DESIGN OF INNER AND OUTER ROLLER BUCKWHEAT THRESHER AND FIELD TEST
/
内外滚筒式荞麦脱粒机设计及田间试验

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ABSTRACT
Aiming at the problems of large loss rate and high damage rate during buckwheat threshing, an inner and outer roller buckwheat thresher was designed. The device is mainly composed of an inner roller and an outer roller, the inner roller is a rod-tooth combination roller, and the outer roller is a grid roller, the inner and outer rollers can be rotated independently. The outer roller is supported on the friction wheels and the supporting wheels, and driven to rotate by the friction wheel transmission system. The compression device is installed at the top to prevent the outer roller from slipping during the rotation. During working, the materials enter between the inner and outer rollers and the separation of grains and stems under the brushing and kneading action of the inner and outer rollers takes place. In order to push the materials between the inner and outer rollers smoothly, a double spiral blade type screw feeding device was designed. By establishing a mathematical model of material pushing, the screw feeding device has a material conveying speed of 1.87 m/s and a conveying capacity of 4.29 kg/s. In order to study the threshing performance, the threshing device was installed on the basis of the Kubota 688 tracked type combine to complete a prototype of a tracked buckwheat combination harvester. Field tests show that the grain impurity rate is 6.50%, the grain damage rate is 1.42%, the threshing loss rate is 0.25%, the cleaning loss rate is 1.01%, the direct loss rate of the header is 2.43%, and the total machine harvest loss rate is 3.69% at the working speed of 0.53 m/s and the feeding rate of 0.41 kg/s. The test results provide a basis for the improvement of buckwheat mechanized harvesting machinery.

摘要
针对荞麦脱粒损失率大、破碎率高等问题，设计了内外滚筒式荞麦脱粒机，该装置主要由内滚筒和外滚筒组成，内滚筒为纹杆—钉齿组合式滚筒，外滚筒为栅格滚筒，内外滚筒均可独立旋转。工作时，物料进入内外滚筒间，在内外滚筒的梳刷、揉搓作用下完成籽粒与茎秆的分离。为了将物料顺利推送至内外滚筒之间，设计了双螺旋叶片式螺旋喂入装置，并通过建立物料推送的数学模型，得到螺旋喂入装置物料输送速度为1874mm/s，输送量为4.29kg/s。为了对该脱粒装置脱粒性能进行研究，在久保田688型履带式联合收获机基础上，安装该脱粒装置，完成履带式荞麦联合收获机样机。通过田间试验得到：该样机在作业速度为0.53m/s，喂入量为0.41kg/s的条件下，籽粒含杂率为6.50%，籽粒破碎率为1.42%，脱粒损失率为0.25%，清选损失率为1.01%，割台直接损失率为2.43%，总损失率为3.69%，试验测试效果良好，为荞麦机械化收获机械的改进提供依据。

INTRODUCTION
When buckwheat is harvested, the maturity of the grains is inconsistent, the mature grains are easy to fall off, and the stem has high moisture content *(Ren Changzhong et al., 2018)*. It has large damage rate and high impurity content during mechanized harvesting, and it is easy to block the threshing roller, which seriously restricts the mechanized development of the buckwheat industry *(Huang Xiaona et al., 2018; Farooq et al., 2016)*. The existing buckwheat combine harvesters are improved machines based on rice, wheat and other small grain combine harvesters, and there are few specialized buckwheat harvesting machines *(Lu Wentao et al., 2017)*.

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The main structure of horizontal-flow threshing device of domestic full-feed combine harvester is single horizontal and cross-flow double-roller threshing device. During field harvesting, the threshing device has limited processing capacity and encountered difficulties in stalk and green leaves. When threshing crops, the threshing loss is large and clogging is easy to occur, which reduces the harvesting efficiency *(Lachuga et al., 2020; Maertens et al., 2004; Petkevichius et al., 2008)*. When the combine harvester's axial flow threshing device works, the crops make spiral movements, and the threshing is gentle and the working time is long. Therefore, it is superior to the traditional cutting device in terms of removal rate, damage rate, and separation rate, and can increase productivity without increasing the volume of the body *(Chuan-udom et al., 2011; Barać et al., 2011; Dhananchezhiyan et al., 2013)*. Theoretical research is the basis of threshing device research. Through the establishment of mathematical models and computer simulation, the movement of seeds in the threshing roll provides a lot of theoretical information for the design of threshing device *(Miu et al., 2007; Powar et al., 2019; Govindaraj et al., 2017)*.

