DESIGN AND EXPERIMENT OF LARGE STRAW CRUSHER WITH CYLINDER FEEDING HAMMER
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圆筒喂料锤片式大型秸秆粉碎机设计与试验

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ABSTRACT
In order to solve the problems of small feeding amount, high manual labor intensity and low work efficiency of the existing straw crusher, a large straw crusher with cylinder feeding hammer is designed. The key parts of the machine are designed and calculated, and the mechanism of corn straw crushing in the crusher is analyzed, and the theoretical factors affecting the working effect of the crusher are obtained. With the rotational speed of crushing shaft, diameter of sieve and clearance of sieve-hammer as test factors, and the productivity, qualification rate of crushing length as performance evaluation indicators, a quadratic regression orthogonal rotation combination test with three factors and five levels was carried out. The regression mathematical model of test factors and performance evaluation indicators was established by using Design-Expert 13.0 software. With the goal of simultaneously maximizing the qualified rate of productivity and crushing length, multi-objective optimization solutions were carried out for the rotational speed of crushing shaft, diameter of sieve and clearance of sieve-hammer, and the optimal parameter combination was determined as follows: the rotational speed of crushing shaft is 1709.24 r/min, the diameter of sieve is 22.83mm, the clearance of sieve-hammer is 15.38 mm, the verification test shows that the productivity is 9187.98 kg/h, and the qualification rate of crushing length is 93.87%. The machine improves the efficiency of crushing operation and can meet the design requirements.

摘要
为解决现有的饲草粉碎机喂入量小，人工劳动强度大，工作效率低等问题，设计了一种圆筒喂料锤片式大型秸秆粉碎机。对该机的关键部件进行了设计计算，并对玉米秸秆在粉碎机内的粉碎机理进行了分析，得到了影响粉碎机工作效果的理论因素。以粉碎轴转速、筛孔直径、筛锤间隙为试验因素，以生产率、粉碎长度合格率为性能评价指标，进行三因素五水平二次回归正交旋转组合试验，利用 Design-Expert 13.0 软件对试验结果进行方差分析，建立了试验因素与性能评价指标的回归数学模型。以生产率和粉碎长度合格率同时最大化为目标，对粉碎轴转速、筛孔直径、筛锤间隙进行多目标寻优求解，确定了最优参数组合为：粉碎轴转速 1709.24r/min、筛孔直径 22.83mm、筛锤间隙 15.38mm，验证试验表明，生产率 9187.98kg/h、粉碎长度合格率 93.87%。该机提高了粉碎作业效率，能够满足设计要求。

INTRODUCTION
Crop straw is an important biomass energy in the world, the global annual output being of up to 2.4 billion tons. China's straw production ranks first in the world. Corn, rice and wheat straw resources account for a large proportion. In recent years, the proportion of straw resources have increased, of which the proportion of corn straw resources increased the fastest, accounting for 32.34%. China's corn stalk output reached 267.4651 million tons. Corn straw is rich in cellulose, hemicellulose and lignin, and has high nutritional value. China has always adhered to agricultural priority in the utilization of crop straw, vigorously advocated the promotion of straw fertilizer, feed, energy, base and raw material utilization, and constantly promoted the comprehensive utilization of straw industry to improve quality and efficiency. In the process of feed utilization, the corn straw is used to feed livestock by cutting, crushing or kneading processing methods, which can improve the grazing rate and digestibility of straw, increase the utilization rate of straw, and effectively solve the problem of feed shortage in animal husbandry *(Xu et al., 2020; Zhao et al., 2019; Zhang et al., 2021)*.

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As one of the important links of straw processing, crushing is to cut off the straw to expose the internal nutrients, improve palatability, and improve the contact area with the digestive liquid of livestock, promote the absorption of nutrients, reduce the rumination and chewing time, and reduce the energy consumed by the chewing of livestock. As a common processing equipment of straw, the operation effect of the mill directly affects the processing cost and quality of straw *(Wu et al., 2022; Li et al., 2023)*. The length of forage fodder required by ruminants is between 30 and 50 mm, and cutting too long or too short is not conducive to absorption. Before mixing, the length of the fodder obtained by crushing needs to be 50-80 mm to prevent it being too short after mixing and cutting.

At present, the straw shredders on the market are small machinery, the process of crushing straw requires manual feeding, labor intensity is large, increasing labor costs, and in the process of artificial feeding, the crushing rotor is idling most of the time, resulting in low work efficiency. With the increase of breeding scale, the existing straw crushing machinery cannot meet the needs of China's large-scale pasture construction *(Liu et al., 2019; Zhang et al., 2024; Chen et al., 2024)*.

Taking corn stalk as the research object, this paper designs a large straw crusher with cylinder feeding hammer, which can realize continuous grinding operation by rotating cylinder, greatly reducing labor cost and improving operation efficiency. The key mechanisms such as feeding and crushing were designed and calculated, the structural parameters were determined, and the performance test was carried out. It provides reference for the research and development of forage processing machinery for the construction of large pastures in China.

