Optimization and experiment of counter-rotating straw returning cultivator based on discrete element method

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Abstract

This study is mainly about the optimization, simulation and experiment of a Counter-rotation Straw Returning Cultivator (CSRC), aiming at the problems that the existing CSRC has serious entanglement of grass, terrible jam of soil, large energy consumption, and poor straw coverage rate. Besides, an optimized Rotary Blade Roller (RBR) and a device to avoid the jam of soil were designed to optimize CSRC. A discrete element simulation model of straw-soil-RBR was established based on the EDEM software. The optimization simulation experiment of 4 factors and 3 levels, which took the single-blade operation width, bending angle, advance speed and rotation speed of RBR as factors, and used the straw coverage rate and power consumption as evaluation indicators, was carried out to optimize the structure parameters and working parameters of the RBR with the method of orthogonal experiment. The simulation experiment results showed that the optimal combination of parameters of the RBR at the tillage depth of 130 mm were 237.58 r/min of RBR rotation speed, 1.11m/s of forward speed, 35 mm of single-blade working width, and 134.09° of bending angle. Field tests showed that the straw coverage rate was 89.29%, the average torque was 517.25 N·m, the soil fragmentation rate was 83.21%, and the flatness of the surface after cultivation was less than 4 cm under the conditions of optimal parameters mentioned above. Therefore, the CSRC perfectly satisfied the industry standards, and meet the design requirements of machinery.

Keywords: Agricultural machinery, Counter-rotation Straw Returning Cultivator, Structural optimization, Parameter optimization, Discrete element method

1. Introduction

Returning straw to the field is currently the main treatment method for straw, which reduces the environmental pollution caused by the burning of straw, and also improves the structure and fertility of soil. The uniaxial RBR with the function of forward-rotation is generally used in the operation of the returning straw to field presently. However, the effect of returning straw to the field and the quality of rotary tillage are poor, which affects the seed germination and emergence(Yonglei et al., 2013; Haishui et al., 2015). Although the biaxial straw returning cultivator (SRC) has a good effect of returning straw to the field, the cultivator has a long longitudinal structure, which causes poor stability of field operation, and affects the quality of rotary tillage. The CSRC, which is widely used in southern paddy fields, has the advantages of good effects of returning straw to the field and high quality of rotary tillage. However, the horizontal CSRC still uses the standard forward-rotating rotary blades at present. The arrangement of the rotary blades is the same as that of the forward-rotating rotary blades, which results in the problem of that the power consumption of the counter-rotating RBR being significantly higher than that of the forward-rotating RBR.

In recent years, many scholars have explored the energy consumption and working performance of SRC. Because the DEM can be used to simulate the formation and destruction of contact between granular materials(Li et al., 2016; Zeng and Chen, 2016), it is suitable for simulating the interaction between rigid body and elastomer(Huimin, Changying and Chандio et al., 2016; Huimin, Changying and Tagar et al., 2016). The DEM has been widely used in the study of the interaction between straw, soil and RBR. Chандio et al. used the DEM to establish a simulation model of the interaction between straw, disc plough and soil, and analyzed the displacement, acceleration and displacement changes of soil particles and straw particles during the work of the tillage(Farman, 2013). Momozu et al. deeply carried out research on
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the soil cutting process of the pendulous shovel by using the DEM and found that the simulation of the DEM can simulate the real power consumption of the pendulous shovel (Momozu et al., 2002). Ucgul et al. established a discrete element model for the interaction between soil shovel and soil, and the results showed that the DEM model can well simulate the interaction between soil and machinery (Ucgul et al., 2014; Ucgul et al., 2015; Ucgul et al., 2017a; Ucgul et al., 2017b; Ucgul et al., 2018). Weimin Ding analyzed the tangent plane of the counter-rotating blade, and considered that it is important to design a proper tangent plane to improve the performance of throwing soil away and reduce the terrible jam of soil in front of the RBR (Weiming et al., 2004). Song Yang compared the power consumption and rotary cultivation quality of various arrangements of counter-rotating RBR, and come to the conclusion that the herring bone arrangement of RBR is more suitable for CSRC (Song et al., 2018). However, these studies only considered the impact of cultivator structure and operating parameters on the energy consumption of the operation, the impact on the quality of the operation was missed. The problems of the serious entanglement of grass and terrible jam of soil in front of the RBR during the operation of CSRC were not effectively solved.

