DESIGN AND TEST OF AN ALL FEED AXIAL FLOW SAME DIAMETER DIFFERENTIAL SPEED THRESHER

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全喂入纵轴流同径不同速脱粒分离装置设计与试验

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ABSTRACT

Grain harvesting equipment completes cutting, threshing, cleaning and separation work simultaneously, but traditional single-speed all-feed axial-flow threshers cannot adapt to complicated work situations. We put forward a design approach for an all-feed axial-flow with a same-diameter differential-speed thresher to further reduce the grain-crushing rate and threshing loss rate when operating. We test for Xieyou No. 518 rice *and obtain the distribution rule of grain mixture after threshed via experimental comparison of a differential-speed thresher versus a single-speed thresher. The results of this research show that the threshing effect of the differential-speed thresher is better than the single-speed thresher and that the first has a lower grain crushing rate and a lower threshing loss rate of 18.0% and 15.8%, respectively. We found this result by analyzing the grain threshed axial distribution, grain crushing rate and threshing loss rate. This study provides a new theoretical and structural reference for the study of separation devices for grain combine harvesters to adapt to the complex harvesting conditions in China.*

摘要

谷物联合收获机工作过程一次性完成收割、脱分、筛分、集粮过程。传统单转速纵轴流脱粒滚筒不能适应复杂的工作情况。为降低全喂入谷物联合收获机纵轴流脱粒分离装置谷物破碎率及清选损失率，提出了一种全喂入纵轴流同径不同速脱粒分离装置。选用协优 518 号水稻品种进行同径不同速脱粒滚筒与单速脱粒滚筒的脱分实验，得到了水稻的脱粒分离规律。对比二种脱粒装置脱出物破碎量轴向分布、籽粒破碎率及清选损失率等得到：同径不同速脱粒滚筒的脱分效果优于单速脱粒滚筒，降低了籽粒破碎率和清选损失率，分别下降了 18. 0%和 15. 8%。本次研究为适合我国多工况谷物联合收获机脱粒分离装置的研究提供了新的理论及结构参考。

INTRODUCTION

China is the world's largest producer of grain, with a planting area of 94,370.8 km^2, accounting for 21.98% of the world’s grain production *(Center A.T.P., 2017*). The wide area, the staggered terrain distribution, and the complicated farming system in China have led to a penetration rate of agricultural machinery of only 63% *(Li H., 2017)*. The difference in seasonal conditions for grain harvesting leads to the difficult and uneven separation of straw and grain. In northern harvests, the proportion of dry straw was larger, while in the southern harvests during rainy season the moisture content of straw was relatively high, resulting in the phenomenon of blocking and incomplete threshing during grain combine harvest. The all-feed axial-flow grain combine harvester was developed in the 1980s. It has the advantages of high production efficiency, a high trash content rate, a low threshing loss rate and high adaptability compared with the all-feed horizontal axial-flow grain combine harvester (*Watanabe N., 2017*). The performance of the grain combine harvester is directly affected by the quality of the threshing during the harvesting process. This topic has been widely studied by scholars in recent years.

