when the fertilizer falls into the bottom of the ditch through the fertilizer guiding pipe. In order to solve this problem, this paper designs an opposed double helix outer sheave fertilizer discharger, and uses discrete element simulation to establish the sheave speed, groove radius, sheave working length and the relationship between the helix angle of the sheave wheel and the fertilizer discharge performance, so as to realize the centering of the bottom of the groove and improve the uniformity of fertilizer discharge.

MATERIALS AND METHODS

THE STRUCTURE AND WORKING PRINCIPLE OF THE OPPOSITE DOUBLE HELIX OUTER GROOVE WHEEL FERTILIZER DISCHARGER

The sheave is one of the core parts of the fertilizer distributor (*Zuo et al., 2016*). The opposed double helix outer sheave fertilizer discharger is mainly composed of left and right fertilizer volume regulators, left and right retaining rings, left and right blocking collars, left and right rotating shafts, fertilizer discharge tongues, opposed double helix sheaves, B-type pins, fertilizer shell, fertilizer outlet and other parts, as shown in Fig. 1. The left and right rotating shafts are respectively fixed on the left and right sides of the fertilizer discharge shell by tightening screws, and are arranged concentrically with the opposite double helical sheaves. Compared with the traditional straight sheave, the sheave adopts helical tooth grooves with the same rotation direction on the left and right sides and oppositely arranged.



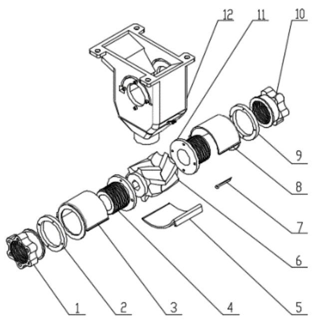


Fig. 1 - Schematic diagram of the structure of the opposite double helix outer groove wheel fertilizer discharger

1- Left fertilizer volume adjuster; 2- Left retaining ring; 3- Left blocking collar; 4- Left rotating shaft; 5- Fertilizer discharge tongue; 6- Opposite double helical sheave; 7- B-type pin; 8- Right blocking collar; 9- Right Retaining ring; 10- Right fertilizer amount adjuster; 11- Right rotating shaft; 12- Fertilizer housing; 13- Fertilizer outlet

During fertilizer discharge, the fertilizer particles enter the fertilizer discharge shell from the fertilizer discharge box by their own gravity, the fertilizer discharge shaft drives the opposite double helix sheave to rotate, and the fertilizer particles are driven by the rotating opposite double helix sheave, and are filled into the spiral groove (*Nukeshev et al., 2016*). With the rotation of the opposite double helical groove wheel, the fertilizer particles turn to the end of the fertilizer discharge tongue, and are automatically discharged from the fertilizer discharge port of the fertilizer discharge shell under the action of its own gravity (*Su et al., 2015*). By turning the left and right fertilizer volume adjusters to drive the left and right blocking collars to move to change the effective working length of the opposed double helical groove wheels to adjust the fertilizer discharge volume, the opening angle of the fertilizer discharge tongue can also be changed by adjusting the position of the B-type pin to adjust the amount of fertilizer discharged.

PARAMETER DESIGN OF OPPOSITE DOUBLE HELIX EXTERNAL SHEAVE

Because the opposed double helix outer groove wheel fertilizer discharger is further optimized and improved based on the traditional outer groove wheel fertilizer discharger, the external groove wheel seed metering device in the agricultural machinery manual should be used as a reference when designing its structural parameters. Referring to the structural parameters of the existing outer sheave fertilizer discharger, the maximum effective working length of the opposed double helical sheave is 60 mm, and the radius of the sheave is 30 mm. The structure diagram is shown in Fig. 2.