Therefore, focusing on the requirements of soil tillage before rice dry direct seeding and the problems of the serious entanglement of grass and the terrible jam of soil, large energy consumption, and poor straw coverage effect of SRC, an optimized CSRC was designed. Based on the EDEM software, a discrete element simulation model of straw-soil-RBR was established. Taking the single-blade operation width, bending angle, CSRC forward speed and RBR rotation speed as factors, and using the straw coverage rate and power consumption as the evaluation indicators, the 4-factors and 3-levels orthogonal test of optimization simulation was carried out to obtain the optimal parameters combination. Field tests were carried out to verify the reliability of the simulation results and the performance of the optimized CSRC.

2. Materials and methods

2.1 Total structure of CSRC

The CSRC is mainly composed of a casing, a RBR, a claw device, a hanging board, a grass barrier, a gear box, and a suspension frame, as shown in Fig. 1. During the operation, the power of output shaft of the tractor is transmitted to the RBR through the gearbox, and the rotary blades perform the rotary tillage from the cultivated land to the uncultivated land. RBR starts to cut straw and soil from the bottom of the plow layer to the ground. After cultivation, the straw-soil mixture is thrown up to the casing and slides along its inner surface. The large soil blocks and the stubble thrown backwards can’t pass through the grass barrier, so they slide behind the RBR and spread on the ground floor first, then the small broken soil will fall to the surface through the grass barrier. There is a time lag between the soil and the straw during the process of falling into the bottom of the trench, so the straw will be covered by the finely broken soil that subsequently falls to achieve the function of straw coverage. This process will help to make the soil form a distribution of the thicker layer below and the finer layer upper after tillage, and also help to establish good air permeability, which helps to crop’s growth (Botta et al., 2015).

![Fig.1 Structural diagram of CSRC. Where, the number 1 is RBR; The number 2 is Grass barrier; The number 3 is Anti-clogging device; The number 4 is Machine casing; The number 5 is Hanging board; The number 6 is Gear box; The number 7 is Suspension frame.](image)

2.2 The key components

2.2.1 Design of anti-clogging device

Aiming at the problem of terrible jam of soil in front of the RBR, the shape of the hanging board and the directional
diversion and re-crushing effect of the thrown soil were improved, which were beneficial to divert the soil to the back of the RBR. Besides, an anti-clogging device which was coaxial with the RBR was designed in the lower part of the hanging board, and it prevented the phenomenon of terrible jam of soil in front of the RBR effectively. Because the shape and position of the machine casing has a certain effect on the soil throwing effect (Bo-quan and Cui-ying, 2000), according to experimental research, the distance between the machine casing and the outer contour of the RBR was advised to be 110mm.

To further accurately describe the load situation of the anti-clogging device in work, it is supposed that the soil density was $\rho$ (kg·m$^{-3}$), and the width of the soil on a claw-shaped structure of the anti-clogging was $B$ (m). Taking a longitudinal section, and using the center of the support tube of the claw-shaped structure $O$ as the origin of the coordinate, the $x$-axis is horizontal to the right, and the $y$-axis is vertical to the bottom, as shown in Figure 2.

Fig. 2 Force diagram of anti-clogging device. Where, the $O'$ is the circle center of the claw-shaped structure, of whose coordinates is $(a, b)$, $R$ is the radius of that, and $\theta$ is the angle between the OP line and the $y$-axis. The shaded part represents the soil, the double-shadow part $dS$ represents the infinitesimal area of the soil element in the $dx$ section, $dG_x$ indicates the infinitesimal gravity of the soil of the $dS$ part at the point P, $dN_x$ indicates the infinitesimal component force in the vertical direction of line OP, and $y_2$ represents the equation of the partial arcs.

According to the equation of the circle, the expression of $y_2$ is shown as Eq. (1).

$$y_2 = b + \sqrt{R^2 - (x - a)^2}, (x_1 \leq x \leq x_2)$$  \hspace{1cm} (1)

The area of $dS$ is shown as Eq. (2).

$$dS = (y_2 - y_1) dx$$  \hspace{1cm} (2)

The gravity $dG_x$ at point P in the area of $dS$ is shown as Eq. (3).

$$dG_x = \rho g dS$$  \hspace{1cm} (3)

The $\theta$ can be calculated by Eq. (4).

$$\tan \theta = \frac{x}{y_2}$$  \hspace{1cm} (4)

