Design and performance analysis of tangential-axial flow threshing device for oat harvester

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Abstract: Aiming at the problems of stalks winding and poor threshing performance in the process of mechanical harvesting of oats, a type of threshing and crushing experimental device was designed. The device was composed of a belt conveyor, a tangential-flow threshing drum, an axial-flow threshing drum, a high-speed camera and a testing device. According to a regression orthogonal test method, using the rotation speed of the axial-flow drum, the horizontal center distance, and the vertical height difference of the two threshing drums as experimental factors; using the mass fraction of long stalks and the threshing rate as experimental indexes, a mathematical regression model of factors and indexes was established, and combined parameters were analyzed for the threshing quality and crushing ability. Experimental results showed that this device had the best crushing performance when the rotation speed of the axial-flow drum was 850 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 10 mm, and this device had optimal threshing performance when the rotation speed of the axial-flow drum was 760 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 20 mm. The parameters were optimized by Design-Expert 11 to obtain an optimization result that the rotation speed of the axial-flow drum was 800 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 10 mm. A verification experiment was carried out by using a high-speed camera, and the two groups of parameters were selected for a comparative experiment. Images of material movement between the two threshing drums were captured by the high-speed camera. Experimental results showed that the optimized parameters were beneficial to improving the threshing performance and anti-winding performance of the oat threshing process. This study provides a technical basis for the research and development of oat combine harvesters.

Keywords: tangential-axial flow threshing device, oat, parameter optimization, threshing performance, crushing performance
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1 Introduction

Oat is a kind of coarse grain crop, mostly cultivated in Inner Mongolia, Shanxi and Qinghai Province of China[1]. At present, there is no combine harvester for oat. Usually, oat is harvested by a rice-wheat harvester. However, parameters of the rice-wheat harvester do not match oat harvest parameters[2], and oat stalks with high toughness and high sugar content are often wound to cause clogging, which affects the threshing performance of oats. A threshing device is a core working component of a combine harvester. Therefore, improving the crushing performance and threshing performance of the threshing device would contribute to the development of an oat combine harvester and promote the development of the oat industry.

Some harvester companies have studied structural design and parameter optimization of threshing devices[3-5]. Kubota Corporation managed to prevent clogging and accumulation of stalks in the early stage of threshing through the cooperation of spiral blades, a dust valve and a guide tube. John Deere designed a new type of tangential-flow harvester[6], which was equipped with a draft feeder and a top cover guide plate to guide the material, and a concave screen plate under a threshing drum, with a clearance adjustable manually according to the material feeding amount and moisture content, thus improving the threshing performance and avoiding the winding problem. Alizadeh et al.[7] researched the rotation speed of a threshing drum and material characteristics, and found that the grain loss rate was reduced significantly when the rotation speed of the threshing drum was 450-550 r/min and the moisture content of rice was 23.0%.

Research on threshing devices mainly focuses on reducing the power consumption of the whole machine[8-10], developing new devices, observing material movement between threshing drums to optimize crushing and threshing work of the machine[11-13], and replacing crushing devices of different materials and types[14-16]. For example, an inclined conveyor chain harrow and a forced feeding device were installed to solve the problems of grain loss, winding and blockage in the harvesting process[17-19]. As another example, two-stage threshing of material was carried out by using an oblique tangential-flow drum and a longitudinal-flow drum[20-22]. The tangential-flow drum carried out preliminary threshing, and the longitudinal-flow drum performed a task of secondary threshing and separation. As yet another example, a tangential-throwing combined threshing device[23] was designed to achieve rapid cutting

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and uniform conveying of material, and this device showed remarkable performance of threshing and separation. In addition, a kneading-type impurity removal device was developed according to the characteristics of oats to improve the threshing rate[24,25]. At present, there are few studies on optimizing threshing parameters, improving threshing performance and reducing stalk winding and clogging in oat harvest.

In this research, a tangential-axial flow threshing and crushing experimental device was designed according to the characteristics of oat harvest. Using the rotation speed of an axial-flow drum, a horizontal center distance and a vertical height difference of two threshing drums as experimental factors, and using the mass fraction of long stalks and threshing rate as experimental indexes, a regression orthogonal experiment was carried out, a mathematical regression model of factors and indexes was established and response surface analysis was carried out. The high-speed camera technology was used to observe the movement of material between the two threshing drums. On the one hand, the high-speed camera technology can mark the movement track of the material between the two drums, and capture the whole process of stem entanglement and material accumulation. On the other hand, it can be used to verify the intuitive situation of material movement and accumulation between two drums before and after parameter optimization.