Qian *et al*. studied the influence factors of the process of rice flexible tooth threshing and analyzed the multi-friction dynamic contact process of the flexible tooth with the material during operation. The combined effect of the combine harvester was improved and the grain crush rate was reduced by using the multi-correlation matrix and the four-point weighted evaluation method (*Qian Z. et al., 2017*). Singh *et al.* designed a rice threshing mechanism for the rice harvest of small fields and steep slopes. The influence of the spacing and height of the threshing ring on the separation effect was analyzed by the response surface method and the optimal parameters were obtained, thus reducing production costs (32 kg and INR 3500 or 88 US$) and increasing the efficiency of the threshing to 94.6% (*Singh K P., 2008*). Valge as well as Kile *et al.* studied the structure of the grain thresher by the method of multi-evaluation index parameter optimization and obtained the best threshing effect, which improved the complete work efficiency and grain harvest operation (*Kile R J., 2013; Valge A.M. et al, 2017; Ye J. et al, 2017*). Putri *et al.* redesigned the grain thresher by the method of rapid upper limb assessment (RULA), which effectively reduced injury to farmers and improved the machine's efficiency (*Putri N.T. et al, 2016*). Dogra *et al.* developed a long nail-toothed threshing mechanism for bean crops, and the multi-level parameter optimization for threshing linear velocity and feeding was studied. The optimal parameters were determined and obtained the threshing break rate, non-collectable losses, the threshing clear rate and threshing efficiency were 0.68%, 0.27%, 98.63% and 99.56% respectively (*Dogra B, 2014*). Yousif *et al.* developed a threshing device for harvesting sorghum in the event of rain and verified the working and economic efficiency by test experiments (*Yousif L.A. et al, 2012*). Li *et al.* studied the different threshing structures such as spike tooth cylinder, rectangular tooth cylinder, and combined spike tooth with short-rasp-bar tooth. The results showed that the combined spike tooth with short-rasp-bar tooth has a better threshing effect and lower power consumption by analysis of the multi-indicator assessment factors (*Li Y et al, 2009*). Soon afterwards, Tang *et al.* studied the influence of different threshing elements in terms of the shear flow and longitudinal axial-flow thresher on operation performance and showed that the shear flow thresher using a blade tooth and the longitudinal axial-flow thresher using a spike tooth have better operational effectiveness when the feed is larger (*Tang Z. et al, 2011*). Dai *et al.* developed a new type of longitudinal axial-flow thresher device to increase the axial material delivery speed and reduce power consumption, obtaining better efficiency of the grain combine harvester (*Dai F., 2011*). Tong *et al.* presented a numerical simulation of the mixed flow field in the blower threshing drum and structural improvement method of the axial-flow (*Tong S. et al, 2016*). They analyzed the influence of vibrating screen surface airflow velocity on the airflow in the thresher cylinder and optimized the parameters by the orthogonal test, and the optimization results were then verified by the field-threshing test.

Although the all-feed axial-flow thresher has been widely used in the threshing system of the grain combine harvester, there are some shortcomings. In the traditional single-speed all-feed axial-flow thresher, the feeding amount is larger, which can cause the feed inlet to block, leading to a higher threshing loss rate and grain crushing rate as well as a poor threshing effect. In this paper, we developed a new type of all-feed axial-flow separation device with same-diameter differential-speed without increasing the length of the threshing cylinder, to overcome the above shortcomings, and more adaptability. The effect of the new thresher is verified by test experiments.

MATERIALS AND METHODS

Materials of experiments

Test for Xieyou No. 518 rice: yield of about 7500 kg/hm^2, natural plant height of 1200 mm. The average length of the stalk was 855 mm when threshing, the grain thousand-seed weight was 35.89g, the ratio of grass and grains was 1.76, and the water contents of grains and stalks were 14.6% and 58.6%, respectively.

Experimental installation

The experimental installations were the traditional all-feed axial-flow single-speed thresher and the all-feed axial-flow differential-speed thresher designed by our laboratory. The two kinds of threshers had the same total length, diameter of threshing cylinder, and threshing device structure. The speed of the high and low differential-speed threshing cylinders was 799 r/min and 555 r/min, respectively, according to formula (1); the length of the high and low speed threshing cylinders was 430 mm and 1050 mm, respectively, according to formula (2). Moreover, the anti-interference device was designed according to two differential-speed threshing cylinders.

As shown in Figure 1, the coaxial differential-speed threshing drum was made up of a low-speed threshing cylinder with an active bevel gear *3* and a driven bevel gear *6*, and a high-speed threshing cylinder with an active bevel gear *4* and a driven bevel gear *5*.