The infinitesimal component force $dN_x$ in the vertical direction of line OP $dN_x$ is shown as Eq. (5).

$$dN_x = dG_x \sin \theta$$  \hspace{1cm} (5)

Therefore, the torque $dM_x$ from point P to point O can be calculated by Eq. (6).

$$dM_x = \sqrt{x^2 + y_2^2} dN_x$$  \hspace{1cm} (6)

Substituting Eq. (1) to Eq. (5) into Eq. (6), then obtain the Eq. (7) shown as follow.

$$dM_x = \left[ \rho g \frac{\left( y_2 - y_1 \right) \sin \left( \frac{x_2}{y_2} \right) \sqrt{x^2 + (y_2^2)}} \right] dx, \left( y_2 = b + \sqrt{R^2 - (x - a)^2}\right), (x_1 \leq x \leq x_2)$$  \hspace{1cm} (7)

The total torque of the support tube $M$ can be calculated by Eq. (8).
The torque of the support tube was calculated by Eq. (8) and the strength check was performed. The model of the anti-clogging device created in the 3D software was imported into the finite element software for analysis, constraints were imposed on it, and the calculation was performed. The moment of the support tube of the anti-clogging device was calculated, and the stress cloud diagram was obtained, as shown in Figure.3. The stress cloud diagram shows that the maximum stress on the anti-performed clogging device is distributed at the root of the claw arm, and the value is about $3.02 \times 10^7$ Pa, which is far low than allowable stress of material of $2.35 \times 10^8$ Pa.

![Stress cloud diagram of claw-shaped structure](image)

**2.2.2 Design of sliding knife**

Due to the large quantity of straw and weeds on the field, the counter-rotating blades of CSRC cut from the tillage layer to the unconstrained zone during the soil-cutting process. Considering the serious entanglement of weeding on the blade holders and the RBR, a sliding knife is installed on the blade roller, which welded to the blade holders on the side of the rotary blade edge (Modak et al., 2016), as shown in Fig.4. The radius of sliding knife is designed to be 245 mm, which is the same as the rotary blade. This structure can extend the slip-cutting area of the counter-rotation operation of the rotary blade, and help to throw straw backward through blade holders and rotary blades.

![Schematic diagram and installation diagram of arc slide cutter](image)

**2.2.3 Analysis of counter-rotation process**

The working parameters of the RBR play a decisive role in the quality and power consumption of the work. When the RBR rotates counterclockwise, its mathematical model and coordinate system of movement can be simplified as follows: Firstly, the center of the RBR should be defined as the origin of the coordinate system, and then the forward direction of the CSRC can be set as the positive direction of $x$-axis as well as the upward vertical direction as the positive direction of $y$-axis, as shown in the Fig.5.
Fig. 5 Movement trajectory of the tool nose of the counter-rotating blade. where, \( v_m \) is the forward speed of CSRC, m/s; \( \omega \) is the angular speed of the RBR, rad/s; \( S \) is the soil-cutting pitch, mm; \( H \) is the soil-cutting depth.

Assuming that the tool nose of the counter-rotating blade is \( Q(x, y) \), the movement trajectory of \( Q(x, y) \) can be expressed by the Eq.(9).

\[
\begin{align*}
x &= R \cos \alpha + v_m t = R \left( \cos \alpha + \frac{\alpha}{\omega} \right) \\
y &= R \sin \alpha = R \sin \alpha \\
\end{align*}
\]  

(9)

where \( v_m \) is the forward speed of CSRC, m/s; \( R \) is the radius of the RBR, m; \( \omega \) is the angular speed of the RBR, rad/s; \( t \) is the movement time of the RBR, s; \( \alpha \) is the rotation angle of the rotary blade, (°); \( \lambda \) is the ratio between the linear speed of the tool nose of the counter-rotating blade and forward speed of CSRC, \( \lambda = \frac{\omega R}{v_m} \) (Qi, 2016).