In recent years, a large number of scholars have studied the threshing device of combine harvesters. *Liu Zhenghuai et al. (2018)* designed a rotary grid concave plate threshing device to effectively prevent the threshing roller from blocking and improve the threshing effect. *Hou Shouyin et al. (2012)* designed a vertical axial flow soybean breeding threshing machine, and provided a basis for the design of the vertical axial flow soybean breeding thresher. *Di Zhifeng et al. (2018)* designed a combined axial flow threshing roller to provide a theoretical basis for the development of a grain harvester. *Zong Wangyuan et al. (2013)* designed a combined rapeseed threshing device, which can effectively improve the efficiency of threshing and separation of rapeseed and reduce the loss rate.

Based on the axial flow threshing device, this paper designs an independent rotary buckwheat threshing device with inner and outer rollers, and applies it to a track-type combine harvester, which is the basis for the development of buckwheat mechanized harvesting machinery.

MATERIALS AND METHODS

Inner and outer roller buckwheat threshing device

The overall structure

The overall structure of the inner and outer roller buckwheat threshing device is shown in Fig. 1. It is mainly composed of feeding inlet, top cover, screw feeding device, outer roller pressing device, grid roller, tie rod roller, main shaft, nail tooth roller, speed reducer, grass discharge port, frame, friction wheel drive shaft, friction wheel and so on. The spiral feeding device, which is welded by double spiral blades and cone barrels, is connected to the tie rod roller and nail tooth roller through the main shaft to form an inner roller. The grid roller is an outer roller, the two ends of the outer roller are supported by the support wheels and friction wheels, and driven to rotate by the friction wheel. In order to prevent jumping and slipping during the rotation of the outer roller, an elastic pressing device is installed on the top of the outer roller. The inner and outer rollers are eccentrically mounted at 22.5 mm in the vertical direction, the maximum gap at the top is 46 mm, the minimum gap at the bottom is 10 mm, and the gap between other positions is between 10 mm~46 mm. While ensuring threshing, there is enough space for the material to flip and push backwards, which improves the threshing and separation effect. A side cover is installed on the right wall of the box rack, which can be opened for cleaning.

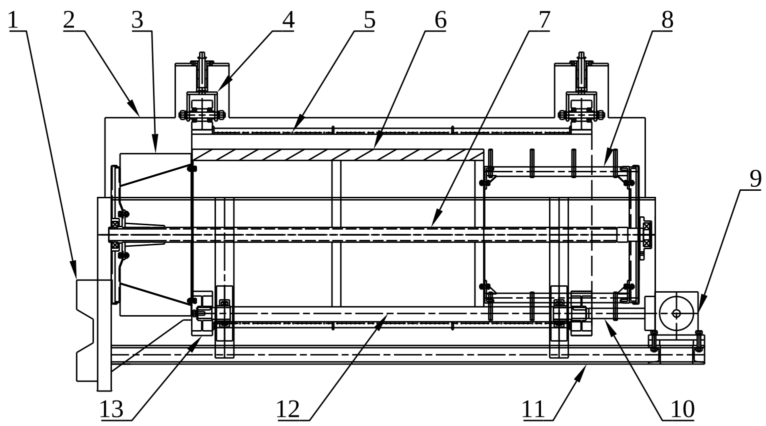

Fig. 1 - Structure of buckwheat threshing device

1- Feeding inlet; 2- Top cover; 3- Screw feeding device; 4- Outer roller pressing device; 5- Grid roller; 6- Tie rod roller; 7- Main shaft; 8- Nail tooth roller; 9- Speed reducer; 10- Grass discharge port; 11- Frame; 12- Friction wheel drive shaft; 13- Friction wheel

Inner roller

The inner roller of this design adopts the rod-tooth combination roller, with the tie rod roller in front, the nail tooth roller behind. Buckwheat completes the separation of the main grains under the action of the tie rod roller, after the hard-to-remove grains enter the nail roller, they are further separated by the impact of the nail tooth roller, and finally the straw is thrown out of the machine.