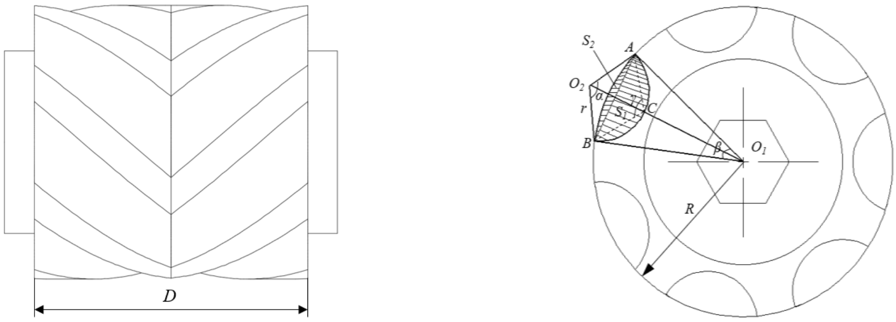


Fig. 2 - Schematic diagram of the structure of opposed double spiral grooved wheels

The groove section of the opposed double helix outer sheave was circular arc, the number of grooves was chosen to be 7, and the groove section area could be calculated by Eq. (1).

$$S = S_1 + S_2 = \frac{R^2}{8}(\beta - \sin\beta) + \frac{1}{2} r^2 \sin^2_{\frac{\alpha}{2}}(\alpha - -\sin\alpha) \tag{1}$$

The opposed double helical sheave needs to be driven by the fertilizer discharge shaft to rotate, and moves continuously in the helical groove under the action of various forces. During the fertilizer discharge process, the fertilizer particles located in the spiral groove are not only subject to the normal pressure F_N of the spiral groove, but also to the tangential friction force f_s generated by the contact between the fertilizer particles and the spiral groove. The resultant force of the two is F, and the resultant force F can be decomposed into the axial force F_2 parallel to the axis direction and the axial force F_1 perpendicular to the axis direction. The force acting on the fertilizer particles is shown on the left side of Fig. 3.

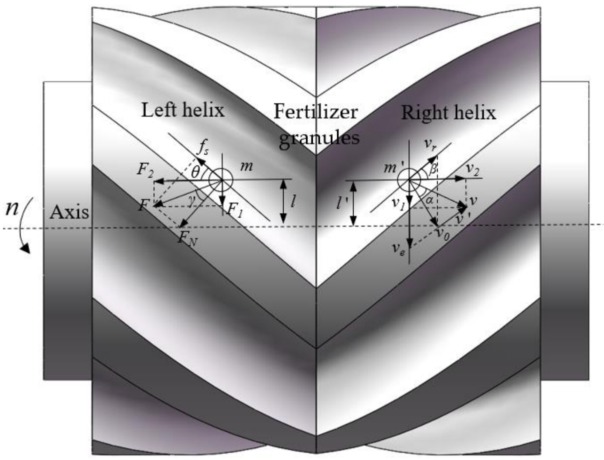


Fig. 3 - Force and Velocity Analysis of Fertilizer Particles in Helical Sheave

It can be seen from Fig. 3 that the angle between the normal pressure F_N and the resultant force F is the friction angle γ, and the helical line is replaced by an oblique line, then θ represents the helix angle of the opposing double helical sheave, and the friction angle γ is determined by the tangential direction. Caused by the friction force f_s, the expression formula of each parameter is as follows:

$$\begin{cases} F = \sqrt{F_1^2 + F_2^2} = \sqrt{f_s^2 + F_N^2} \\ F_1 = F\cos(\theta+\gamma) \\ F_2 = F\sin(\theta+\gamma) \end{cases} \tag{2}$$

In Eq. (2), F is the resultant force of the opposing double helical grooves acting on the fertilizer particles, N; f_s is the tangential friction force generated by the contact between the fertilizer particles and the helical groove, N; F_N is the normal pressure of the spiral groove on the fertilizer particles, N; F_1 is the axial component force, N; F_2 is the circumferential component force, N; θ is the helix angle of the opposed double helix groove wheel, °; γ is the friction angle between the opposed double spiral groove wheel and the fertilizer grain, °(*KIM et al., 2008*).

As can be seen from Eq. (2), when the fertilizer particles move in the groove of the opposed double spiral groove wheel, the axial and circumferential components of resultant force on the fertilizer particles vary with the distance between the fertilizer particles and the axis, with the increase of the spiral angle, the opposed double spiral sheave gradually becomes straight sheave, the pulsation of fertilizer discharge is increased. The proper selection of the spiral angle of the sheave has a direct effect on the force acting on the fertilizer particles in the opposed double spiral groove, being the key to achieving even fertilizer discharge.