As shown in Figure. 5, the RBR performs a circular and an advanced motion at the same time. Therefore, the absolute motion of the RBR is a combination of rotation and forward motion, and its motion track is cycloid. From Eq. (9), it can be known that the trajectory of the RBR is affected by various factors. According to Eq. (9), the component velocity of the tool nose of the counter-rotating blade in the \( x \) and \( y \) directions can be obtained as Eq. (10).

\[
\begin{align*}
v_x &= \frac{dv_x}{dt} = v_m - \omega R \sin(\alpha) = v_m(1 - \lambda \sin \alpha) \\
v_y &= \frac{dv_y}{dt} = \omega R \cos(\alpha) = R \omega \cos \alpha \\
\end{align*}
\]  

(10)

At this time, the absolute velocity of the tool nose of the counter-rotating blade \( v \) can be calculated from Eq. (11).

\[
v = \sqrt{v_x^2 + v_y^2} = \sqrt{v_m^2 + R^2 \omega^2 - 2v_m R \omega \sin(\alpha)} = v_m \sqrt{1 - 2\lambda \sin \alpha}
\]  

(11)

In Eq. (9), the value of \( \lambda \) directly affects the important operating quality indicators such as the trajectory of the tool nose of the counter-rotating blade, the cutting pitch, the power consumption of the CSRC, and the quality of the tillage layer. The soil-cutting angle of the rotary blades is mainly between \( 3\pi/2 \) and \( 2\pi \). From Eq. (10) and Eq. (11), it can be known that the horizontal component speed of the tool nose of the counter-rotating blade, \( v_x \), is consistent with the forward speed of CSRC, so whatever \( \lambda < 1 \) or \( \lambda > 1 \), rotary blade can perform the function of soil-cutting certainly. In the case of the same structural parameters and motion parameters of rotary blades, RBR can work at a lower rotation speed, which reduces the power consumption of CSRC and improves the working performance of RBR. The soil-cutting pitch \( S \) is defined as the advanced distance within the time interval of successive soil-cutting by the rotary blade. \( S \) can be expressed as Eq. (12).

\[
S = v_m t = \frac{2\pi R}{z} \frac{1}{\lambda} = \frac{60v_m}{zn}
\]  

(12)

where \( z \) is the number of rotary blades in one plot area in where rotary blades cooperate with each other to cut soil; \( n \) is the rotation speed of the RBR, r/min.

The soil-cutting pitch directly affects the quality of soil crushing and soil flatness after rotary cultivation (Marenya, 2015). During the counter-rotation operation of CSRC, there is inevitable repeated soil-cutting in the cultivated land at a certain degree. Therefore, the soil-cutting pitch can be increased to reduce the repeated cutting of the thrown soil, so that the CSRC has a high soil fragmentation rate under condition of lower power consumption. It can be known from Eq. (12) that increasing the forward speed of CSRC, reducing the speed of RBR, and reducing the number of rotary blades in one plot area can increase the soil-cutting pitch. However, when the value of soil-cutting pitch is larger than normal range, it is hard to meet the quality requirements of CSRC, which includes the soil crushing rate and the soil flatness. According
to the characteristics of low soil moisture and moderate viscosity in dry soil, the soil-cutting pitch is set to 10 cm.

### 2.2.4 Arrangement of counter-rotation blades

RBR is mainly composed of blade shaft, knife holders and counter-rotation blades. Select the hollow steel pipe with diameter of 80 mm as the blade shaft. The value of \( z \) is set to 2, and the RBR is divided into two sections, which are installed on both sides of the gear box by the way of a V-shaped arrangement. The included angle between the left-handed blade and the right-handed blade in the same radial plane is 150°, the included radial angle and the distance between two adjacent blade holders is 60° and 72 mm respectively. Then, according to Eq. (13), the number of rotary blades on the blade shaft can be calculated.

\[
N = \frac{1000Bz}{b + b'}
\]

where \( N \) is the total number of rotary blades; \( B \) is the rotary tillage width, mm; \( b \) is the distance between the blade holders, mm; \( b' \) is the width of the blade holder, mm.

The distance between adjacent rotary blade holders and the number of rotary blades in every plot of the rotary tillage area both have no appropriation to be too small. The rotary tillage width of CSRC is designed to be 2200 mm. Therefore, the distance and the radial angle between adjacent rotary blade holders is set to 72 mm and 60°. According to Eq. (13), the total number of rotary blades is 52, that is, there are 26 rotary blades on the left as well as right sides. The arrangement of counter-rotation blades is shown in Figure 6. This can guarantee the stability of the operation of CSRC, reduce the power consumption of the operation effectively, and have a good rotary tillage effect.