MATERIALS AND METHODS

Overall composition and working principle

The whole machine is mainly composed of frame, walking wheel, feeding device, crushing device, screw discharge device, conveyor belt, hydraulic system and transmission system. The overall structure is shown in Fig. 1.

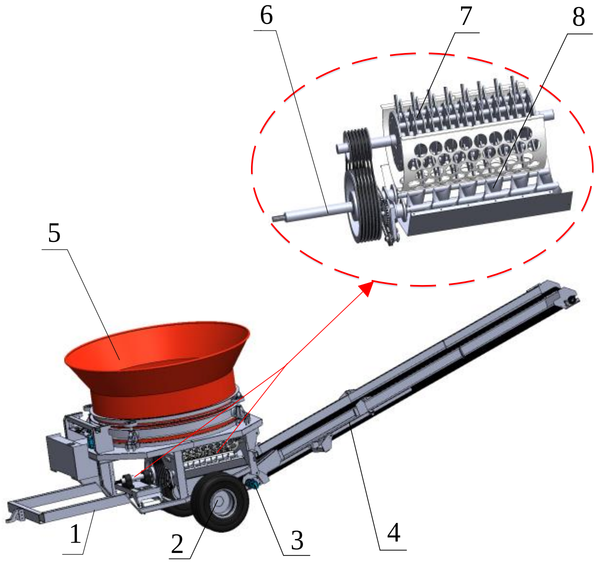

Fig. 1 - Structure diagram of cylinder feeding hammer type large straw crusher

1. Machine frame; 2. Walking wheels; 3. Hydraulic system; 4. Conveyor belt; 5. Feed cylinder; 6. Transmission system; 7. Crushing and sifting device; 8. Discharge device

The crusher is pulled by the tractor, and the rear power output shaft of the tractor drives the transmission system and the hydraulic system to provide power for the crusher to crush. During operation, the grasping machine grabs the straw into the cylinder, the straw enters the crushing bin under the action of gravity and rotating driving force, the rotor assembly in the crushing bin rotates at a high speed under the drive of the belt drive to crush the straw, the crushing straw enters the discharge bin through the sieve, and the double screw conveyor in the discharge bin transmits the broken straw to the discharge port by the chain drive and falls on the conveyor belt. The conveyor belt is driven by the hydraulic motor to transport the broken straw back for collection and complete the crushing operation.

In order to prevent overloading of crushing rotor due to excessive feeding amount, a feed cylinder speed control system was established, as shown in Fig. 2.

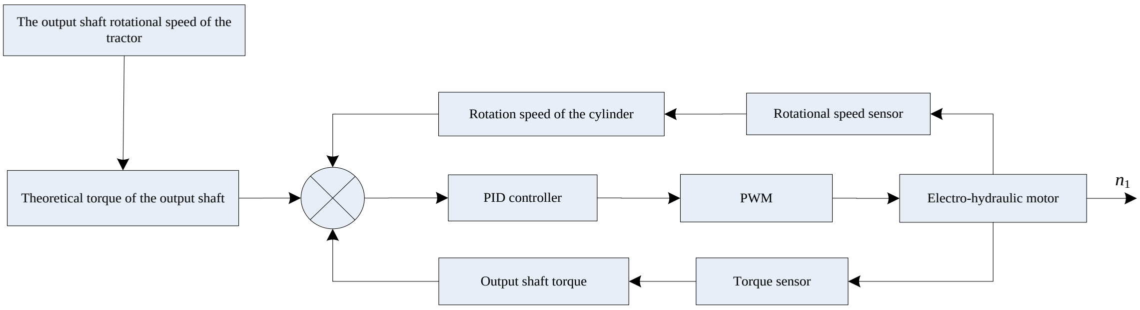

Fig. 2 - Feed cylinder speed control schematic diagram

Key component design

Cylinder design

As shown in Fig. 3, v_1 is the feed speed of the straw at the middle point of the circumference radius of the bottom surface of the cylinder, A_1 is the cross-sectional area of the volume of each cut of the hammer, and H is the feed distance of the straw during each cut interval of the hammer.

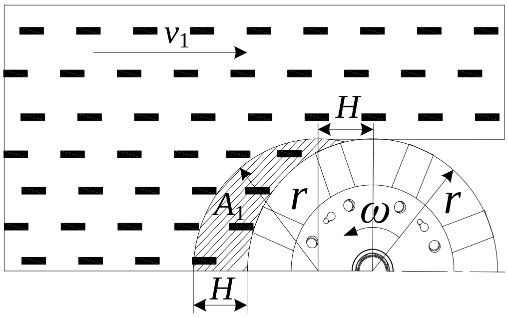

Fig. 3 - Feeding diagram

According to the target production efficiency of the machine, the feeding efficiency V should not be less than 50m^3/h, and the feeding efficiency is:

$$V = 60znlA_1 \tag{1}$$

where: z is the number of cuts for one rotation of the grinding shaft, 8; n is the crushing rotor rotational speed; l is the length of hammer mounting disc, 750 mm.