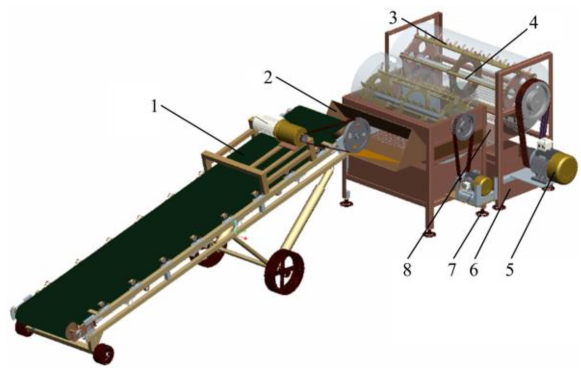
2 Materials and methods

2.1 Experimental materials

Youyu No. 4 oat was selected as the experimental material, which was planted in Youyu County of Shanxi Province. The average plant height of oats is 1264 mm, the average stalk diameter is 5.5 mm, the average ear length is 12.2 mm, the moisture content of oat stalks is 7%-10%, and the plant moisture content is 7.9%.

2.2 Experimental device

The experimental device is composed of a belt conveyor, a tangential-flow threshing drum, and an axial-flow threshing drum (Figure 1).



1. Belt conveyor 2. Feeding inlet 3. Tangential-axial flow drums 4. Discharge port 5. Motor 6. Receiving box 7. Adjustment bolt 8. Transition box

Figure 1 Tangential-axial flow experimental device

The belt conveyor was driven by a motor through a V-belt, and the material can be transported at different feeding speeds. The tangential-flow drum is the first-stage drum for feeding and preliminary threshing. The axial-flow drum is a second-stage drum for threshing. The power of the two drums was provided by two independent motors (YVF2-90l-2). The rotation speeds of the motors were controlled by a frequency converter (SVF-7), and the rotation speeds of the threshing drums are measured by a hand-held tachometer. The horizontal center distance and the vertical height difference between the two threshing drums can be adjusted by rotating bolts at the bottom of the threshing drums and moving a threshing drum frame. A transition box was transparent for observing the movement of the internal material. The parameters of the experimental device are listed in Table 1.

Table 1 Parameters of the experimental device

Parameter	Tangential-flow drum	Axial-flow drum
Drum rotation speed/r min^{-1}	0-1000	0-1000
Concave screen plate clearance/mm	15	15
Drum length/mm	650	1350
Drum diameter/mm	550	550
Bar spacing/mm	8	8
Concave wrapangle/(°)	34	210
Horizontal center distance/mm	600-1000	
Vertical height difference/mm	−50-50	
Total supporting power/kW	25	

The tangential-flow drum is shown in Figure 2. It includes a spike tooth threshing element and a grid concave screen plate. The material was hit by spike teeth in the tangential-flow drum to accomplish preliminary threshing of the oat, and then oat stalks were thrown into the axial-flow drum along the tangent. The spike tooth threshing element has a good performance of grasping and striking the slender and tough oat stalks and is suitable for the characteristics of oats.

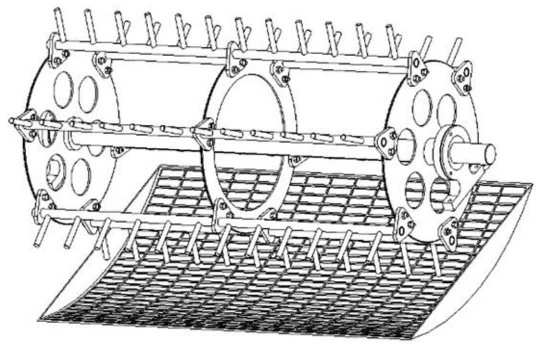
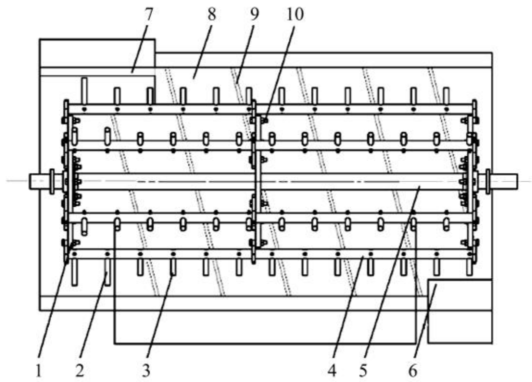