In the same way, treating the fertilizer particles inside the spiral grooves as a mass point m, the velocity of this mass point was analyzed as shown in Fig. 3, right side.

The movement of fertilizer particles in the opposite double helical grooves is driven by the fertilizer discharge shaft, the implicated velocity v_e is that the linear velocity of the particle is perpendicular to the axis direction, and the relative velocity v_r is parallel to the helix direction. In the ideal case without considering friction, the absolute velocity is v_0. However, in practice, the velocity v' generated by friction will deviate from the ideal absolute velocity v_0. The deviation angle is α, and the actual absolute speed after the deviation is v. At the same time, it can also be decomposed into circumferential speed v_1 and axial speed v_2, which can be expressed as Eq. (3).

$$\begin{cases} \vec{v}_0 = \vec{v}_e + \vec{v}_r \\ \vec{v} = \vec{v}_1 + \vec{v}_2 = \vec{v}_0 + \vec{v}\,' \end{cases} \tag{3}$$

The circumferential speed v_1 and axial speed v_2 decomposed by the actual absolute speed v can be expressed as Eq. (4):

$$\begin{cases} v_1 = v\cos(\alpha+\beta) \\ v_2 = v\sin(\alpha+\beta) \end{cases} \tag{4}$$

Through trigonometric transformation, it can be obtained:

$$\begin{cases} v_e = \omega l = \dfrac{\pi n l}{30} \\ v = \dfrac{v_0}{\cos\alpha} = \dfrac{v_e\cos\beta}{\cos\alpha} \\ v_1 = \dfrac{\pi n l}{30}\dfrac{\cos\beta}{\cos\alpha}\cos(\alpha+\beta) \\ v_2 = \dfrac{\pi n l}{30}\dfrac{\cos\beta}{\cos\alpha}\sin(\alpha+\beta) \end{cases} \tag{5}$$

In formulas (3) to (5): v_e is the implicated speed, m/s; v_r is the relative speed, m/s; v_0 is the ideal absolute speed, m/s; v' is the speed due to friction, m/s; v is the actual absolute speed, m/s; v_1 is the circumferential speed, m/s; v_2 is the axial speed, m/s; n is the rotational speed of the opposed double helical sheave, r/min;

The ω is the angular velocity of the opposing double helical sheave, rad/s; l is the distance from the fertilizer particle to the axis, mm; α is the angle at which the actual absolute velocity deviates from the theoretical velocity, °. β is the helix angle of the opposing double helical sheave, ° (*Zha et al., 2020*).

According to the above formula, the velocity variation of fertilizer particles in the groove of the opposed Double Helix grooved wheel is related to the spiral angle of the grooved wheel, the distance of fertilizer particles from the axis and the rotation speed of the grooved wheel.

DISCRETE ELEMENT SIMULATION TEST

With the popularity of the discrete element method in the field of agricultural engineering, it has been gradually used by more and more people in scientific research (*Coetzee et al., 2011*; Pasha *et al., 2016*). In this paper, the process of fertilizer discharge of opposed double spiral external grooved wheel fertilizer discharger is analyzed by means of discrete element software EDEM2018, and the method of combining discrete element simulation with bench test is used, the effect of relative parameters of opposed double helix external grooved wheel on its fertilizer discharge performance was studied (*Hu et al., 2016*; *Liu et al., 2017*).

Establishment of discrete element simulation model

Discrete element model of fertilizer discharge device

The created opposed double helix outer groove wheel fertilizer discharge device model is mainly composed of a fertilizer discharge box, a mounting plate, a fertilizer discharge shaft, an opposed double helix outer groove wheel fertilizer discharger and a fertilizer discharge port, as shown in Fig. 4.