As shown in Fig.2, the area of A_1 is:

$$A_1 = Hr \tag{2}$$

$$H = \frac{60v_1}{nz} \tag{3}$$

The feed velocity v_1 of the straw at the midpoint of the circumference radius of the bottom of the cylinder is:

$$v_1 = \frac{2\pi n_1 r_1}{60} \tag{4}$$

Where: n_1 is rotational speed of cylinder; r_1 is the radius at the midpoint of the circumference of the bottom of the cylinder, 1150 mm.

According to formula (1)~(4), n_1 should be greater than or equal to 2.15 r/min. In the actual working process, there will be relative sliding between the straw and the cylinder, and the straw is not tightly filled, so the rotational speed of n_1 of the cylinder is 15~20 r/min.

Hammer design

At present, the blade of straw crusher can be divided into hammer claw type, straight knife type, curved knife type and T-type according to the shape *(Liu et al., 2011)*. Hammer claw blade has large volume and mass, large moment of inertia, good crushing effect, but large power consumption. The straight blade has the advantages of simple structure, small mass, small efficiency consumption, suitable for soft straw, usually used with fixed knife, and good crushing quality. The machete is suitable for hard straw, but the blade strength is low. T-type has complex structure, many cutting edges, large moment of inertia and large power consumption, which is suitable for straw crushing.

In this paper, the hammer is designed as a rectangular zigzag shape, which can increase the friction between the hammer and the material while striking and breaking the straw, and also produce better sliding and stabbing effects. The structure is shown in Fig.4.

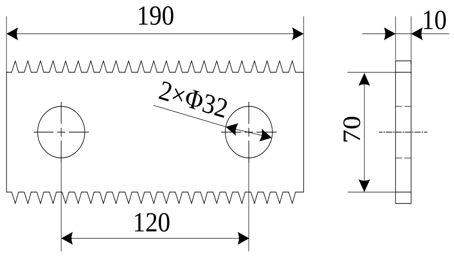

Fig. 4 - Hammer structure diagram

Determination of rotary radius and crushing speed of hammer

The size of the rotary radius of the hammer has a direct influence on the crushing effect, balance and overall size of the crusher. Increasing the rotary radius of the hammer can increase the cutting line speed of the hammer without changing the crushing speed, but increasing the rotary radius of the hammer will increase the overall size of the machine, increase the dynamic unbalance factor of the machine, and increase the energy consumption. Combined with the design size and production efficiency of the machine, the rotary radius r of the hammer is determined to be 330 mm. Then the grinding speed is:

$$n = \frac{60v}{2r\pi} \tag{5}$$

where: n is crushing speed, r/min; v is Hammer cutting line speed, m/s

According to the agricultural machinery design manual (*Agricultural Machinery Design Manual: The First Volume.*, *2007)*, the linear cutting speed of the hammer≥34 m/s is appropriate. According to formula (5), when the grinding shaft speed is≥996 r/min, the hammer cutting line speed is≥34 m/s, so the minimum grinding speed is determined to be 996 r/min.

Design of sieve

The sieve is a part that screens and separates the crushed straw, so that the crushing straw with a geometric size less than the diameter of the sieve hole is separated from the crushing bin, and can also collide with the material that is not completely crushed to promote the further crushing of the material *(Cao et al., 2016; Tian et al., 2016)*. Because of its simple structure and convenient manufacture, the round hole screen is widely used in the crusher *(Cao et al., 2016; Tian et al., 2011)*. The diameter of sieve is an important parameter that affects the grinding quality and productivity of the mill. The diameter of the sieve hole is large, which can make the crushed material pass through the sieve plate more easily. Although the productivity of the machine is increased and the power consumption is reduced, the length of the crushed corn stalk is larger. The diameter of sieve is too small, so that the crushed material cannot easily pass through the sieve, resulting in excessive crushing, and increased power consumption. The relationship between the diameter of the screen and the length of the broken straw should be as follows:

$$l = (0.25 \sim 0.33)d \tag{6}$$

where: l is length of broken straw, mm; d is diameter of sieve, mm

According to the calculation of equation (6), combined with the actual requirements of crushing operation, the diameter of sieve should range from 15 to 25 mm. The structure is shown in Fig. 5. Two circular screen sieves with the same parameters should be used together.

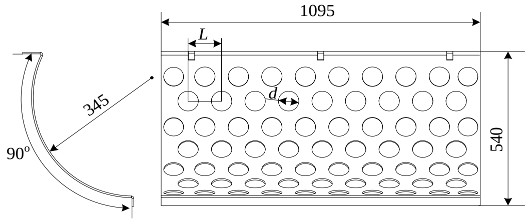

Fig. 5 - The structure of sieve

In order to further clarify the influence of sieve diameter on the crushing efficiency and quality of the machine, this paper optimizes it through experiments.