Figure 2 Structure of tangential-flow drum

The axial-flow drum is shown in Figure 3. It has spike teeth spirally distributed thereon, and spiral guide plates on a top cover.



1. Spoke plate 2. Spike tooth for throwing grass 3. Spike tooth for threshing 4. Bar 5. Main shaft 6. Feeding port 7. Top cover 8. Guide groove 9. Guide plate 10. Fixing bolts

Figure 3 Structure of axial-flow drum

2.3 Experimental index

Oats were used as the experimental object to study the crushing performance and threshing quality of the threshing device. According to the pre-experiment, long stalks are liable to wind between the two threshing drums, which will affect the threshing performance. The long stalks here refer to stalks longer than

300 mm. When the threshing drum rotates at a high speed, the better the crushing performance of the experimental device is, the stronger the anti-winding ability is. Therefore, the proportion of the mass of the long stalks in the total mass at a discharge port is an index to investigate the anti-winding performance. With the improvement of the crushing performance, more impurities will fall into receiving boxes through a sieve plate, which will cause a burden to the cleaning work. Therefore, the threshing rate is used as an index of the threshing performance.

The calculation of the mass fraction is shown in Equation (1).

$$y_1=\frac{m_1+m_2}{M}\times 100\% \tag{1}$$

where, y_1 is the mass fraction; M is the mass of oat stalks before crushing, g; m_1 is the mass of long stalks at the discharge port, g; m_2 is the mass of long stalks in the transition box after shut-down, g.

The calculation of the threshing rate is shown in Equation (2).

$$y_2=\frac{m_3+m_4}{m_0}\times 100\% \tag{2}$$

where, y_2 is the threshing rate; m_3 is the total mass of grains in the tangential-flow drum, g; m_4 is the total mass of grains in the axial-flow drum, g; m_0 is the total mass of the material in the two receiving boxes, g.

2.4 Experimental methods

A combine harvester is mainly used to perform grain harvesting, threshing, cleaning and other work, and is mainly composed of a header device, an auger, a threshing device, a cleaning device and a conveying device. Oat in the field was cut by the header device and transported to a feed port of the threshing device by the auger device. In threshing, the high-speed rotating threshing element collided with oat stems and ears, separated grains entered the cleaning device through a sieve plate, and broken oat stems were discharged through a straw outlet.

The material entered the tangential-flow drum through the conveyor belt according to a certain amount of feed. Under the effect of high-speed rotation, stalks were broken and easily falling oat grains were separated and fell into the receiving box through the concave sieve plate. In the axial-flow drum, the material moves along a spiral track in the high-speed rotating drum in the direction of the top cover guide plate. After being hit by the spike teeth, the grains in the material were ejected and fell into the receiving box. The crushed stalks were discharged from the discharge port at the end of the axial-flow drum, and the discharged material was collected into a storage bag.

This experiment is based on the study of anti-winding performance of tangential-flow drums[26]. In this experiment, the rotation speed of the tangential-flow drum was fixed at 700 r/min. The axial-flow drum rotation speed (x_1), the horizontal center distance of the two threshing drums (x_2), and the vertical height difference of the two threshing drums (x_3) (which is a positive number when the axial flow drum is higher than the tangential flow drum) were selected as the experimental factors. The mass fraction of long stalks (y_1) and the threshing rate (y_2) were used as the experimental indices. According to the designed orthogonal experiment (Table 2), the regression orthogonal experiments of three factors and three levels were carried out[27].

3 Results and analysis

3.1 Variance analysis of experimental results

Regression orthogonal experimental results are listed in Table 3.

Table 2 Coding of experimental factor level

Level	Factor		
	x_1/r min^{-1}	x_2/mm	x_3/mm
1	700	800	−50
2	800	850	0
3	900	900	50

Note: x_1 is the axial-flow drum rotation speed; x_2 is the horizontal center distance of the two threshing drums; x_3 is the vertical height difference of the two threshing drums, the same as below.