The structure of the tie rod roller is shown in Fig. 2. The hexagonal star-shaped front panel, hexagonal star-shaped intermediate panel, and hexagonal star-shaped rear panel are welded on the inner roller's main shaft. 6 D-shaped left-handed rods are fixed on the raised portion of the plate by bolts. In order to balance the rotation process, 6 even-numbered rods are used. The thick iron sheet is covered between the rod and the roller to form a closed roller, prevent the straw from intertwining with the main shaft during the threshing process, and reduce the leakage and break of the kernel. The length of the tie rod roller is 988 mm, and the working outer diameter is φ580 mm.

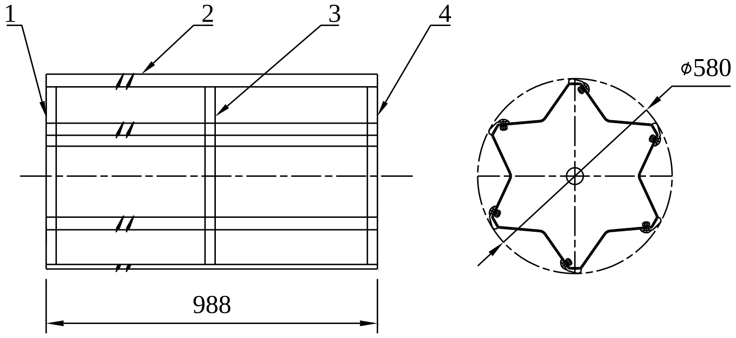

Fig. 2- Structure of tie rod roller

1- Front plate; 2- D-shaped left-handed rod; 3- Middle plate; 4- Rear plate

The structure of the nail tooth roller is shown in Fig. 3. The circular front panel and the circular rear panel are connected into a cylindrical structure by bolts through 6 nail connecting rods. The nails are welded with nail rods distributed in an axial spiral. The diameter of the nails is φ12 mm and the length of the nails is 60 mm. In order to prevent the grass from hanging during the rotation, each nail is installed at an angle of 11° backward in the direction of rotation.

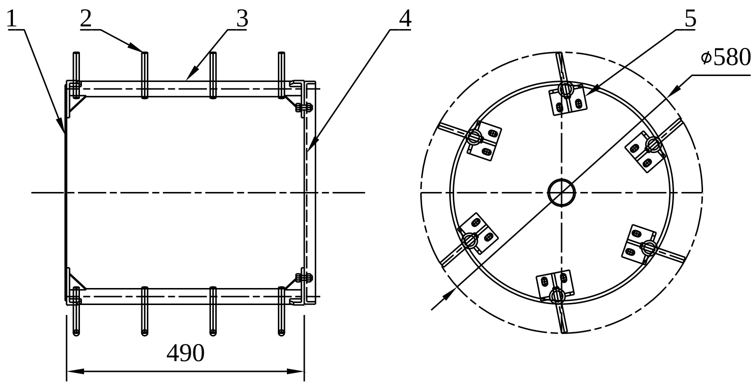

Fig. 3 - Structure of nail tooth roller

1- Front panel; 2- Nail; 3- Nail rod; 4- Rear panel

Outer roller

In order to improve the effect of threshing and separation, the grid concave plate is designed as a round outer roller and can be rotated freely, which effectively solves the problems of common grid concave plate easy to block causing serious wear during the threshing process. The extract passes through the outer roller of the grid, which can be evenly spread on the vibrating screen, and beneficial to the further separation and cleaning of the buckwheat extract. The structure of the outer grid roller is shown in Fig. 4. Equivalently spaced 4 internal ribbed plate fixing slots with internal grooves, 120 holes perforated ribbed plates are evenly fixed in the inner circumferential direction to form a cylindrical grid roller. A circular iron wire is worn every 15 mm in the axial direction of the roller, and the diameter of the iron wire is φ3 mm. In this way, the surface of the roller constitutes a grid of hole length 14 mm and hole width 12 mm. The top surface is higher than the iron wire 5 mm in order to block crops, improve the impact of the roller on the crops, and the brushing effect.