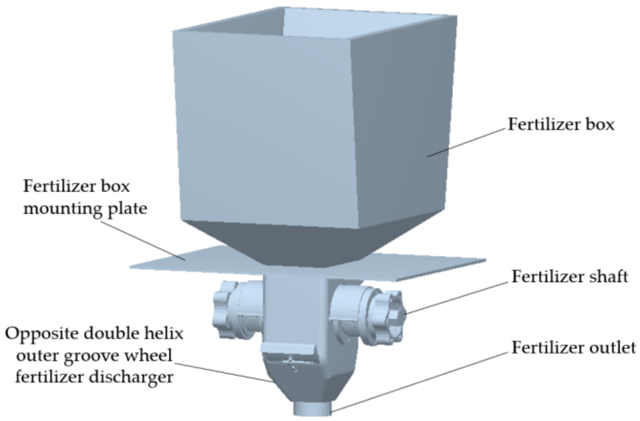


Fig. 4 - Discrete element model of fertilizer discharging device with opposite double helix outer groove wheel

Discrete Element Model of Fertilizer Particles

It was simulated the fertilizer rejection process of fertilizer in a counter placed double spiral outer slot wheel fertilizer remover by discrete element method, and the closer the selected fertilizer grain shape and size were to the true values, the more reliable the fertilizer rejection test results were (*Yuan et al., 2014*; *Yang et al., 2020*; *Ma et al., 2013*). Relevant literature shows that fertilizer grains have a higher sphericity and tend to be greater than 90% (*Coskun et al., 2006*; *Liu et al., 2018*; *Su et al., 2015*). In this paper, 50 grains each of urea, composite and organic fertilizers, which are commonly used fertilizers, were selected to measure their dimensions such as length, width and thickness, and the equivalent diameter and sphericity of the fertilizer grains are available from equations (6) and (7).

$$D=\sqrt[3]{LKH} \tag{6}$$

$$\varphi=\frac{D}{L} \tag{7}$$

In Eqs. (6) and (7): D is the equivalent diameter of fertilizer granules, mm; L is the length of fertilizer granules, mm; K is the width of fertilizer granules, mm; H is the thickness of fertilizer granules, mm; φ is the sphericity of fertilizer granules, % (*Van et al., 2009*).

It was measured that the sphericity of three fertilizer particles, urea, compound fertilizer and organic fertilizer, was high, 97.67%, 96.45% and 95.48%, respectively, which can be approximated as spherical (*Yang et al., 2019*), and combined with the relevant dimensions of the three fertilizers, a ball with a diameter of 3.30 mm was selected as the three-dimensional discrete element model of fertilizer particles in this experiment.

Discrete Element Contact Model

Although fertilizer particles are prone to deliquescence, they are solid and dry granules in the actual fertilization process and do not stick to each other. In order to accurately simulate the fertilization process, Hertz-Mindlin (no slip) was used as the contact model between the fertilizer particles and the fertilization device with the opposite double helix outer sheave (*Chen et al., 2011*; *Zhu et al., 2019*; *Marigo et al., 2015*). The manufacturing material of the opposed double helix outer groove wheel fertilizer spreader is resin. By referring to the relevant literature, the simulation parameters of the relevant materials are determined as shown in Table 1 (*Wang et al., 2017)*.

Table 1

Simulate material and contact mechanics parameters

Parameter	Property	Value
Fertilizer granules	Poisson's ratio	0.25
	Shear modulus/Pa	1.0×10^7
	Density (kg m^{-3})	1320
Fertilizer	Poisson's ratio	0.4
	Shear modulus/Pa	1.0×10^6
	Density (kg m^{-3})	3500
Fertilizer Granules and Fertilizer Granules	Crash recovery factor	0.11
	Static friction coefficient	0.3
	coefficient of kinetic friction	0.1
Fertilizer Granules & Fertilizers	Crash recovery factor	0.41
	Static friction coefficient	0.32
	coefficient of kinetic friction	0.18

Method for measuring the coefficient of variation of fertilizer uniformity

The test evaluation index selected in this paper is the coefficient of variation of uniformity of fertilizer discharge. Select areas with stable fertilization within the simulated fertilizer ditch area, use the Grid Bin Group function to select a stable fertilization area in the simulated fertilizer ditch area and set up 6 (120mm×200mm×50mm) fertilization monitoring areas with a total length of 1200 mm, and number each area in turn. It is convenient to perform quality statistics on the fertilizer particles in each area after the simulation is over, and according to the formula (8) to (10), the coefficient of variation of the uniformity of fertilizer discharge can be calculated.