Table 3 Regression orthogonal experimental results

Number	Factor			Index	
	x_1/r min^{-1}	x_2/mm	x_3/mm	y_1/%	y_2/%
1	700	800	0	26.6	59.5
2	900	800	0	18.5	51.4
3	700	900	0	29.3	51.2
4	900	900	0	26.8	48.7
5	700	850	−50	33.2	53.5
6	900	850	−50	24.5	42.8
7	700	800	50	28.5	55.9
8	900	850	50	21.1	50.5
9	800	800	−50	24.6	53.4
10	800	900	−50	31.3	44.7
11	800	800	50	22.5	54.5
12	800	900	50	27.5	50.5
13	800	850	0	18.3	59.7
14	800	800	0	17.5	60.5
15	800	850	0	19.6	59.5
16	800	850	0	17.9	59.8
17	800	850	0	16.2	60.8

Note: y_1 is the mass fraction of long stalks; y_2 is the threshing rate.

Through regression response analysis by Design-Expert 11, a regression model of the long stalks mass fraction y_1 and the threshing rate y_2 was obtained.

$$\begin{aligned} y_1 &= 1452.467-0.898x_1-2.53315x_2+0.057x_3+\\ &0.000028x_1x_2+0.000065x_1x_3-0.00017x_2x_3+\\ &0.000387x_1^2+0.00141x_2^2+0.00202x_3^2 \end{aligned} \tag{3}$$

$$\begin{aligned} y_2 &= -9.602+0.00325x_1+0.02185x_2-0.00569x_3\\ &+2.8e^{-6}x_1x_2+2.65e^{-6}x_1x_3+4.7e^{-6}x_2x_3-3.73e^{-6}x_1^2\\ &-0.000015x_2^2-0.000023x_3^2 \end{aligned} \tag{4}$$

Analysis of variance was carried out on the regression model of the long stalks mass fraction and the threshing rate. Variance analysis results are listed in Table 4.

Table 4 Analysis of variance of multi-factor experiment

Parameter	Long stalks mass fraction		Threshed rate	
	F	p	F	p
x_1	59.11	0.0001**	93.46	0.0001**
x_2	42.75	0.0003**	73.64	0.0001**
x_3	16.26	0.05*	37.89	0.0005**
x_1x_2	5.20	0.0565	8.22	0.0251*
x_1x_3	0.28	0.6128	7.36	0.03*
x_2x_3	0.48	0.511	5.79	0.047*
x_1^2	63.22	0.0003**	61.44	0.0001**
x_2^2	52.32	0.006**	58.19	0.0001**
x_3^2	107.38	<0.0001**	141.22	<0.0001**
Lack of fit	1.48	0.9721	5.77	0.0617

Note: $p<0.01$ (very significant, **); $p<0.05$ (significant, *); $p>0.25$ (not significant).

The factors have significant effects on the two evaluation indices. The misfit value p is less than 0.01, showing a good fitting effect. For the long stalks mass fraction, the order of the influencing factors is that the rotation speed of axial-flow drum > the horizontal center distance>the vertical height difference. For the threshing rate, the order of the influencing factors is that the rotation speed of the axial-flow drum > the horizontal center distance > the vertical height difference.

3.2 Response surface analysis

Figure 4 shows the influence of the factors on the crushing ability. Figure 5 shows the influence of the factors on the threshing quality. The response surface analysis of the experiment was carried out by Design-Expert 11.