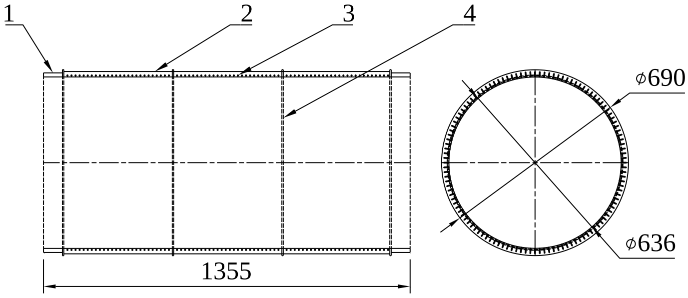

Fig. 4 - Structure of outer roller

1- Support plate; 2- Rib; 3- Iron wire; 4- Rib fixed plate

Screw feeding device

The spiral feeding device is shown in Fig. 5. Its main function is to forcibly squeeze the materials entering the feed inlet between the inner and outer rollers through spiral blades to complete the threshing. Its performance directly affects the feeding amount and threshing performance of the threshing device. The spiral feeding device is welded by the front panel, cone cylinder, rear panel and spiral blades. The diameter of the front panel is φ460 mm, the diameter of the rear panel is φ415 mm, the diameter of the small end of the cone cylinder is φ272mm, the diameter of the large end of the cone cylinder is φ415 mm, and the height of the cone cylinder is 241 mm, the blade rise angle is 48°.

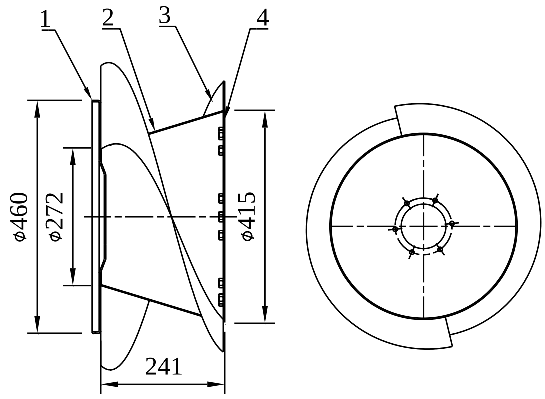

Fig. 5- Structure of screw feeding device

1- Front panel; 2- Cone cylinder; 3- Spiral blade; 4- Rear panel

Friction wheel transmission system

The friction wheel transmission system used in the threshing device is shown in Fig. 6, which is mainly composed of friction wheels, transmission shafts, bearings with vertical seats and coupling. The left friction wheel is connected to the left end of the drive shaft by bolts and flat keys, the right friction wheel is connected to the right end of the drive shaft by a flat key and a snap ring, and the right end of the drive shaft is connected to the outer roller reducer through a coupling to drive the spindle to rotate.

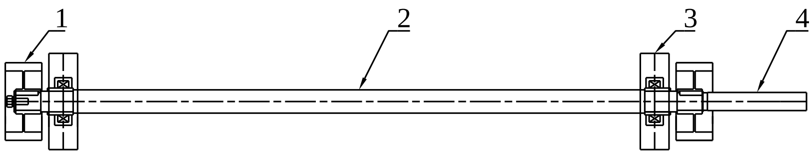

Fig. 6- Structure of friction wheel transmission system

1- Friction wheel; 2- Drive shaft; 3- Bearing with vertical seat; 4- Coupling

Outer roller pressing device

The outer roller pressing device is mainly composed of pressure wheel, pressure wheel shaft, pressure wheel frame, pressure wheel frame fixed shaft, copper sleeve, as shown in Fig. 7. The pressure wheel is mounted on the pressure wheel shaft through bearing. The pressure wheel shaft is connected to the frame, and the top of the frame is welded with a fixed shaft, there is copper sleeve between them so that the wheel frame can slide freely up and down along the sleeve. A spring is installed between the wheel frame and the top cover.

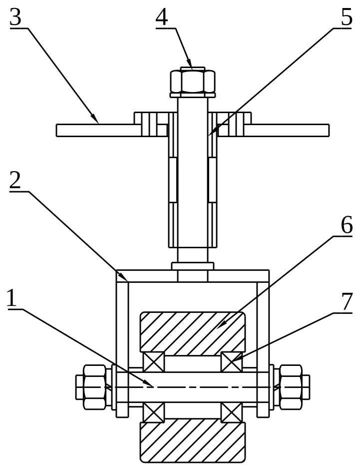

Fig. 7- Structure of outer roller pressing device

1- Pressure wheel shaft; 2- Pressure wheel frame; 3- Top cover; 4- Pressure wheel frame fixed shaft;
5- Copper sleeve; 6- Pressure wheel; 7- Bearing