![Fig. 6 The arrangement of counter-rotation blades](image)

### 2.2.5 Structure parameters of rotary blade

One of the most critical components of the CSRC is the rotary blade. The choice of the structural parameters of the rotary blade significantly affects the operating quality and power consumption of CSRC (Asl and Singh, 2009; Li et al., 2018). The tangent plane is an important part of the rotary blade. In the process of returning straw to the field, the tangent plane has functions such as soil-turning over, soil-crushing, and soil-throwing. The power consumption of the tangent plane accounts for 50% to 80% of full power consumption. Therefore, the shape and parameters of the tangent plane have a direct impact on the performance and power consumption of the rotary blade (Celik and Altikat, 2008; Ramazanova et al., 2016; Singh and Wadhwa, 2007; Vegad and Yadav, 2018; Zhang et al., 2019). There are three main structural parameters that affect the tangent plane.

- **Gyration radius \( R \) of the rotary blade**

  The design requirements of the rotary tillage depth of CSRC determine the size of the gyration radius of the rotary blade. Further analysis shows that the rotary blade has a higher cutting speed at the same speed by using the counter-rotation cultivating operation, compared with the forward-rotation cultivating operation. Therefore, in permission of meet the design requirements of the rotary tillage depth of CSRC, the gyration radius of RBR is reduced as much as possible, so as to achieve the purpose of reducing energy consumption. \( R \) was set to 245 mm for facilitating the design of later comparative tests.

- **Bend angle \( \alpha \) of the rotary blade**

  Bend angle \( \alpha \) is the included angle between the tangent plane and the side plane of the rotary blade. When \( \alpha \) is too large, the tangent plane will squeeze the soil during operation, then causing unnecessary power consumption. When \( \alpha \) is too small, the ability of soil-cutting and soil-throwing become strong, it improves straw coverage effect, but increases power consumption. \( \alpha \) is set to between 105° and 135° as the experimental research range.
• Working width \( L \) of the rotary blade

When the value of \( L \) is too small, the phenomenon of lacking rotary tillage is serious. Increasing the value of \( L \) can reduce the number of rotary blades at the arrangement of RBR, but the too large value of \( L \) will affect the stiffness of the rotary blade and the quality of the soil-cutting, and increase the resistance of soil-cutting (Matin et al., 2014; Matin et al., 2016; Matin et al., 2015). At present, China's CSRC still uses the standard forward-rotation blade, the RBR is easy to be entangled with straw and grass, and the rotary blade has poor soil-throwing performance.

Based on the structure of IT245 rotary blade, this paper changes the tangent plane parameters by changing the bending angle \( \alpha \) and the working width \( L \) to improve the soil-throwing performance of tangential plane and reduce the secondary repeated rotary tillage of the cultivated land. The structure of the rotary blade is shown in Figure. 7.

![Fig. 7 Structure of the rotary blade. Where, R is gyration radius of the rotary blade; R1 is radius of the end point of sliding knife edge; L is working width; \( \alpha \) is bend angle of tangent plane; r is bending radius of the tangent plane; h is height of the end of tangent plane; i is width of the top of tangent plane; a is thickness of tangent plane.](image)

### 2.3 Simulation analysis

In order to obtain the optimal parameters combination of the working performance of CSRC, a simulation model of CSRC was established, and the orthogonal test method was used to perform the numerical simulation test. In this paper, the DEM is used to establish a particle mechanical model of soil, straw and CSRC, and the discrete element software EDEM is used to perform a simulation test of CSRC.

#### 2.3.1 Simulation parameter setting

When using EDEM software to simulate the process of returning straw to the field, the material characteristics parameters and mechanical characteristics parameters of the simulation model need to be defined. The material characteristic parameters and interaction contact parameters of soil, straw and RBR are shown in Table 1 and Table 2 (Huimin, 2016; Lenaerts et al., 2014; Tamas et al., 2013; Chen et al., 2013; Nona et al., 2014).

| Material | Shear modulus /MPa | density /kg·m⁻³ | Poisson's ratio |
|----------|--------------------|-----------------|----------------|
| Straw    | \( 1 \times 10^6 \) | 241             | 0.4            |
| Soil     | \( 1 \times 10^6 \) | 1850            | 0.38           |
| RBR      | \( 7.9 \times 10^{10} \) | 7865           | 0.3            |

| Material | Coefficient of Restitution (Soil / Straw) | Coefficient of Friction (Soil / Straw) | Coefficient of Static Friction (Soil / Straw) |
|----------|------------------------------------------|--------------------------------------|---------------------------------------------|
| Soil     | 0.6/0.5                                  | 0.6/0.5                              | 0.4/0.05                                    |
| Straw    | 0.5/0.3                                  | 0.5/0.3                              | 0.05/0.01                                   |
| RBR      | 0.6/0.3                                  | 0.6/0.3                              | 0.05/0.01                                   |