Design of discharge mechanism

The discharge device of the crusher designed in this paper adopts the double screw conveyor mechanism to change the passive discharge into the active discharge, which can improve the discharge efficiency *(Chen et al., 2015; Xu et al., 2019; Xu et al., 2020)*. According to the production efficiency and discharge requirements of the designed crusher, the design structure of the double screw conveyor is shown in Fig.6.

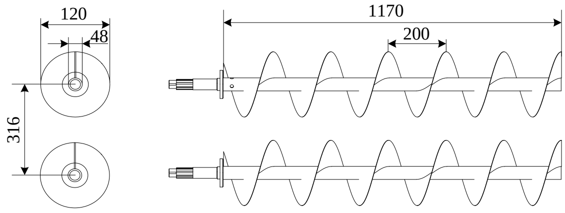

Fig. 6 - Structure diagram of double screw conveyor

In addition to the characteristics of the material itself, the factors that affect the change of the movement trajectory of the broken straw also include the stress and speed distribution, etc. In order to study the discharge stability of the device, the speed distribution of any broken straw is analyzed, as shown in Fig. 7.

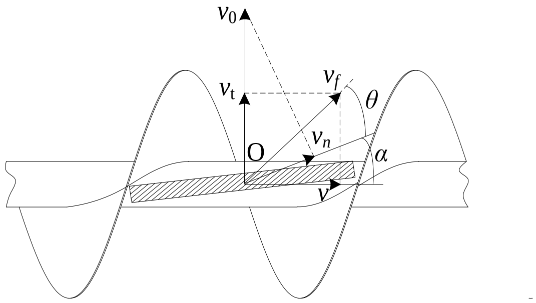

Fig. 7 - Velocity distribution broken straw

where: *O* is the position of the broken straw; v_0 is the implicated velocity, v_n is the absolute velocity when friction is ignored, v_f is the absolute velocity when friction is considered, v is the axial velocity after v_f decomposition, v_t is the tangential velocity after v_f decomposition, m/s. α is the angle between v_n and v, (°); θ is the angle between v_f and v_n, (°).

If a broken straw is selected at any radius r, there are two main motion modes, that is, relative sliding with the spiral surface and horizontal motion along the direction of the spiral axis. The circumferential velocity (implicated velocity) of the broken straw is $v_0=r\omega$, and the direction is the tangent direction of the broken straw. Absolute velocity $v_n=v_0\sin\alpha$ without friction; Considering the absolute velocity $v_f=v_n/\cos\theta$ in the case of friction, v_f is decomposed to obtain axial velocity v and tangential velocity v_t.

The axial speed makes the straw move along the direction of the spiral axis, and the tangential speed makes the broken straw flip in the screw conveyor. According to the velocity analysis, the axial velocity of the broken straw is:

$$v = v_f \cos(\alpha+\theta) = \frac{r\omega\sin\alpha}{\cos\theta}\cos(\alpha+\theta) \tag{7}$$

From the above analysis, it can be seen that when the movement speed of the broken straw in the conveying direction is v>0, the broken straw can move along the conveying direction, and vice versa. According to the requirements of smooth and efficient discharge, the rotational speed of the screw conveyor is set to 1000-2000 r/min, and the corresponding speed range of the conveying direction can be calculated to be 0.72-1.08 m/s, and the speed values are greater than 0, reaching the condition of the movement of the broken straw.

Analysis of corn straw crushing mechanism

The main crushing forms of corn stalk include smash, impact crushing and rubbing crushing *(Ma et al., 2016; Wang et al., 2017)*. Smash crushing refers to the crushing form caused by the high-speed rotating hammer hitting the corn stalk, impact crushing refers to the crushing form caused by the corn stalk hitting the screen after being hit by the hammer, and rubbing crushing refers to the crushing form caused by the rubbing between the corn stalk, the sieve and the hammer.

Smashing process

The corn stalk enters the crushing bin through the feed port and is hit by the high-speed rotating hammer and broken, as shown in Fig.8.

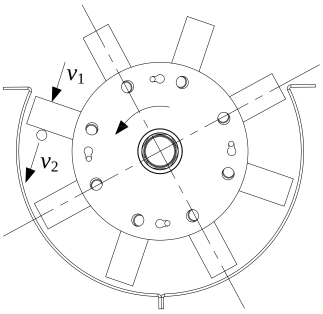

Fig. 8 - Schematic diagram of smashing process of corn stalk

Under the condition that the weight of the hammer plate and the airflow resistance are ignored, it can be known by the impulse-momentum theorem:

$$P\Delta t = m(v_1 - v_2) \tag{8}$$

Namely:

$$P = \frac{m(v_1 - v_2)}{\Delta t} \tag{9}$$

where: P is the impact force of the hammer on the corn stalk, N; Δt is strike action time, s; m is corn stalk mass, kg; v_1 is linear velocity at the end of the hammer, m/s; v_2 is the velocity of the corn stalk before the strike force, m/s.