$$\bar{m}=\frac{1}{n}\sum m_i \tag{8}$$

$$s=\sqrt{\frac{1}{n-1}\sum(m_i-\bar{m})^2} \tag{9}$$

$$\delta=\frac{s}{\bar{m}}\times100\% \tag{10}$$

In formulas (8) to (10), The $\bar{m}$ is the average mass of fertilizer particles in the monitoring area, g; The m_i is the quality of fertilizer particles in the i monitoring area, g; n is the number of monitoring areas, n=6; s monitoring area Standard deviation of the total mass of the inner fertilizer particles, g; δ denotes the coefficient of variation of the uniformity of fertilizer discharge, %; δ is inversely proportional to the fertilizer discharge stability and uniformity of the fertilizer discharge device with double spiral outer grooved wheel (*Zhu et al., 2018)*.

RESULTS

Simulation Orthogonal Test and Result Analysis

Test design

Import the model of opposed double spiral external grooved wheel fertilizer discharger into EDEM. A non top shell with a length of 3000 mm, a width of 200 mm and a height of 20 mm is set at the 120 mm position at the lower end of the fertilizer discharge port, the fertilizer spreader being located on the central axis of the housing, it is used to simulate fertilizer ditch and observe the distribution of fertilizer on the ground. In order to simplify the simulation motion setting, the shell (simulating the ground) is set here to move the conveyor belt at the speed of 0.5 m/s, and the fertilizer discharge device is stationary to simulate the fertilizer discharge process. Put the established particle factory directly above the fertilizer discharge box and generate 12000 particles in total at the speed of dynamically generating 6000 particles per second through normal distribution. Set the starting time of the opposed double helix sheave to two seconds after starting to generate fertilizer particles. Set the total simulation time to 18 s and the time step to 18.122% of the Rayleigh time step.

Through the analysis of the relevant parameters of the opposed double helix external grooved wheel affecting the fertilizer discharge effect, combined with the working principle of the opposed double helix external grooved wheel fertilizer discharge device, this paper selects the rotating speed of the grooved wheel, the groove radius, the working length of the grooved wheel and the spiral rising angle of the grooved wheel as the experimental factors, and determines that the diameter of the opposed double helix grooved wheel is 60 mm, the number of spiral grooves is 7 and the forward speed of the machine is 0.5 m/s to design the orthogonal test. The levels of selected test factors are shown in Table 2.

Table 2

Test factor level table

Level	Sheave speed （A）/ r/min	Groove radius (B)/mm	Sheave working length(C)/mm	Null List	Sheave helix angle （D）/°
1	15	9.5	20		45
2	20	10	30		50
3	25	10.5	40		55
4	30	11	50		60

Simulation analysis of movement process of fertilizer particles

From the beginning of the simulation, the fertilizer particles continue to fall from the particle factory within 0~3 seconds, and finally all fall into the fertilizer box. In order to study the movement process of fertilizer particles in the opposed double spiral external grooved wheel fertilizer discharge device, it is convenient to directly analyze the movement track and velocity change of fertilizer particles. According to the movement path of fertilizer particles, the whole process of fertilizer discharge was divided into zones, it is divided into five areas: AB (fertilizer box area), BC (fertilizer housing), CD (slot wheel area), EF (fertilizer tongue area) and GH (fertilizer mouth area). The speed of fertilizer particles is colored to distinguish between the maximum speed of red, yellow, and green which represents the minimum value. The distribution of fertilizer particle velocity in the process of fertilizer discharge is shown in Fig. 5.