Test prototype

The prototype of a tracked buckwheat combine harvester is shown in Fig. 8. The main machine and chassis are equipped with a Kubota 688 tracked combine harvester, the threshing device uses an independently designed internal and external roller rotary buckwheat threshing device. The main working parameters are shown in Tab. 1. During work, the reel wheel will turn the cut buckwheat plant to the screw conveyor, and enter the feeding bridge under the action of the screw conveyor, and then enter the internal and external roller rotary thresher through the feeding chain through the bridge. During the rotation of the inner and outer rollers, the buckwheat plants are brushed and rubbed to achieve the separation of buckwheat grains and stalks. The mixture is taken out and thrown out of the outer roller to fall into an air-screen cleaning device, the straw is discharged at the discharge port. The separated mixture fall into the cleaning device and is separated by the fan and the vibrating screen. After the selection, the grains fall into the grain conveyor and are sent to the grain silo, the debris is shaken out of the machine by the shaker.

Fig. 8 - Tracked buckwheat combine harvester prototype

Table 1

Tracked buckwheat combine harvester technical parameters

Project Name		Technical Parameters
Dimensions, [mm]		4950×2440×2800
Quality, [kg]		2790
Matching engine	Model	V2403-M-DI-T-ES04
	Power, [kW]	49.2
	Rotating speed, [r/min]	2700

Table 1
(continuation)

Project Name	Technical Parameters
Header width, [mm]	2000
Minimum stubble height, [mm]	40
Threshing pattern	Internal and external roller rotary
Feed amount, [kg/s]	1.5
Threshing gap, [mm]	10
Speed of inner roller, [r/min]	530
Speed of outer roller, [r/min]	+50
Screen type	Woven screen
Vibration screen frequency, [Hz]	6
Fan speed, [r/min]	1100
Minimum ground clearance, [mm]	275
Working speed, [km/h]	0~4.93

Test material

Field test is in Shouyang Shanxi Province, October 2020. The test buckwheat is "Red Mountain" buckwheat, and its characteristics are shown in Tab. 2.

Table 2

Main properties of buckwheat

Parameter	Value
High of buckwheat, [mm]	1500
Average grain moisture content, [%]	19.9
Stem average moisture content, [%]	82.9
Grain to grass ratio	1:3.57
Thousand weights, [g]	27.2

Test method

The tests are carried out in accordance with GB/T 8097-2008 "Test methods for harvesting machines and combine harvesters" and GB/T 5262-2008 "General rules for the determination of test conditions for agricultural machinery". Three test areas are selected in the test field, the test area is 50 m in length and 2 m in width, and signposts are set up at both ends of the test area *(Li Yaoming et al., 2018; Chen Jin et al., 2018)*. When the header enters the test area, it starts timing and works at normal speed. When it leaves the test area, it stops timing.

The quality of the stalks on the receiving cloth, the quality of the grains mixed in the stalks, the quality of the unsettled grains on the stalks, and the quality of the grains that fell on the ground when the cutting platform passed are collected by artificial methods, and the natural fall of the measurement area is measured before testing. Calculating threshing loss rate, cleaning loss rate, header loss rate, natural fall loss and total loss rate. Three samples are randomly sampled from each of the test areas, 500 g each, and the damage kernels and impurities are manually selected to calculate the damage rate and impurity rate.

$$S_t = \frac{W_t}{W} \tag{1}$$

$$S_x = \frac{W_x}{W} \tag{2}$$

$$S_g = \frac{W_g}{W} \tag{3}$$

$$S_r = \frac{W_r}{W} \tag{4}$$

$$S = S_t + S_x + S_g + S_r \tag{5}$$

$$W = W_z + W_t + W_x + W_g + W_r \tag{6}$$

where:

S_t is threshing loss rate, [%]; S_x is cleaning loss rate, [%]; S_g is direct header loss rate, [%];
S_r is natural grain loss rate, [%]; S is total loss rate, [%]; W_t is grain quality of threshing loss, [g];
W_x is grain quality of cleaning loss, [g]; W_g is grain quality of direct header loss, [g];
W_r is grain quality of natural loss, [g]; W_z is grain quality of sample, [g].

