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Experimental Study on Direct Harvesting of Corn Kernels

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Abstract: The mechanical harvesting of corn has always been a problem for the development of the corn industry. In the present investigation, a tangential flow–transverse axial flow threshing test system was designed based on the 4YL-4/5 harvester. The structure design was modular, and the threshing drum and other key parts could be changed, or the technical parameters could be adjusted according to the needs. Thus, the system becomes suitable to carry out the threshing test of various grains. In this paper, two kinds of systems, a cylindrical plate-tooth mixed row threshing drum and a full cylindrical threshing drum, were designed. Using the same materials and technical conditions, a comparative experiment of the corn grain harvest was carried out to explore the mechanical–technical conditions and methods to reduce the grain breakage rate of corn's direct harvest.The results showed that the threshing ability and adaptability of the cylinder with a plate-tooth mixed arrangement structure were higher than those of the full cylinder arrangement structure. It was also found that for a higher moisture content (above 28%) of the maize ear, the grain breakage rate met the national standard. On the other hand, the cylinder with a plate-tooth threshing drum can support a wider range of moisture contents and drum peripheral velocities than the full cylinder threshing drum. Within the range of all tested moisture contents and drum peripheral velocities, the minimum grain breakage rate of the full cylinder tooth drum was 3.7%, and the minimum grain breakage rate of the cylinder with the plate-tooth threshing drum was 1.5%, which means a reduction of 59.5% of the breakage rate was achieved.

Keywords: threshing drum; grain breakage rate; moisture content; drum peripheral velocity; direct harvest method

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1. Introduction

In the post-harvest processing and production of maize grain at the industrial level, the problem of a high breakage rate duringthe direct harvest of ears with a high moisture content has been the main limiting factor in the development of corn mechanization [1]. In particular, the annual wheat–corn rotation of China's Huang-Huai-hai region has been suffering with this problem more strongly [2]. Damaged corn grains not only reduce their market value, but also enhance the respiration of damaged fresh grains, which easily causes fever fermentation and infection by disease mold. In the aspect of breeding, varieties with an ultra-short growth cycle and rapid dehydration characteristics have not yet been developed. Thus, the progress of mechanical harvesting technology has become the main concern to attempt to solve the current problem [3]. The most important performance indexes of the threshing system of corn via a combined harvester include the threshing loss rate, grain damage rate, and impurity rate. These parameters are affected by the corn variety, biological traits, and moisture content, and the material feeding amount, threshing drum peripheral velocity, threshing gap, and other factors of the harvesters [4–6]. The threshing process also needs to overcome the friction between the grains and the binding force between the grains and the core, which is related to moisture content and grain position [7]. Due to the influence of the weather and/or ambient temperature and humidity [8,9], the time of harvesting on the same day also has an impact on the grain breakage rate [10,11].

In order to reduce the grain's breakage rate and to put trust in mechanized grain harvesting, many researchers from home and abroad have studied the mechanism of corn grain's breakage [12,13] based on the mechanical characteristics of the grain itself [14–16], and the mechanical adaptability of maize grain's harvesting of different varieties has been quantitatively evaluated [17]. A mathematical model of contact mechanics was established to study the interaction between grain and the threshing element [18,19]. By building a small threshing test bench, the influence of the main operating parameters such as the moisture content and drum peripheral speed on the grain breakage rate was explored [20,21]. The interaction between the materials and the threshing system in the process of corn ear threshing is an extremely complex dynamic process. Various theoretical analyses and mathematical models have been regularly proposed [22–25], and the crushing mechanism of corn threshing under certain conditions has been theoretically expounded.

In the present research, a tangential flow–transverse axial flow corn threshing test bench is established, and two types of transverse axial flow threshing drums are designed.In order to analyze and evaluate the advantages and disadvantages of the two types of threshing drums, the influence of threshing parameters, such as the corn ear feeding amount, drum peripheral velocity, and threshing gap on the grain breakage rate with different moisture contents, was studied [26,27]. The results of this research will play a role in the technological progress of corn grain harvesting.

2. Materials and Methods

2.1. Test Material

In the present experiment, the corn ear used for the threshing test belonged to the corn cultivar Qiaoyu No. 8. After monitoring the changes in the maize ear moisture content in the experimental field, maize ears with bracts that are suitable for testing were harvested manually in time and transported to the laboratory for threshing test research.The five-point sampling method was used for the statistical analysis of the biological characters such as ear length, ear diameter, ear row number, grain number, ear weight, thousand-grain weight, etc., in the experimental field. This enabled adjustment of the technical parameters of the experimental system. The statistical results obtained in the research are shown in Table 1.

Table 1. Biological characteristics of Qiaoyu 8.