According to the design method of bevel gear drive, *Tao Z. (2015)* obtained that the tooth number of the active bevel gear *3* was 21, the tooth number of the driven bevel gear *6* was 32, the transmission ratio was 0.66, the tooth number of the active bevel gear *4* was 18, the tooth number of driven bevel gear *5* was 20 and the transmission ratio was 0.9.

$$n_2 = Kn_1 = \frac{30Kv_1}{\pi r} \tag{1}$$

where, n_2 is the high speed drum speed (r/min); n_1 is the low speed drum speed (r/min); *K* is the high speed drum and low speed roller linear speed ratio, (K=26/18=1.44); *v*1 is the low speed drum linear speed (r/min); *r* is the radius of the threshing drum, (*r*=0.31m).

$$L_1 = \frac{\varepsilon q}{AR\phi} \tag{2}$$

Where:

L_1 is the length of the grid-type concave plate in the low-speed drum segment (mm);
ε - the percentage of the feeding which has been separated (%); ε= 0.55 ~0.60 set 0.60;
q - the feeding amount (kg/s), set 3.5 kg;
A - the unit area productivity of the grid-type concave plate (kg/m²·s), set 1.5;
R - arc radius (mm), set *R* =33 mm (included in the clearance of inlet plate 2 mm);
ϕ -the curved plate Angle (°), set ϕ = 220°.

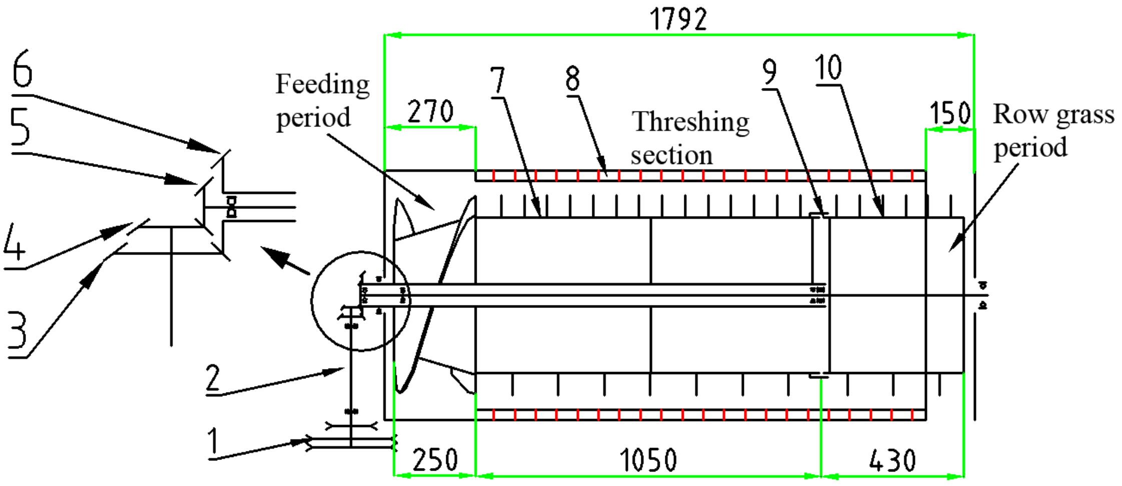


Fig. 1 - All-feed axial-flow same-diameter differential-speed thresher

1-Power pulley; 2- The shaft; 3-Low speed cylinder driving bevel gear; 4-High speed cylinder driving bevel gears; 5-High speed driven bevel gears; 6-Low speed driven bevel gears; 7-Low speed cylinder; 8-Grid concave plate; 9-Transition ring; 10-High speed cylinder

Experiment design

In accordance with the actual harvest process and the feeding amount of 3.0 kg/s, the procedure can be briefly described as follows: the speed of the single rotational speed threshing cylinder is set at 650r/min and the high and low rotational speed cylinders of same-diameter differential-speed thresher are 799 r/min and 555 r/min respectively. Then the materials are put evenly onto the conveyor belt and packing auger transports them into the threshing cylinder. Most of the weeds were expelled from the drain when threshed and other materials fell down from the grid concave plate into the collection box. The material collection box was a total of 60 squares (the square area was axial 140mm x radial 130 mm) (*Dai F et al, 2011; Li Y et al, 2008*), as shown in Table 1. The power consumed was the average value of the sample time beginning with the materials entering the threshing drum to the materials being discharged completely. In order to ensure the accuracy of the measurement results, all the materials in receiving boxes and the loss of the granules were manually treated.