According to equation (9), when the mass m of the corn stalk is constant, the greater the relative velocity of the hammer to the corn stalk, the greater the strike force on the corn stalk. The strike time Δt depends on the hardness of corn stalk, and the higher the hardness, the shorter the strike time; low hardness means long strike time. When the strike force exceeds the cohesion of the corn stalk, the corn stalk is broken.

Impact crushing

After being hit by the hammer, the corn stalk quickly hits the sieve, as shown in Fig. 9. When the impact force is greater than its cohesive force, the corn stalk is further broken.

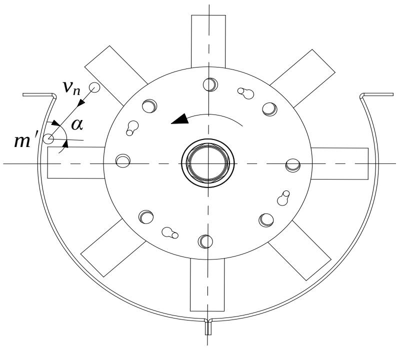

Fig. 9 - Schematic diagram of corn stalk impact crushing process

According to the impulse-momentum theorem, the impact force between the corn stalk and the sieve is:

$$N_1 = \frac{m'}{\Delta t_1}(1+\lambda)v_n \cos\alpha \tag{10}$$

where: N_1 is Impact force between the corn stalk and the sieve, N; v_n is Initial impact velocity of corn stalk, m/s; m' is the mass of corn stalk before impact, kg; Δt_1 is Impact time, s; λ is elastic recovery coefficient of corn stalk; α is incidence angle of corn stalk to sieve, (°).

According to formula (10), under the condition that the structure of the crushing chamber is fixed, the impact force between the corn stalk and the sieve is mainly affected by the initial impact velocity v_n and the elastic recovery coefficient λ of the corn stalk. The elastic recovery coefficient λ of corn stalk is related to its water content. Corn straw is a fibrous material, elastoplastic deformation is large, and most of its impact with the sieve will bounce back, only a small amount of corn straw will be broken, therefore, impact crushing is not the main crushing form of this crusher.

Rubbing crushing

Because there is relative movement between the corn stalk and the hammer and sieve, the corn stalk is further broken by rubbing, as shown in Fig.10.

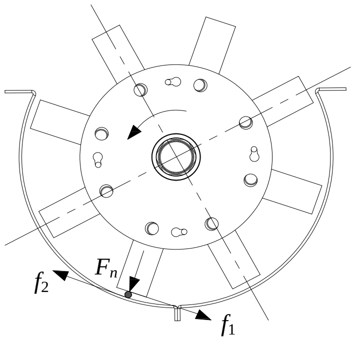

Fig. 10 - Schematic diagram of corn straw rubbing crushing process

The end of the hammer piece and the surface of the screen piece have extrusion and kneading effect on the corn stalk respectively, and the kneading force is respectively:

$$f_1 = \mu_1 F_n \tag{11}$$

$$f_2 = \mu_2 (m \frac{v^2}{D+\delta} + F_n) \tag{12}$$

where: f_1 is the kneading force of corn stalk and hammer, N; f_2 is the kneading force of corn stalk and sieve, N; F_n is extrusion pressure of the hammer on the corn stalk unit, N; μ_1 is friction coefficient between the corn stalk element and the hammer; μ_2 is friction coefficient between corn stalk and sieve; v is the speed of the corn stalk, m/s; D is rotor assembly diameter, m; δ is clearance of sieve hammer, m.

When the kneading force is greater than the cohesion of the corn stalk, the corn stalk will be broken.

RESULTS AND DISCUSSIONS

Performance test

Test condition

The test was carried out at the test site of Inner Mongolia Ruifeng Agricultural and Animal Husbandry Machinery Co., LTD. The corn straw used in the experiment was provided by corn growers in Datong District, Daqing City, Heilongjiang Province, with a moisture content of 35%. The test site is shown in Fig. 11.

Fig. 11 - Test site

Experimental design

With the rotational speed of crushing shaft, diameter of sieve and clearance of sieve-hammer as test factors, and the productivity, qualification rate of crushing length as performance evaluation indicators (calculation method is shown in the formula 13-14), the orthogonal rotation combination test of three factors and five levels of quadratic regression was carried out. The rotational speed of crushing shaft 1000-2000 r/min, diameter of sieve 15-25 mm, clearance of sieve-hammer 10-20 mm are selected, test factor coding as shown in the table 1, each group of tests were repeated three times, the average value of which was taken as the final test result, data processing and statistical analysis were carried out by Design-Expert 13.0 software. The test results are shown in the table 2.