#### 2.3.2 Establishment of simulation model

In order to balance the computing performance and simulation time of a computer, the soil model is usually simplified to spherical particles (Mak et al., 2012; Shmulevich et al., 2007). Considering the situation that the soil particle size varies in actual, the basic diameter of soil particle generated in the particle factory is set to 10 mm, and the diameter range of...
particle generated is set to 0.8 to 1.2 times the original particle size. The Hertz-Mindlin with bonding model was used to simulate particle-particle interactions. The soil particle model is shown in Figure 8(a). In the EDEM simulation model, the ball model is usually used to establish a straw model. This paper uses 21 ball models with a diameter of 6 mm to fill the simulation model of wheat straw, as shown in Figure 8(b).

![Fig. 8. Simulation modal](image)

A simplified model of RBR with different structural parameters and soil trough model (1800mm×1150mm×200mm) were established in SolidWorks software and imported into EDEM software. Then the rotation speed and advance speed of RBR was set, and the machine casing and the RBR was set at the same advance speed. It is set to generate soil particles in the soil trough firstly, and then generate the straw model on the surface to simulate the field environment in which the straw covers the ground. The simulation model of RBR is shown in Figure 9(a). The Rayleigh time step was set to $2.59 \times 10^{-5}$ s in the solver (simulator) of EDEM software, the total simulation time was set to 6 s, and the grid cell size was set to 3 mm. The simulation process is shown in Fig.9(b).

![Fig. 9. Simulation model of RBR](image)

2.3.3 Design of simulation test

From the analysis above, it can be known that the structural parameters of rotary blade (bending angle $\alpha$, working width $L$) and working parameters of RBR (rotation speed $n$ and forward speed $v$) have significant influences on CSRC’s power consumption and working quality (Li et al., 2016; Sarkar and Wassgren, 2010). Therefore, based on the general rotary blade IT245, these four parameters are selected as variable factor, and the torque and straw coverage rate are used as performance evaluation indicators. Set a section with a certain height above the ground surface in the EDEM software. The value of height of the section is the same as the average value of the surface flatness. The straw above the section (including in the section) is defined as the uncovered straw, and the straw coverage rate is calculated as (the number of initial straws-the number of uncovered straws) / the number of initial straws. Orthogonal table $L_9 (3^4)$ is selected for the 4 factors 3 levels orthogonal test (Chengjun, 2009). The test factors and levels are shown in Table 3, and the design and results of simulation test are shown in Table 4.

| Levels | Bending angle A (°) | Work width B (mm) | Forward speed C (m/s) | Rotation speed D (r/min) |
|--------|---------------------|------------------|----------------------|-------------------------|
| 1      | 135                 | 65               | 1.4                  | 260                     |
| 2      | 120                 | 50               | 1.1                  | 230                     |
| 3      | 105                 | 35               | 0.8                  | 200                     |

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3. Results and discussion of field test

3.1 Conditions of field test

The field test site was in Dingyuan County, Anhui Province. The previous stubble before cultivation was wheat straw,
and the height of the stubble was 5 to 8 cm. The soil moisture content was 32%. The required equipment in the field test composed of an CSRC, a LX754 Dongfanghong tractor (YTO Group Corporation, power: 90 horsepower, maximum output power: 55kw), a 12 V battery, a CKY-810 torque sensor (Beijing AVIC Measurement & Control Technology Co., Ltd., range: 0–1500 N·m, accuracy: 0.5%), an SK-100 Soil moisture sensor (Wenzhou Jingcheng Measuring Equipment Co., Ltd., range: 0 – 99.9%, accuracy: 0.1%), a YH-JCS Electronic balance (Wuxi Yingheng Electronic Co., Ltd., range: 0 – 200 g, accuracy: 0.001 g), a ruler, a tape measure, a spirit level, a 1m×1m square frame and a 0.5m×0.5m square frame.