Table 1

The distribution design of test collection

Feeding mouth	Axial direction(1400mm)									
Radial direction (1040mm)	1-1	2-1	3-1	4-1	5-1	6-1	7-1	8-1	9-1	10-1
	1-2	2-2	3-2	4-2	5-2	6-2	7-2	8-2	9-2	10-2
	1-3	2-3	3-3	4-3	5-3	6-3	7-3	8-3	9-3	10-3
	1-4	2-4	3-4	4-4	5-4	6-4	7-4	8-4	9-4	10-4
	1-5	2-5	3-5	4-5	5-5	6-5	7-5	8-5	9-5	10-5
	1-6	2-6	3-6	4-6	5-6	6-6	7-6	8-6	9-6	10-6
	1-7	2-7	3-7	4-7	5-7	6-7	7-7	8-7	9-7	10-7
	1-8	2-8	3-8	4-8	5-8	6-8	7-8	8-8	9-8	10-8
										Straw outlet

RESULTS

- **The power consumption of the same diameter differential speed thresher**

In the case of continuous feeding, the removal of cylinder consumption power *N* can be obtained by the following formula *(Li Y. et al, 2009; Tang Z. 2012)*

$$N = N_0 + N_t = A\omega + B\omega^3 + \xi \frac{qv^2}{1-f} \tag{3}$$

where:

N_0 is the consumption power of the empty drum of threshing, (KW);

N_t - the consumption power of threshing, (KW);

A - the resistance coefficient caused by friction of bearing;

B - the resistance coefficient caused by air resistance;

ω - angular velocity of the threshing cylinder, (1/s);

ξ - material elastomer correction coefficient;

q - feeding amount, (kg/s);

v - linear speed of the threshing cylinder (m/s);

f - the friction coefficient of the materials through the gap ($f = 0.75$).

The angular velocity of the high rotational speed cylinder was 1.4 times the angular velocity of the low rotational speed cylinder, according to the calculation results of Section 2.2.

The proportion of materials in the high-speed rotational cylinder was less than 1/3, and the grain was threshed; the consumption power of the high rotational speed cylinder was lower. When the feeding quantity was 2.0 kg/s, the consumption power of the high rotational speed cylinder was about 47% of the low rotational speed cylinder. Therefore, the total consumption power of the differential-speed thresher was lower.

- **Analysis of the distribution of the threshed grain**

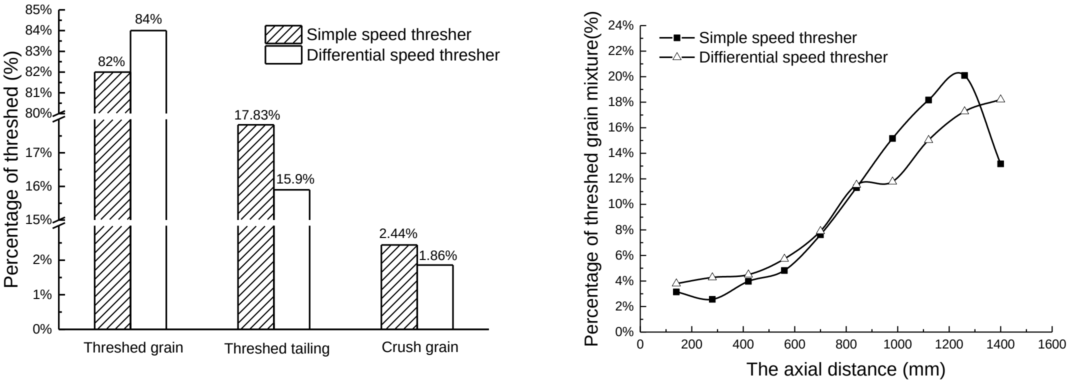
Figure 2 shows the sample collection after the test of the single-speed and differential-speed threshers. As shown in Figure 3 (a), the percentage of threshed grain by the differential-speed thresher was higher than that of the single-speed thresher, and the threshing loss rate and grain-crushing rate of the differential-speed thresher were lower than that of the single-speed thresher.