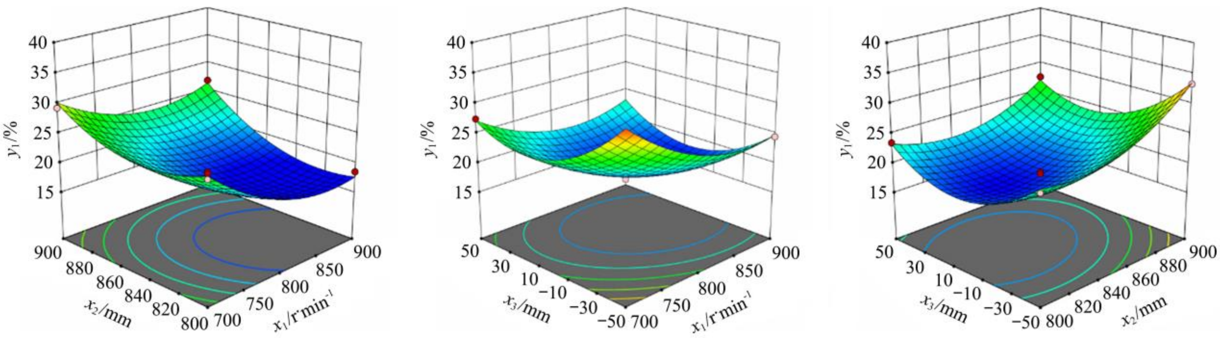
3.2.1 Analysis of effects of the factors on the crushing ability

Figure 4a is a response surface diagram of the effect of the rotation speed of the axial-flow drum rotation speed and the horizontal center distance of the two threshing drums on the mass fraction of long stalks when the vertical height difference is 0 mm. When the horizontal center distance is fixed, the mass fraction of the long stalk decreases with the increase of axial-flow drum speed. When the rotation speed is fixed, the mass fraction of long stalks decreases first and then increases with the increase of the horizontal center distance. The mass fraction of the long stalk is the smallest when the rotation speed of the axial-flow drum is 800 r/min and the horizontal center distance is 850 mm.

Figure 4b is a response surface diagram of the effect of the rotation speed of the axial-flow drum and the vertical height difference of the two drums on the mass fraction of long stalks when the horizontal center distance is fixed at 850 mm. When the rotational speed of the axial-flow drum is fixed, the mass fraction of the long stalk decreases rapidly and then increases slowly as the vertical height difference of the two threshing drums changes from negative to positive. When the vertical height difference is fixed, the mass fraction of long stalks decreases with the increase of the rotation speed of the axial-flow drum. The mass fraction of long stalks is the smallest when the rotation speed of the axial-flow drum is 800 r/min and the vertical height difference of the threshing drum is 0 mm.

Figure 4c is a response surface diagram of the effect of the horizontal center distance and the vertical height difference of the two threshing drums on the mass fraction of long stalks when the rotation speed of the axial-flow drum is fixed at 800 r/min. With the increase of horizontal center distance and vertical height difference, the mass fraction of the long stalk first decreases and then increases. The long stalks mass fraction is the smallest when the horizontal center distance is 850 mm and the vertical height difference is 0 mm.

Using the minimum mass fraction of long stalks as the evaluation index, an optimal combination of parameters was obtained by regression formula and software: the rotation speed of the axial-flow drum was 851 r/min, the horizontal center distance was 825.150 mm, and the vertical height difference was 6.789 mm. Considering the actual working conditions, the optimized parameters were adjusted to values as follows: the rotation speed of the axial-flow drum was 850 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 10 mm.



a. $y_1=f(x_1, x_2, 0)$ b. $y_1=f(x_1, 850, x_3)$ c. $y_1=f(800, x_2, x_3)$

Figure 4 Effects of interaction on the mass fraction of long stalks

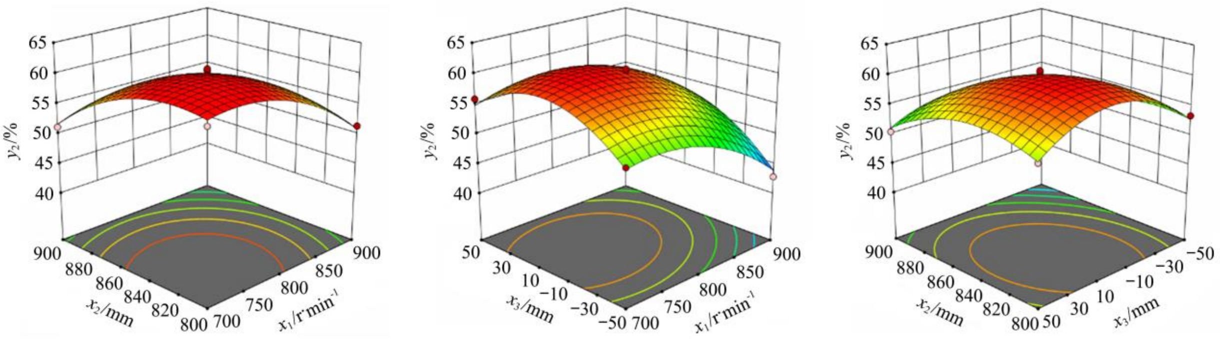
3.2.2 Analysis of effects of the factors on the threshing quality