RESULTS

Analysis of conveying capacity

The material under the action of the spiral blade is simplified into particles M *(Peng Yuxing et al., 2016)*, and the force analysis is performed as shown in Fig. 9. The force exerted by the spiral blade on the material particle M is F. Because the material is affected by the frictional force of the blade, the F direction is offset from the normal direction of the spiral blade by an angle β. The β is determined by the friction angle ρ of the material on the spiral blade and the surface roughness of the spiral blade. For spiral blades made of hot-pressed or cold-rolled steel plates, the effect of surface roughness on β can be ignored, so β=ρ. F can be decomposed into a normal component force F_1 and a tangential component force F_2, where the angle between F_1 and the axial direction is the helical blade lift angle α, and the projection of F in the axial direction F_t is the axial component force on the material M. Material M performs compound motion in the trough under the action of force F, which moves both axially and tangentially, as shown in Fig. 10, and the axial velocity V_1 and the tangential peripheral velocity V_2, the combined velocity V.

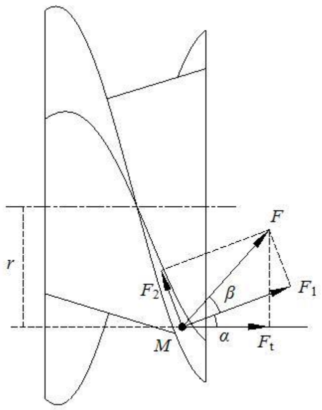

Fig. 9 - Material force analysis

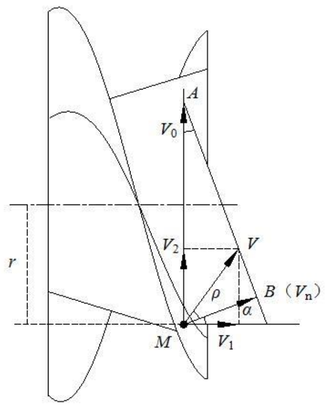

Fig. 10 - Material moving speed analysis

When the spiral blade rotates around the axis at an angular velocity ω, the speed of the material M at the radius r from the axis of the spiral blade can be solved by the speed triangle, as shown in Figure 10. V_0 is the impulsive motion speed of the material M, which is represented by the vector MA, and the direction is along the tangential direction of rotation of the point M, the relative sliding speed of the material M relative to the spiral blade is parallel to the spiral tangent direction of the point M, and is expressed by the vector AB. Regardless of the friction of the spiral blade, the absolute moving speed V_n of the material M should be along the normal direction of the M point on the spiral blade, which is expressed by the vector MB. Because the spiral blade has a friction effect on the material, the moving speed V direction of the material M and the normal direction are offset by the friction angle ρ. By decomposing the speed V, the axial speed V_1 and tangential peripheral speed V_2 of the material M can be obtained, where V_1 is the speed of the material in the material tank in the axial direction, and V_2 is the blocking speed of the material by the spiral blade. According to the analysis of the moving speed of the material M, the axial conveying speed of the material M is:

$$V_1 = V\,cos\left(\alpha + \rho\right) \tag{7}$$

Because:

$$V = V_n / \cos\rho \;,\; V_n = V_0 \sin\rho$$

So:

$$V_1 = V_0 \frac{\sin\alpha}{\cos\rho}\cos(\alpha+\rho) \tag{8}$$

$$V_0 = \omega \cdot r = \frac{2\pi n}{60} \cdot \frac{S}{2\pi \tan\alpha} = \frac{n \cdot S}{60 \tan\alpha} \tag{9}$$

$$\cos\alpha = \frac{1}{\sqrt{1+\left(S/2\pi\, r\right)^2}} \tag{10}$$

$$\tan\alpha = \frac{S}{2\pi\, r} \tag{11}$$

Substituting formula 3, formula 4, and formula 5 into formula 2, the axial conveying speed of material M can be obtained:

$$V_1 = \frac{Sn}{60} \cdot \frac{1 - f\, S/2\pi\, r}{1+\left(S/2\pi\, r\right)^2} \tag{12}$$

Similarly, the circumferential tangential velocity of the material M can be obtained:

$$V_2 = \frac{Sn}{60} \cdot \frac{f + S/2\pi r}{1+\left(S/2\pi r\right)^2} \tag{13}$$

Where:

S is pitch of spiral blade, 241 mm; n is rotating speed of screw conveyor, 430 r/min; f is coefficient of friction between material and spiral blade, $f = \tan\rho$=0.1; ρ is friction angle between material and spiral blade, 6°; α is rising angle of spiral blade, 48°;

Calculated from formula 6, the axial conveying speed of material M is 1.87 m/s.