The working efficiency was improved according to the different disposal of materials under the different rotation speeds of the differential-speed thresher, and the weeds were removed while the low rotational speed threshing cylinder was working, reducing the threshing loss rate and grain breakage rate.

As shown in Fig. 3 (b), a materials packing phenomenon could be observed in the feeding end with both kinds of speed threshers, however, the distribution of materials by the differential-speed threshing was uniform. The differential-speed thresher distributed the power evenly with balanced consumption by the threshing cylinder.

(a) Single-speed thresher (b) Differential-speed thresher

Fig. 2 - Single- and differential-speed threshed mixture distribution



(a) (b)

Fig. 3 - Single- and differential-speed threshed mixture distribution

(1) Analysis of the distribution results of the grains threshed

As shown in Fig 4, the distribution trend of the grains was consistent with the distribution trend of the threshed mixture and was mainly concentrated in the first half of the threshing cylinder, because more than 90% of the grain was threshed in the forepart of the thresher *(Tang Z, Li Y, Xu L, et al. 2011)*. The differential-speed thresher was favourable to material flow in the threshing cylinder, which made the distribution of the threshed grains more uniform than was observed in the single-speed thresher.

(2) Analysis of the distribution results of the threshing trash accounts

As shown in Fig 5, the threshing trash accounts distribution of the single speed thresher at the 320 mm-1400 mm section (the front of the axial cylinder), which was significantly higher than that of the 0-320 segment (the posterior segment of the axial cylinder) according to the axial distribution; the trash distribution of the differential speed thresher was more uniform and reasonable than that of the single-speed thresher.

The threshing trash accounts distribution of the forepart of the differential-speed thresher was significantly lower than the forepart of the single-speed thresher, which was beneficial to grain mixture screening.

(3) Analysis of the distribution results of the crushing grains threshed

As shown in Fig. 6, the precursors of the single rotational speed-threshing cylinder (320-1400 segment) are significantly higher than the posterior segment (0-320 segment). Furthermore, the single rotational speed will thresh the grain and strike again, leading to a higher grain fragmentation rate. According to the grain crushing rate statistical result, the differential-speed thresher operation was superior to that of the single-speed thresher, but only by about 5%, meaning that it is able to perform sufficiently during operations.