Productivity y_1

The weighed straw was fed, the time required to crush all the straw was recorded, and the productivity y_1 was calculated as:

$$y_1 = \frac{m}{t} \times 3600 \tag{13}$$

where: m is quality of straw for test, kg; t is test time, s.

Qualification rate of crushing length y_2

At the same time interval, the sample of the crushing straw was picked up at the discharge port for 3 times, each time 300 g, and the mass was weighed after mixing and screening, and the qualified rate of crushing length y_2 was calculated:

$$y_2 = \frac{m_0}{m_1} \times 100\% \tag{14}$$

where: m_0 is the mass of the broken straw with a length of 50~80 mm in the sample, kg; m_1 is sample mass of broken straw, g.

Table 1

Factor level coding table

Coding	Factor		
	Rotational speed of crushing shaft x_1 / r·min^{-1}	Diameter of sieve x_2 / mm	Clearance of sieve-hammer x_3 / mm
1.682	2000	25	20
1	1797.27（1800）	22.97（23）	17.97（18）
0	1500	20	15
-1	1202.73（1200）	17.03（17）	12.03（12）
-1.682	1000	15	10

Table 2

Test scheme and results

Number	x_1	x_2	x_3	Y_1/kg·h^{-1}	Y_2/%
1	1	1	1	9090.21	94.61
2	1	1	-1	8865.40	94.64
3	1	-1	1	9452.07	93.21
4	1	-1	-1	9257.15	93.08
5	-1	1	1	8895.94	93.32
6	-1	1	-1	9013.76	93.41
7	-1	-1	1	9082.55	92.12
8	-1	-1	-1	9088.32	92.79
9	1.682	0	0	8970.74	94.29
10	-1.682	0	0	8700.32	92.60
11	0	1.682	0	8890.60	94.59
12	0	-1.682	0	9649.43	92.52
13	0	0	1.682	9508.91	92.31
14	0	0	-1.682	9266.34	93.43
15	0	0	0	9637.16	92.38
16	0	0	0	9617.43	92.51
17	0	0	0	9474.76	92.37
18	0	0	0	9594.31	92.73
19	0	0	0	9570.22	92.69
20	0	0	0	9668.64	92.52
21	0	0	0	9671.60	92.39
22	0	0	0	9706.13	92.34
23	0	0	0	9595.08	92.82

Analysis of variance and significance test were performed on the experimental results. The results are shown in the table 3.

Table 3

Analysis of variance

Evaluation index	Source of variance	Sum of square	Degree of freedom	Mean square	F	P	Significance
Y_1	Model	2.06E+06	9	2.29E+05	27.82	< 0.0001	**
	x_1	1.17E+05	1	1.17E+05	14.21	0.0023	**
	x_2	3.13E+05	1	3.13E+05	37.97	< 0.0001	**
	x_3	16820.25	1	16820.25	2.04	0.1765	-
	x_1^2	8953.23	1	8953.23	1.09	0.316	-
	x_2^2	12681.08	1	12681.08	1.54	0.2365	-
	x_3^2	11778.82	1	11778.82	1.43	0.253	-
	x_1x_2	1.24E+06	1	1.24E+06	150.1	< 0.0001	**
	x_1x_3	2.49E+05	1	2.49E+05	30.28	0.0001	**
	x_2x_3	1.11E+05	1	1.11E+05	13.51	0.0028	**
	Residual error	1.07E+05	13	8232.29	-	-	
	Lack of fit	69639.88	5	13927.98	2.98	0.0823	
	Error	37379.83	8	4672.48	-	-	
	Sum total	2.17E+06	22	-	-	-	
Y_2	Model	1.33E+01	9	1.47E+00	35.2	< 0.0001	**
	x_1	3.30E+00	1	3.30E+00	78.78	< 0.0001	**
	x_2	4.96E+00	1	4.96E+00	118.47	< 0.0001	**
	x_3	0.46	1	0.46	11.05	0.0055	**
	x_1^2	0.15	1	0.15	3.68	0.0774	-
	x_2^2	0.099	1	0.099	2.36	0.1481	-
	x_3^2	0.025	1	0.025	0.6	0.4508	-
	x_1x_2	1.80E+00	1	1.80E+00	42.89	< 0.0001	**
	x_1x_3	2.24E+00	1	2.24E+00	53.38	< 0.0001	**
	x_2x_3	2.80E-01	1	2.80E-01	6.7	0.0225	*
	Residual error	5.40E-01	13	0.042	-	-	
	Lack of fit	0.29	5	0.058	1.83	0.2132	
	Error	0.25	8	0.032	-	-	
	Sum total	1.38E+01	22	-	-	-	