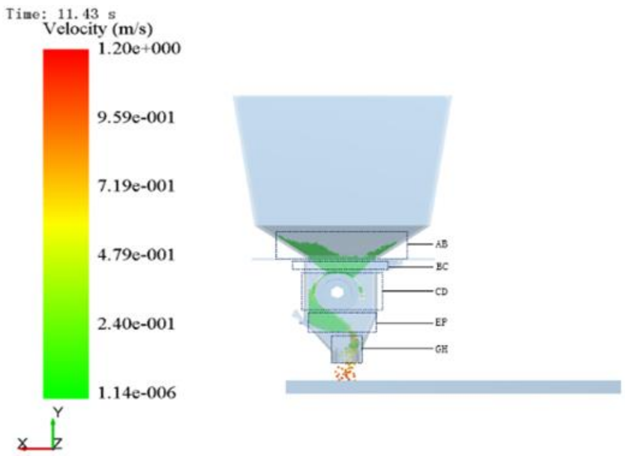
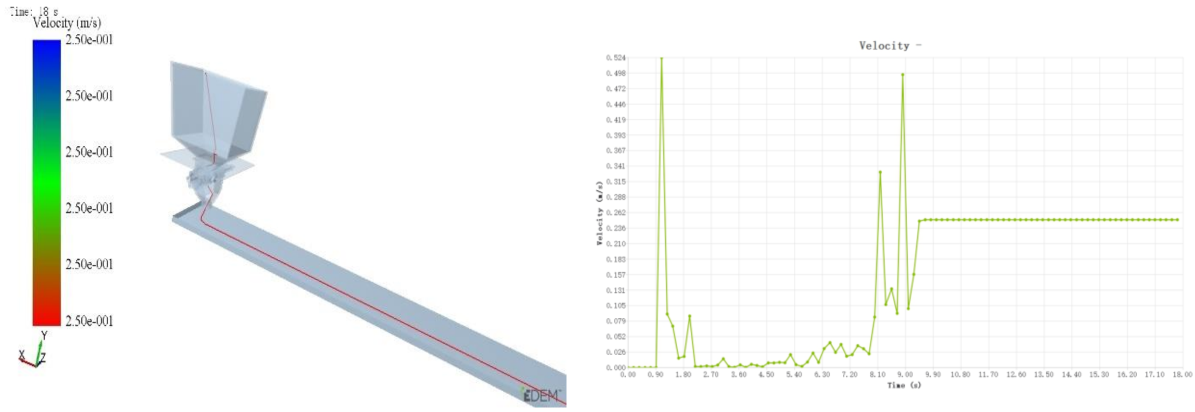


Fig. 5 - Fertilizer particle velocity distribution map

Under the action of its own gravity, the fertilizer particles generated by the particle factory fall into the fertilizer box and enter the fertilizer discharge box of the opposite double helix outer groove wheel fertilizer discharger, and move to the fertilizer discharge tongue under the rotation of the opposite double helix groove wheel. Through the continuous rotation of the groove wheel, the fertilizer continues to accumulate at the fertilizer discharge tongue, and under the action of gravity, it falls to the fertilizer discharge port to complete the fertilizer discharge.

In order to further analyze the movement law of fertilizer particles in the opposite double helix outer groove wheel fertilizer discharge device during the fertilizer discharge simulation process, the Manual Selection function in EDEM is used to select a single fertilizer particle for research. The selected fertilizer particle number is No. 5994. Taking this as the object, analyze its motion trajectory and speed change, as shown in Fig. 6.



a. Motion trajectory diagram of selected fertilizer particles *b. The selected fertilizer particle velocity change curve*

Fig. 6 - Movement trajectory and speed change diagram of selected fertilizer particles

It can be seen from Fig. 6 that the created particle factory produces fertilizer particles No. 5994 at 0.9 s, and falls to the AB fertilizer box area by its own gravity. Within 0.9~1.2 s, the speed of No. 5994 fertilizer particle increases first and then decreases, reaching a maximum value of 0.524 m/s at 1.0 s. Within 1.2~2.7 s, the particle is in the AB area, and the velocity fluctuates with the accumulated fertilizer particles. Within 2.7~7.8 s, the particle entering the BC fertilizer box area, the speed does not change much and shows a slight fluctuation state. Within 7.8~8.5 s, the particles enter the CD opposed double helix sheave area. Driven by the sheave, the speed first increases and then decreases. The maximum value was reached at 8.2 s, which was 0.341 m/s. Within 8.5~8.9 s, the particles entered the EF fertilizer tongue area, and the speed first increased and then decreased, but the fluctuation was not large. Within 8.9~9.2 s, the particles Entering the GH fertilizer discharge area, the speed still increases first and then decreases, and reaches the maximum value at 9.1 s, which is 0.498 m/s. Within 9.2 s to the end of fertilizer discharge, the particles fall on the simulated ground, and the speed increases, after reaching 0.25 m/s, do a uniform motion to complete the whole process of fertilization.