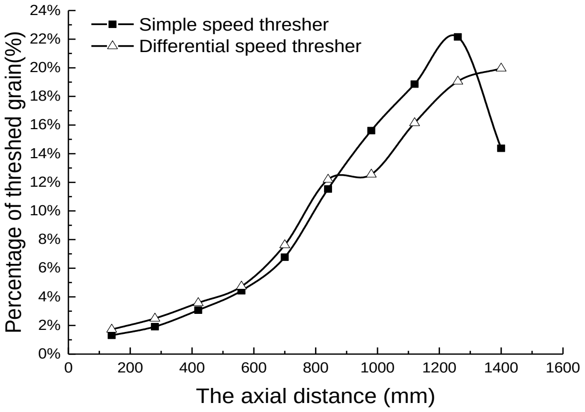


Fig. 4 - Single- and differential-speed threshed grain distribution

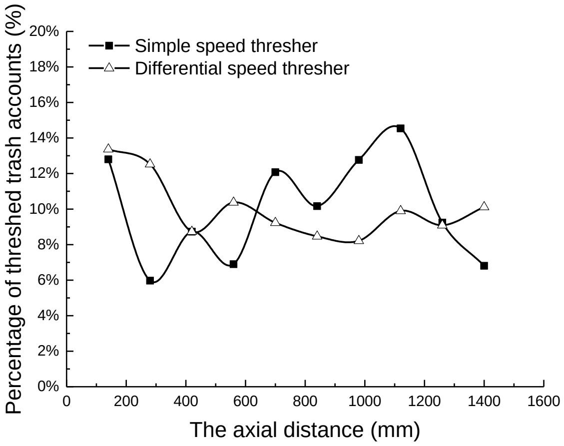


Fig. 5 - Single and differential-speed impurity distribution

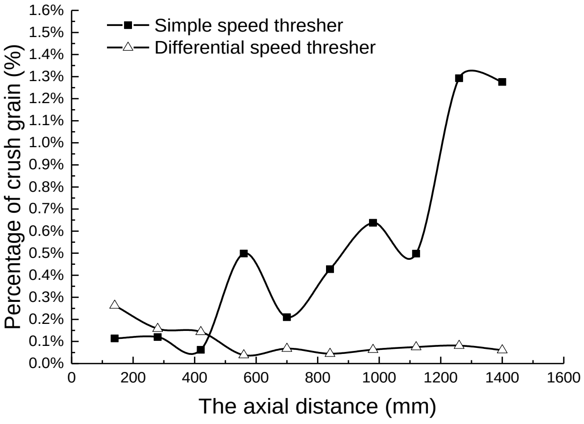


Fig. 6 - Single and differential-speed rice grain crushing distribution

- **Analysis of the grain crushing rate and threshing loss rate**

We selected the rice varieties provided in section 2.1 to carry out the rice threshing comparative test. Under the same working conditions, we calculated the grain crushing rate and threshing loss rate according to the specified calculation method *(Dai F, Gao A, Sun W, et al. 2011; Tong S, Shen Q, Tang N, et al. 2016)* as shown in Tables 2 and 3. The threshing loss rate of the differential-speed thresher was 15.8% lower than that of the single-speed thresher and had a good threshing effect. The grain crushing rate of the differential-speed thresher was 18% lower than that of the single-speed thresher when harvesting high-yield rice, which is in line with the requirements for high-quality operations.

Table 2

Test of grain threshing loss

No.	Percentage of cleaning loss (%)		Remark
	Differential speed	Single speed	
1	12	14.4	The accumulation condition of the left side of the front of a single-speed threshing sieve when the feed is larger
2	8.6	9.8	
3	11.8	13.9	
4	13.5	15.1	
5	12.2	15.8	
Average	11.6	13.8	

Table 3

Test of rice grain crushing

No.	Percentage of crushing (%)		Remark
	Differential speed	Single speed	
1	0.06	0.08	The accumulation condition of the left side of the front of a single speed threshing sieve when the feed is larger
2	0.10	0.12	
3	0.08	0.09	
4	0.05	0.06	
5	0.12	0.15	
Average	0.082	0.10	

CONCLUSIONS

In this paper, we compared the traditional all-feed axial-flow single-speed thresher and the all-feed axial-flow same-diameter differential-speed thresher by grain mixture threshing experiments, and reached the following conclusions:

(1) We designed an all-feed axial-flow same-diameter differential-speed thresher to improve the comprehensive effect of a grain combine harvester and determined the rotational speed and the length of the high and low rotational speed cylinders according to actual operation conditions.

(2) The distribution of axial distribution of grain mixture, grains, trash accounts, and crushed grain was obtained by comparing a single-speed thresher and a differential-speed thresher. The results show that the distribution of the threshed grain mixture and the threshed grain gradually decreased from the previous to the latter, and the greatest packing phenomenon occurred closest to the feeding mouth. The distribution of the differential-speed thresher was more uniform than that of the single-speed thresher. The waste distribution of the forepart of the differential-speed thresher was significantly lower than the forepart of the single-speed thresher, which was beneficial to grain mixture screening.

(3) The experimental results of the two kinds of separation devices were compared and analyzing the grain crushing rate and the threshing loss rate, we found that the grain-crushing rate and the threshing loss rate of the differential-speed thresher were lower than that of the single-speed thresher. This is in line with the demands for high-quality operation of combine harvesters.

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