The conveying amount Q is an important index for measuring the conveying capacity of the screw feeding device.

The formula for calculating the conveying amount Q is as follows:

$$Q = A \cdot \lambda \cdot V_1 \cdot \varepsilon \tag{14}$$

$$A = \phi \cdot D^2 \cdot \pi/4 \tag{15}$$

Where:

Q is conveying amount of the screw feeding device, [kg/s]; A is cross-sectional area of material in the trough, 36512 mm^2; φ is material fill factor, φ=0.125; D is spiral blade diameter, 610 mm; λ is buckwheat material density, 0.1×10^{-6} kg/mm^3; ε is conveying coefficient of screw conveying device, ε=0.70;

Comprehensive calculation, the conveying capacity of the spiral feeding device Q=4.29 kg/s.

Field test result

The field test results are shown in Tab. 3. Under the conditions of working speed of 0.53 m/s, feed rate of 0.41 kg/s, the field operation quality indicators of the crawler buckwheat combine harvester are as follows: the grain impurity rate is 6.50%, the grain damage rate is 1.42%, the threshing loss rate is 0.25%, the cleaning loss rate is 1.01%, the direct header loss rate is 2.43%, the natural grain loss rate is 2.98%, and total loss rate is 6.67%. If the natural grain loss rate is not included, the total machine harvest loss rate is 3.69%. The average grain yield of buckwheat in the measurement area is 15.87 kg, the biological yield is 38.53 kg, the average test time is 105.06 s, the average productivity is 3788.72 m^2/h, and the average stubble height is 376.56 mm. The test results are good, and basically meet the requirements of the indicators formulated by the national project.

It can be seen from the test results that as the working speed decreases, the feed rate gradually decreases, and the header loss rate gradually increases. The grain damage rate, threshing loss rate, and cleaning loss rate all decrease first and then increase, so is the total loss rate. Therefore, the harvest effect is best when the working speed is at a medium speed.

Table 3

Field test results

Test item	Test result				
	1	2	3	4	average
Test length, [m]	50.00	50.00	50.00	50.00	50.00
Test width, [m]	2.00	2.00	2.00	2.00	2.00
Test time, [s]	59.52	107.50	112.56	140.66	105.06
Working speed, [m/s]	0.84	0.47	0.44	0.36	0.53
Stubble height, [mm]	359.25	376.67	388.33	382.00	376.56
Feed rate, [kg/s]	0.65	0.37	0.37	0.26	0.41
Productivity, [m^2/h]	6048.40	3348.84	3198.29	2559.36	3788.72
Biological yield, [kg]	35.84	40.26	41.71	36.32	38.53
Grain yield, [kg]	15.28	17.11	16.69	14.40	15.87
Grain impurity rate, [%]	5.72	4.10	9.30	6.87	6.50
Grain damage rate, [%]	1.84	1.46	1.15	1.22	1.42
Threshing loss rate, [%]	0.4	0.21	0.13	0.27	0.25
Cleaning loss rate, [%]	1.36	1.11	0.74	0.83	1.01
Header loss rate, [%]	2.06	2.40	2.42	2.83	2.43
Natural grain loss rate, [%]	3.09	2.76	2.79	3.26	2.98
Total loss rate, [%]	6.91	6.48	6.08	7.19	6.67

CONCLUSIONS

(1) The inner and outer roller rotary buckwheat threshing device was designed. The device is mainly composed of an inner threshing roller and a grid outer roller. The inner and outer rollers rotate at the same time to knead and squeeze the material to complete the separation of buckwheat grains and stalks. On the basis of the Kubota 688 tracked combine harvester, the threshing device was installed to complete a tracked buckwheat combined harvester prototype.

(2) The screw feeding device was designed, and the mathematical model of the screw feeding device was established. By calculation, the material feeding speed of the screw feeding device was 1.87 m/s, and the conveying capacity was 4.29 kg/s.

(3) The field operation quality indicators of this model were as follows: the average grain impurity rate was 6.50%, the grain damage rate was 1.42%, the threshing loss rate was 0.25%, the cleaning loss rate was 1.01%, the direct header loss rate was 2.43%, the natural grain loss rate was 2.98%, and the total machine harvest loss rate was 3.69%. The test results provided a basis for the improvement of buckwheat mechanized harvesting machinery.

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