Figure 5a is a response surface diagram of the effect of the rotation speed of the axial-flow drum and the horizontal center distance of the two threshing drums on the threshing rate when the vertical height difference is 0 mm. When the horizontal center distance of the two threshing drums is fixed, the threshing rate increases slowly at first and then decreases with the increase of the rotation speed of the axial-flow drum. When the rotation speed of the axial-flow drum is constant, the threshing rate decreases with the increase of the horizontal center distance. When the rotation speed of the axial-flow drum is 800 r/min and the horizontal center distance is 850 mm, the threshing rate reaches the maximum value.

Figure 5b is a response surface diagram of the effect of the rotation speed of the axial-flow drum and the vertical height difference of the two threshing drums on the threshing rate when the horizontal center distance is 850 mm. When the vertical height difference of the two threshing drums was fixed, the threshing rate increases first and then decreased as the rotation speed of the axial-flow drum increased. When the rotation speed of the axial-flow drum is 800 r/min and the vertical height difference is 0 mm, the threshing rate reaches the maximum value.

Figure 5c is a response surface diagram of the horizontal center distance and the vertical height difference of the two threshing drums when the rotation speed of the axial-flow drum is 800 r/min. When the horizontal center distance and the vertical height difference of the two threshing drums continue to increase, the threshing rate shows a trend of increasing first and then decreasing. When the horizontal center distance is 850 mm and the vertical height difference is 0 mm, the threshing rate reaches the maximum value.

Using the maximum threshing rate as the index, an optimal combination of parameters was obtained according to the regression formula and software: the rotation speed of the axial-flow drum was 757.28 r/min, the horizontal center distance was 818.100 mm, and the vertical height difference was 21.656 mm. Considering the actual working conditions, the optimized parameters were adjusted to values as follows: the rotation speed of the axial-flow drum was 760 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 20 mm.



a. $y_2=f(x_1, x_2, 0)$ b. $y_2=f(x_1, 850, x_3)$ c. $y_2=f(800, x_2, x_3)$

Figure 5 Effects of interaction on the threshed rate

3.3 Parameter optimization

Based on the importance of the two indicators, a weighted comprehensive scoring method was used. The weight of the long stalks mass fraction was 0.5, the weight of the threshing rate was 0.5, and the weighted values were used as evaluation criteria. The software Design-Expert 11 was used to optimize the combination of parameters to meet the performance requirements.

Objective function:

$$\max y(x_1,x_2,x_3)=0.5y_2-0.5y_1\ ,\quad \begin{cases}\max y\\ 700\le x_1\le 900\\ 800\le x_2\le 900\\ -50\le x_3\le 50\end{cases} \qquad (5)$$

The optimal combination of influence parameters was as follows: the rotation speed of the axial-flow drum was 800 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 10mm. At this time, the mass fraction of long stalks was 17.25%, and the threshing rate was 61%.

4 Verification

4.1 Experimental device of high-speed camera

High-speed camera equipment was connected to the tangential-axial flow experimental device (Figure 6).

Figure 6 High-speed camera experimental device

The high-speed camera equipment included cameras (Phantom MiroM310 Miro LC320s, Vision Resesarch, Inc, USA), Nikon lens (AF-ZOOM-Nikon, 24-85mm, f/2.8-4DIF, Nikon Corporation, Japan), a light (LED, WINSURE, China), a computer (ThinkPad E555, Lenovo, China) and image processing software (Phantom Camera Control Application, PCC, USA).

The positions of a camera tripod and a light source were adjusted to make the images clear. PCC software parameters were adjusted so that the movement process of the material in the transition box can be completely captured. The flow states of the material before and after optimization of experimental parameters were compared and analyzed.