### 3.2 Method of field test

In order to verify the effect of the optimized CSRC in reducing the consumption, the conventional CSRC and the optimized CSRC performed the comparison test, as shown in Figure. 10. The test was divided into three groups: (A) an RBR equipped with traditional rotary blades but no sliding knife; (B) an RBR equipped with optimized rotary blades but no sliding knife; (C) an RBR equipped with optimized rotary blades and sliding knife. The average torque, straw coverage rate, surface flatness, and soil fragmentation rate of the three comparison tests of the conventional CSRC, as well as the optimized CSRC was measured in the field condition. During the test, the rotary tillage depth was fixed at 130 mm, and the forward speed of 1.11 m/s, the rotation speed of 237.58 r/min, the average torque data was collected every 2 m, and each group was tested 5 times. The evaluation of operation quality referred to the China industry standard(2008). A five-point sampling method is used in the area of the cultivated land to collect data for each test point after rotary tillage.

**Fig. 10. Field test**

### 3.3 Results and analysis of field test

#### 3.3.1 Analysis of average torque

During the process of returning the straw to the field, the power consumption of the rotary blade is directly proportional to the value of the torque of RBR. Therefore, the power consumption of the conventional CSRC and the optimized CSRC can be reflected by comparing the average torque of the two different RBR(Ahmadii, 2017). The results of field test are shown in Table 6. The average torque of the conventional RBR in group A is 572.57 N·m, the average torque of the optimized RBR in group B is 525.41 N·m, and the average torque of the optimized RBR in group C is 517.25 N·m. Comparing with the conventional RBR, the average torque of optimized RBR reduce 7.88% and 9.63% respectively, which shows that the optimized RBR is obviously better than the conventional RBR. Therefore, it can be concluded that the power consumption of the optimized RBR during the operation of returning straw to the field is significantly reduced, that is to say, the saving-energy effect of the optimized RBR of the group C is better.

| Measuring point | 1     | 2     | 3     | 4     | 5     | Average torque |
|-----------------|-------|-------|-------|-------|-------|----------------|
| Torque of conventional RBR (A) | 579.65 | 568.82 | 557.86 | 580.22 | 576.29 | 572.57         |
| Torque of optimized RBR (B)     | 538.87 | 519.67 | 525.74 | 530.29 | 512.47 | 525.41         |
| Torque of optimized RBR (C)     | 525.64 | 512.37 | 521.78 | 523.86 | 502.62 | 517.25         |

Note: The unit of torque is N·m.

#### 3.3.2 Analysis of straw coverage rate

According to the five-point sampling method, the 1m×1m square frame was used to measure the amount (ai) of
surface straw on the uncultivated land and the amount \((a_2)\) of surface straw at the corresponding point on the cultivated land, and the straw coverage rate can be calculated as the ratio of \((a_1-a_2)/a_2\). The process of measuring the straw coverage rate is shown in Figure. 11. The results are shown in Table 7. The average straw coverage rates of the optimized RBR of group B and group C were 89.29% and 88.87% respectively, which was greater than that of the conventional RBR of group A, and far greater than the China technical standard for straw returning machines.

![Fig.11. Determination of straw coverage rate](image)

| Measuring point | 1  | 2  | 3  | 4  | 5  | Average value |
|-----------------|----|----|----|----|----|---------------|
| Straw coverage rate of conventional RBR (A) | 82.19 | 83.64 | 84.36 | 86.08 | 84.23 | 84.1 |
| Straw coverage rate of optimized RBR (B) | 88.29 | 88.97 | 89.65 | 89.2 | 90.37 | 89.29 |
| Straw coverage rate of optimized RBR (C) | 88.53 | 87.85 | 88.37 | 89.66 | 89.94 | 88.87 |

Note: The unit of straw coverage rate is %.

### 3.3.3 Analysis of surface flatness

The sampling survey area was determined according to the five-point sampling method, and a reference line parallel to the ground surface was set in each survey area along the direction perpendicular to the operation direction of CSRC. The horizontal height of the reference line from the ground is 20 cm. A width which was greater than the working width of CSRC was set randomly. It divided into 10 equal parts, and the distance from each equal point on the reference line to the ground was measured, as shown in Figure. 12. It shows the surface flatness of the optimized RBR in group B after field test in Table 8. The China standard for surface flatness after cultivated in dry land is stipulated to be no more than 4 cm. As can be seen from Table 8, the maximum difference between the highest point and lowest point in each measurement area is less than 4 cm. Therefore, the surface flatness after the operation performed by optimized RBR in group B satisfies the industry standard of China.