Analysis of variance

As can be seen from the table, the rotational speed of crushing shaft x_1 and the diameter of sieve x_2 have extremely significant effects on the productivity, while the clearance of sieve-hammer x_3 has no significant effect on the productivity y_1. The rotational speed of crushing shaft x_1, the diameter of sieve x_2, and the clearance of sieve-hammer x_3 all have extremely significant effects on the qualification rate of the crushing length y_2. The main and second order of influencing factors on productivity are respectively the diameter of sieve, the rotational speed of crushing shaft and the clearance of sieve-hammer, and the main and second order of influencing the qualification rate of the crushing length are respectively the rotational speed of crushing shaft, the diameter of sieve and clearance of sieve-hammer. The interaction between the rotational speed of crushing shaft and the diameter of sieve (x_1x_2), the interaction between the rotational speed of crushing shaft and clearance of sieve-hammer (x_1x_3) has a very significant effect on productivity and the qualification rate of the crushing length. The interaction between the diameter of sieve and clearance of sieve-hammer (x_2x_3) has a significant effect on the productivity and the qualification rate of the crushing length. The significance level and the mismatch test of the regression equation are greater than 0.05, and the difference is not significant, indicating that the predicted value of the regression equation has a significant relationship with the actual value obtained through the analysis of the test results. The regression equation of each factor and evaluation index obtained after removing the non-significant item is shown as follows:

$$\begin{aligned} y_1 &= 9615.38 + 92.54x_1 - 151.29x_2 + 35.09x_3 - 33.45x_1x_2 + 39.81x_1x_3 \\ &- 38.37x_2x_3 - 278.87x_1^2 - 125.26x_2^2 - 83.67x_3^2 \end{aligned} \quad (15)$$

$$\begin{aligned} y_2 &= 92.53 + 0.49x_1 + 0.60x_2 - 0.18x_3 + 0.14x_1x_2 + 0.11x_1x_3 \\ &+ 0.056x_2x_3 + 0.34x_1^2 + 0.38x_2^2 + 0.13x_3^2 \end{aligned} \tag{16}$$

Parameter optimization and verification test

In order to obtain the best parameter combination of crushing machinery operation performance, the multi-objective optimization algorithm in Design-Expert 13.0 software was used to maximize the productivity and the maximum qualification rate of the crushing length. The optimization mathematical model is established through analysis.

$$\begin{cases} \max\ y_1(x_1, x_2, x_3) \\ \max\ y_2(x_1, x_2, x_3) \\ s.t. \begin{cases} 1000r/\min \le x_1 \le 2000r/\min \\ 15mm \le x_2 \le 25mm \\ 10mm \le x_3 \le 20mm \end{cases} \end{cases} \tag{17}$$

The optimal parameters of the crusher are as follows: the rotational speed of crushing shaft is 1709.24 r/min, the diameter of sieve is 22.83 mm, the clearance of sieve-hammer is 15.38 mm, predicted productivity is 9264.69 kg/h, and the qualification rate of the crushing length is 94.04%.

In order to verify the reliability of the optimization results, the optimization results were verified under the same test conditions. Each group of tests was repeated three times, and the average value of the three test results was calculated as the actual value of the evaluation index under the same conditions. The relative error between the actual results and the optimization results is less than 2%, which proves that the mathematical model and the optimization results are accurate and reliable, and the crusher has a good working performance. The crushed straw is shown in Fig.12.

Fig.12 - Straw after grinding

CONCLUSIONS

(1) Aiming at the low crushing efficiency of the existing straw shredder, a large straw shredder with cylinder feeding hammer was designed, which improved the crushing efficiency through continuous cylinder feeding and could meet the needs of China's large pasture construction.

(2) Through the variance analysis of the test results, it is found that the main and secondary factors affecting the productivity are the rotational speed of crushing shaft, the diameter of sieve and the clearance of sieve-hammer. The main and secondary factors affecting the qualification rate of the crushing length are the rotational speed of crushing shaft, the diameter of sieve and the clearance of sieve-hammer.

(3) Optimized by Design-Expert 13.0 software to obtain the best combination of parameters for crushing operation: the rotational speed of crushing shaft is 1709.24 r/min, the diameter of sieve is 22.83 mm, the clearance of sieve-hammer is 15.38 mm, the verification test shows that the productivity is 9187.98 kg/h, and the qualification rate of the crushing length is 93.87%.

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REFERENCES

[1] Bao, L., Li, Z., & Dongxing, Z. (2011). Force and motion states of hammer mill at unloaded running (锤片式粉碎机空载运行中锤片的受力及运动状态) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.27, pp. 123-128. Henan/China.

[2] Defu, W., Mo, W., & Liqiao, L. (2017). Mechanism Analysis and Parameter Optimization of Hammer Mill for Corn Stalk (锤片式粉碎机粉碎玉米秸秆机理分析与参数优化) [J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.48, pp. 165-171.Heilongjiang / China.