Test Results and Analysis

The L_{16} (4^5) orthogonal test table was selected for the test by consulting the data to analyze the influence of the selected test factors on the coefficient of variation of fertilizer discharge uniformity (*Siemens et al., 2016)*. The fertilizer discharge simulation test process is shown in Fig. 7, and the experimental design and results are shown in Table 3.

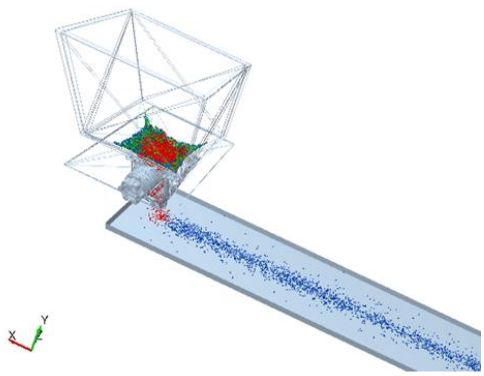


Fig. 7 - Fertilization simulation test process

Table 3

Experimental Design and Results

Test number	A	B	C	Empty column	D	Fertilization uniformity coefficient of variation (%)
1	1	1	1	1	1	6.08
2	1	2	2	2	2	13.25
3	1	3	3	3	3	11.44
4	1	4	4	4	4	6.13
5	2	1	2	3	4	11.54
6	2	2	1	4	3	6.21
7	2	3	4	1	2	5.22
8	2	4	3	2	1	9.86
9	3	1	3	4	2	12.14
10	3	2	4	3	1	3.08
11	3	3	1	2	4	7.89
12	3	4	2	1	3	12.74
13	4	1	4	2	3	3.86
14	4	2	3	1	4	6.43
15	4	3	2	4	1	7.20
16	4	4	1	3	2	5.17
K_1	9.225	8.405	6.338	7.618	6.555	
K_2	8.208	7.243	11.183	8.715	8.945	
K_3	8.963	7.938	9.968	7.808	8.563	
K_4	5.665	8.475	4.573	7.920	7.998	
Very poor	14.24	4.93	26.44	4.39	9.56	
Factor Primary - Secondary	C>A>D>B					
Best plan	$A_4B_2C_4D_1$					

The simulation test results show that the optimal structure parameters for the fertilizer discharge effect of the opposed double helix outer groove wheel fertilizer discharger are: the rotation speed of the grooved pulley is 30 r/min, the cross-sectional radius of the groove is 10 mm, the working length of the grooved pulley is 50 mm, and the Helix Angle of the grooved pulley is 45°. The primary and secondary order of the factors influencing the uniformity of fertilizer discharge is: the working length of the grooved pulley, the rotating speed of the grooved pulley, the helix angle of the grooved pulley, and the cross-sectional radius of the groove.

In order to further understand the importance of the test parameters of the opposed double spiral external grooved wheel fertilizer ejector on the fertilizer discharge performance, the test results are analyzed by variance, and the results are shown in Table 4.

Table 4

Variance analysis

Source of variation	Deviation sum of squares	Degrees of freedom	Sum of mean squares	F	Salience
A	31.686	3	10.562	2.403	*
B	3.866	3	1.289	0.293	
C	114.041	3	38.014	8.648	**
D	2.8	3	0.933	0.215	
error	13.186	3			

*Note: * Significant impact (F0.01>F>F0.05); ** The impact is very significant (F>F0.01)*

It can be seen from Table 4 that the working length of the opposed double spiral grooved wheel has a very significant effect on the fertilizer discharge effect, and the rotating speed of the grooved wheel, the spiral rising angle of the grooved wheel and the groove section radius have no significant effect on the fertilizer discharge effect.

BENCH TEST

Based on the above simulation orthogonal test results, the structural model of opposed double helix external grooved wheel fertilizer ejector under the horizontal combination of the optimal structural parameters when the rotating speed of the grooved wheel is 30 r/min, the groove section radius is 10 mm, the working length of the grooved wheel is 50 mm and the spiral rising angle of the grooved wheel is 45 ° is manufactured. The actual fertilization effect is verified by means of bench test verification.