4.2 Image analysis

Parameters of the optimized experiment were as follows: the rotational speed of the tangential-flow drum was 700 r/min, the rotational speed of the axial-flow drum was 800 r/min, the horizontal center distance of the two threshing drums was 820 mm, the vertical height difference was 10 mm, and the feeding rate was 1 kg/s. The images of the high-speed camera experiment are shown in Figure 7.

a. Material in process of passing b. After the material passed

Figure 7 Experimental images of optimization group

Parameters of the comparison group were adjusted to values as follows: the rotation speed of the tangential-flow drum was 700 r/min, the rotation speed of the axial-flow drum was 700 r/min, the horizontal center distanced was 900 mm, and the vertical center height difference was 0 mm. Experimental results are shown in Figure 8. These parameters are general parameters of a grain combine harvester.

a. Material in process of passing b. After the material passed

Figure 8 Experimental images of control group

In the stage of the material passing through the transition box, by comparing Figure 7a with Figure 8a, it can be seen that in the optimization group, the material passed smoothly without obvious blockage, the number of long stalks was less, and the crushing performance was better.

By comparing Figure 7b with Figure 8b, it can be seen there was less residue in the transition box, and there was no stalk wound on the threshing element in the optimization group, which would not affect the later material movement. According to the experimental analysis, the crushing capacity of the oat threshing device was significantly improved, the material flow was smooth, and the blockage phenomenon was avoided.

In the three experiments of the optimization group, the mass fractions of long stalks were 17.7%, 18.4%, and 16.6%, respectively. The threshing rates were 63.1%, 63.9%, and 64.8% respectively.

Compared with the values of Table 3, the mass fraction of long stalks was at a lower value, indicating that there were fewer long stalks, and the crushing performance of the threshing device was better than before. The threshing rate was at a higher value, indicating that the threshing performance of the threshing device was better than before.

5 Discussion

In this study, the experimental material is "Youyu No.1" oat in Youyu County, Shanxi Province. By selecting three factors of the rotation speed of the axial-flow drum, the horizontal center distance and the vertical height difference of the double drums as the three factors, the anti-winding and crushing ability of the test devices were analyzed. When the vertical height difference of the two drums was negative, the air flow resistance between the drums was large and the material circulation was not smooth, which led to poor crushing effect and threshing effect. With the vertical height difference changing from negative to positive, the air resistance of the oats threshing process became smaller and the flow was smoother. When the vertical height difference between the two drums was 10 mm, the threshing effect and anti-winding effect were the best. When the horizontal center distance and the vertical height difference of the two drums reached an appropriate level, the flow between the drums was very smooth. After a short period of stagnation between the drums, the long stalks broken by the tangential flow drum quickly entered the axial flow drum.

During threshing, the oat stalks collided with threshing element. Under different rotation speeds of the drums, the strength of the stalks was different. The movement tracks and speeds of the grains carried by the stems with different degrees of fragmentation between the sieve plates were very different, which is also an important reason for the blockage between the sieve plates and the winding of the stems. In this study, the high-speed camera test was carried out to verify the material flow between the two drums before and after the optimization. In the later stage, the high-speed camera platform was used to capture the flow track and velocity of stems and grains with different lengths, and the fluid software was used to carry out the simulation. The reason for material clogging was analyzed, and the threshing performance and winding performance of the tangential-axial flow double drum test-bed were further optimized.

6 Conclusions

The extremely significant factors that influence the crushing performance of the experimental device are the rotation speed of the axial-flow drum and the horizontal center distance of the two threshing drums. The factors that influence the threshing quality are the horizontal center distance of the two threshing drums, the rotation speed of the axial-flow drum and the vertical height difference.

The optimal parameters of the crushing performance were that the rotation speed of the axial-flow drum was 850 r/min, the vertical height difference of the two threshing drums was 10 mm, and the horizontal center distance was 820 mm. The optimal parameters of the threshing rate were that the rotation speed of the axial-flow drum was 760 r/min, the horizontal center distance was 820 mm, and the vertical height difference was 20 mm. The optimal parameters of the combined threshing rate and crushing performance were that the rotation speed of the axial-flow drum was 800 r/min, the horizontal center distance of the two threshing drums was 820 mm, and the vertical height difference was 10 mm.

This paper obtained the regression model of the threshing and crushing performance of the threshing device of the oat harvester. Through high-speed camera analysis, the anti-winding ability of the threshing device significantly improved while the requirement on the threshing quality.

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