[3] Fudi, Z., Siming, W., & Wenming, H. (2019). Analysis of mechanization utilization and development path of corn straw (玉米秸秆机械化利用情况与发展途径分析) [J]. *Agricultural Machinery Use and Maintenance*, Vol.51, pp. 48. Heilongjiang/China.

[4] Haijun, Z., Yi, Q., & Haiqing, T. (2024). Design and Experimental Optimization of V-shaped Hammer for Hammer Mill. *INMATEH-Agricultural Engineering*, Vol. 73, pp.191-200. Zhejiang/China.

[5] Haiqing, T., Fengfu, Q., Weifeng, L., Baosheng, H., Chunguang, W. (2011). Design and Experiment of Piecewise Arc-shaped Screen on Hammer Mill to Grinding Performance (锤片式粉碎机分段圆弧筛片设计与粉碎性能试验) [J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.42, pp.92-95. Inner Mongolia/China.

[6] Haiqing, T., Haiqing, W., Tao, H., Di, W., Fei, L., & Baosheng, (2018). Design of combination sieve for hammer feed mill to improve crushing performance (锤片饲料粉碎机组合形筛片设计改善粉碎性能) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.34, pp. 45-52. Inner Mongolia

[7] Hongcheng, L. (2023). Study on Influence Mechanism and Optimization of the Hammer Mill Grinding Performance (锤片式粉碎机工作性能影响机理与优化研究). Hubei/China.

[8] Hongyang, X. (2020). Mechanization treatment of corn stalk and its development characteristics (玉米秸秆的机械化处理方式与发展特点) [J]. Agricultural Machinery Use and Maintenance, pp.101. Heilongjiang/China.

[9] Kun, W., & Yuepeng, S. (2022). Research Progress Analysis of Crop Stalk Cutting Theory and Method (农作物茎秆切割理论与方法研究进展分析) [J]. *Transactions of the Chinese Society for Agricultural Machinery*, (in Chinese). Vol.53, pp. 1-20. Shandong / China.

[10] Liying, C., Yuepeng, Z., Yubao, Z., & Yanyan, L. (2016). Influence of screen parameters optimization on screening efficiency of feed hammer mill (筛片参数优化对饲料粉碎机筛分效率的影响) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 32, pp. 284-288. Inner Mongolia

[11] Liying, C., Xinghua, S., Jianxin, W., & Yu, B. (2016). Design and Experiment of Separation Device of Hammer Feed Mill (锤片式饲料粉碎机分离装置设计与试验)[J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 47, pp. 128-133.Inner Mongolia/China.

[12] Qian, M., Fei, L., & Manquan, Z. (2016). Working mechanism and structure optimization of hammer of rubbing machine (揉碎机揉碎机理分析及锤片结构优化)[J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.32, pp. 7-15. Inner Mongolia/China.

[13] Tao, C., Shujuan, Y., Yifei, L., Guixiang, T., Xin, M., & Shanmin, Q. (2024). Design and Test of Cutting and Crushing Cooperative Silk Kneading Machine (铡切揉碎协同式牧草揉丝机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 55, pp. 149-159. Heilongjiang

[14] Tiejun, W., Tieliang, W., Hongguang, C., Yuanjuan, G., Subo, T., & Ruili, W. (2021). Design and Experiment of Adjustable Feeding Straw Bale-breaking and Rubbing Filament Machine (喂入调节式秸秆破包揉丝机设计与试验)[J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.52, pp. 148-158. Liaoning / China.

[15] Xiaoqing,Z., Zifan, W., & Muyou, C. et al. (2021). Analysis of current situation of crop straw yield and comprehensive utilization in China (中国农作物秸秆产量及综合利用现状分析). *Journal of China Agricultural University*, Vol.26, pp. 30-41. Inner Mongolia/China.

[16] Xiongfei, C., Xiwen, L., Zaiman, W., Minghua, Z., Lian, H., Wenwu, Y., Shan, Z., Ying, Z., Houding, W., & Le, Z. (2015). Design and experiment of fertilizer distribution apparatus with double-level screws (两级螺旋排肥装置的设计与试验) [J]. *Transactions of the Chinese Society of Agricultural Engineering*, Vol.31, pp. 10-16. Guangdong / China.

[17] Xuemeng, X., Feixiang, L., Yongxiang, L., Changpu, S., Kunpeng, M., & Jing, C. (2019). Design and Experiment of Quantitative Variable Pitch Screw (定量变距螺旋结构设计与试验)[J]. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.50, pp. 89-97. Henan/China.

[18] Xuemeng, X., Feixiang, L., Changpu, S., Yongxiang, L., & Dongtao, C. (2020). Optimization Design and Experiment of Wheat Flour Equal Pitch Screw Feeding Device (小麦粉等距螺旋喂料装置优化设计与试验)[J]. *Transactions of the Chinese Society for Agricultural Machinery,* Vol.51, pp.150-157. Henan/China.