Test Materials and Devices

The test site of this bench is Hubei Zhongxuan Agricultural Intelligent Technology Co., Ltd, and the time is August 10, 2020. Using the SL6003D printer made by Zhongrui Technology Company to process the opposed double spiral external grooved wheel fertilizer discharger (resin material). The compound fertilizer produced by Stanley Chemical Fertilizer Co., Ltd. was used as the test material, and the self-built test-bed, as shown in Fig. 8.

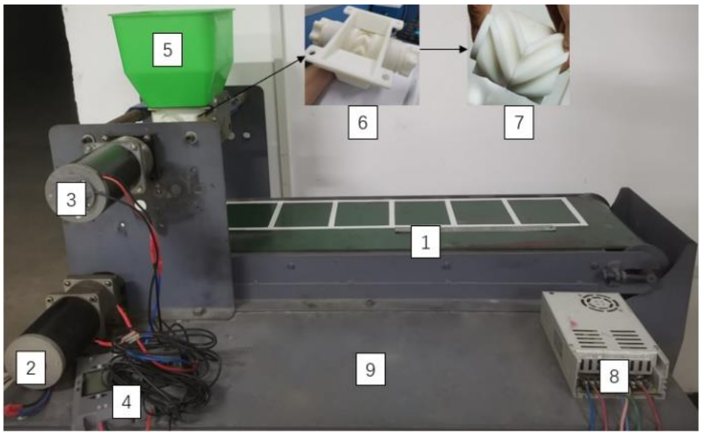


Fig. 8 - Physical map of the structure of the fertilizer test bench

1- Conveyor belt; 2- Conveyor motor; 3- Fertilizer motor; 4- Speed regulator; 5- Fertilizer box; 6- Opposite double spiral outer groove wheel fertilizer discharging device; 7- Opposite double spiral groove wheel; 8- Motor Controller; 9- Test Bench

Test plan

During the bench test, set the forward speed of the conveyor belt as 0.5 m/s, the rotating speed of the sheave as 30 r/min, and the distance between the fertilizer discharge port and the conveyor belt as 120 mm. Use white tape to delineate six grid areas on the conveyor belt, the inner size of each grid is 200 × 220 (mm), and number them. After fertilizer discharge, use a brush to collect the fertilizer particles in the grid into sealed bags. If the fertilizer particles just fall on the frame of the tape, then use the “record the top, not the bottom, the left and not the right” principle to collect. The fertilizer collected in each grid is weighed using an electronic balance. Then make statistics on the mass distribution law of fertilizer particles on the conveyor belt. Calculate the coefficient of variation of the uniformity of fertilizer discharge by the formula, repeat the test five times and get the mean.

Analysis of test results

Through the bench test, the variation coefficients of fertilizer discharge uniformity measured in five repeated tests were 3.71, 4.20, 5.21, 3.14 and 3.69 (%) respectively, and the average value was 3.99%. The test results show that the test results of the opposed double spiral external grooved wheel fertilizer ejector are slightly lower than the simulation test results. Considering that the fertilizer granules and fertilizer discharger models in the simulation are inevitably different from the actual ones. Therefore, it can be considered that the simulation test results are basically consistent with the bench test results. It is further verified that it is reliable to study the fertilizer discharge process of the opposed double helix outer groove wheel fertilizer discharger through discrete element simulation software.

CONCLUSIONS

In this paper, an opposed double spiral external grooved wheel fertilizer distributor is designed, the fertilizer discharge can be controlled by changing the working length of the sheave through the fertilizer regulator on the left and right sides. Replacing traditional straight grooved sheave with opposed double spiral grooved sheave. At the same time, the pulsation of fertilizer discharge is reduced, the fertilizer belt falling into the ditch bottom can be centered, and the fertilizer discharge effect is improved. The structural parameters of the opposed double spiral sheave are optimized through discrete element simulation and bench test. The influence of the rotating speed of the opposed double spiral sheave, the radius of the groove section, the working length of the sheave and the spiral angle of the sheave on the uniformity of fertilizer discharge was investigated, the optimal structure parameters of the opposed double spiral sheave are obtained.

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