![Fig. 12. Measurement of the surface flatness](image)
Table 8 Experiment results of the surface flatness

| Measuring point | Point 1 | Point 2 | Point 3 | Point 4 | Point 5 |
|----------------|--------|--------|--------|--------|--------|
| 1              | 20.7   | 21.3   | 20.1   | 19.7   | 20.9   |
| 2              | 20.1   | 19.5   | 18.4   | 21.1   | 20.4   |
| 3              | 21.9   | 18.2   | 19.6   | 20.6   | 21.7   |
| 4              | 19.9   | 20.6   | 20.4   | 20.7   | 19.3   |
| 5              | 18.7   | 21.1   | 20.3   | 19.9   | 21.8   |
| 6              | 19.3   | 20.9   | 17.9   | 20.8   | 18.8   |
| 7              | 21.5   | 19.1   | 19.1   | 19.4   | 20     |
| 8              | 20.8   | 20.4   | 18.6   | 20.3   | 18.4   |
| 9              | 21.3   | 19.7   | 20.8   | 19.8   | 21.5   |
| 10             | 20.2   | 20.8   | 19.3   | 21.2   | 19.6   |
| Range          | 3.2    | 3.1    | 2.9    | 1.8    | 3.4    |

Note: The unit of height is cm.

3.3.4 Analysis of soil fragmentation rate

The process of measuring the soil fragmentation rate is shown in Figure 13. The results of the soil fragmentation rate at each measurement point are shown in Table 9. The cultivated soil fragmentation rate of the conventional RBR of group A was 85.16%, and the optimized RBR of group B and C were 83.21% and 83.96% respectively, which were slightly lower than group A, possibly because of the increase of the working width of optimized RBR to 65 cm. But the cultivated soil fragmentation rate of the optimized RBR is much higher than the China industry standard of 60%.

![Fig. 13 Measurement of soil fragmentation rate](image)

Table 9 Experiment results of soil fragmentation rate

| Measuring point                                      | 1     | 2     | 3     | 4     | 5     | Average value |
|-----------------------------------------------------|-------|-------|-------|-------|-------|---------------|
| Soil fragmentation rate of conventional RBR (A)      | 85.21 | 83.97 | 85.76 | 86.23 | 84.62 | 85.16         |
| Soil fragmentation rate of optimized RBR (B)         | 82.78 | 81.98 | 82.87 | 84.76 | 83.69 | 83.21         |
| Soil fragmentation rate of optimized RBR (C)         | 83.86 | 82.69 | 84.58 | 84.96 | 83.73 | 83.96         |

Note: The unit of soil fragmentation rate is %.

In summary, the CSRC equipped with optimized RBR has similar results between the field test and the simulation test in the straw coverage rate and average torque under the condition of a forward speed of 1.11 m/s, a rotation speed of 237.58 r/min, and a rotary tillage depth of 130 mm. The deviation may be caused by differences in working conditions such as soil moisture content, stubble, soil firmness and vibration during the test(Guo et al., 2016). The field tests show that the simulation of the CSRC is in line with the reality. Optimizing the RBR can not only achieve the purpose of energy saving, and meet the requirements such as straw coverage rate, surface flatness, and soil fragmentation rate of field operations.
4. Conclusions

In this paper, a saving-energy type CSRC was designed. The bending angle and working width of the rotary blade were analyzed and optimized. The hanging board was improved and an anti-clogging device was set up on it. Besides, a sliding knife was added to the RBR. Taking the working width, bending angle, forward speed, and rotation speed as factors, and using the straw coverage rate and power consumption as the evaluation indicators, the orthogonal test design method was used to perform a 4-factor 3-level simulation test to obtain the optimal parameters combination when returning straw to the field, which are the rotary tillage depth of 130mm, a bending angle of 134.09 °, a work width of 35mm, an advance speed of 1.11m/s, and a rotation speed of 237.58 r/min. According to the optimal parameters combination of rotary blade structure parameters and working parameters obtained by simulation test analysis, field tests were conducted to verify the correctness of the simulation results. Field tests showed that the values of indicators of the optimized RBRs were higher than that of the industry standards of China and met the design requirements. The optimized RBR straw coverage rate was higher than the conventional RBR, and the average torque was lower than the conventional RBR, and the group C optimized RBR had better tillage effect and more saving-energy than the group B optimized RBR. It could be seen from the test results of the RBR after the operation that the optimized RBR welded with sliding knives had good performance, and no deformation of the rotary blade occurred. These indicators indicated that the optimized RBR of the optimized CSRC meets the requirements.

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