Parameter	Unit	Range	Average
Ear length (with bracts)	mm	250–270	260
Ear diameter (with bracts)	mm	50–60	55
Number in the vertical rows		35–40	37
Cob mass (moisture 26%)	g	45–60	51
Ear mass with bracts (moisture 26%)	g	290–350	320
Cob diameter	mm	20–30	25

2.2. Test Device Design

With 4YL-4/5 corn harvester as reference, the tangential flow–transverse axial flow corn threshing test bed was established. Its 3D digital model is shown in Figure 1.The corn ear is sent to the feeding port through the material conveying device, and is forcedly fed into the threshing chamber of the transverse axial flow drum under the action of the tangential flow drum. In the process of feeding operation, the tangential flow drum also performs preliminary squeezing and rubbing of the maize ear, which plays a certain role in threshing. After the ear is threshed in the threshing chamber, the grains fall into the lower grain collecting box through the concave plate sieve. Lighter and larger materials such as bracts and shaft cores are guided by the guide plate on the upper cover of the threshing chamber and pushed to the straw–grass separation area, and thrown out of the bench through the miscellaneous discharge port to complete the threshing process.

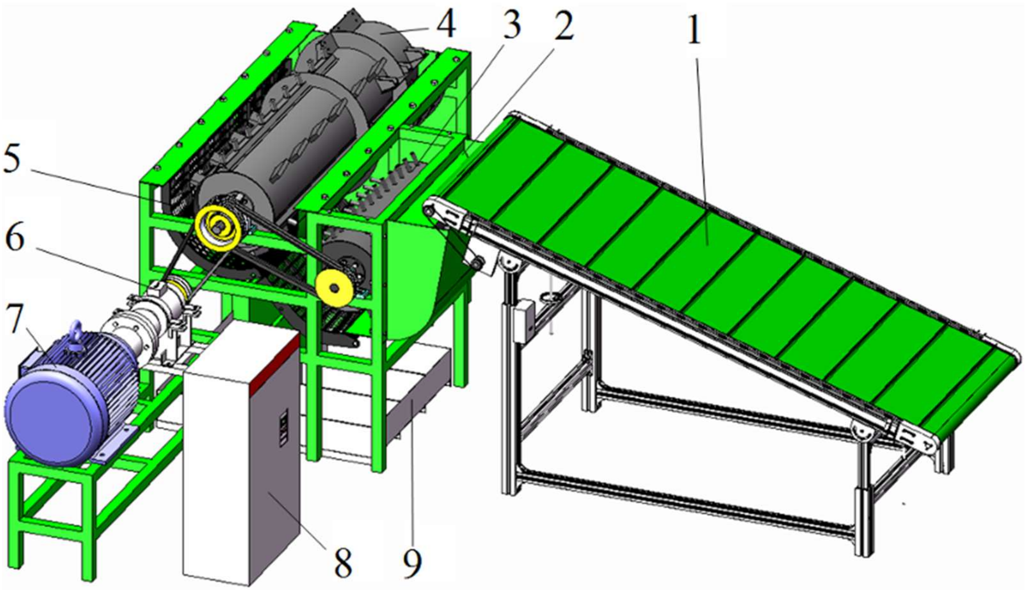


Figure 1. The 3D maize threshing test bench. (1) Feeding device; (2) feeding port; (3) tangential flow drum; (4) axial flow drum; (5) grid grating; (6) torque speed sensor; (7) motor; (8) electrical control cabinet; (9) grain collection box.

According to the threshing operation parameters of 4YL-4/5 corn harvester, data from the test bench were tested and determined, and the results are shown in Table 2.

Table 2. Relationship calibration between feed amount and transmission velocity.

Serial Number	Conveyor Belt Speed Control Motor Speed (rpm)	The Working Speed of the Harvester/Conveyor Belt Speed ($m \cdot s^{-1}$)	Feeding Amount ($kg \cdot s^{-1}$)
1	99.4	0.39	2.2
2	120	0.47	2.6
3	140	0.55	3.0
4	160	0.62	3.4
5	178.3	0.70	3.9
6	185	0.726	4.04

2.2.1. Design of Threshing Drum

Design of Tangential Flow Threshing Drum

The tangentialflow threshing drum and the tangentialflow threshing chamber remained unchanged in all the tests. The tangential threshing drum adopts a closed structure; threshing elements are in the form of cylindrical teeth with cylinder height 60 mm and diameter 20 mm. Six rows of column teeth are arranged in a spiral staggered pattern. It is convenient for combing and feeding corn ears and advancing to the beginning of the transverse axial flow drum threshing chamber in order to ensure the threshing stroke of the ear. Its structural form and column tooth development diagram are shown in Figure 2.

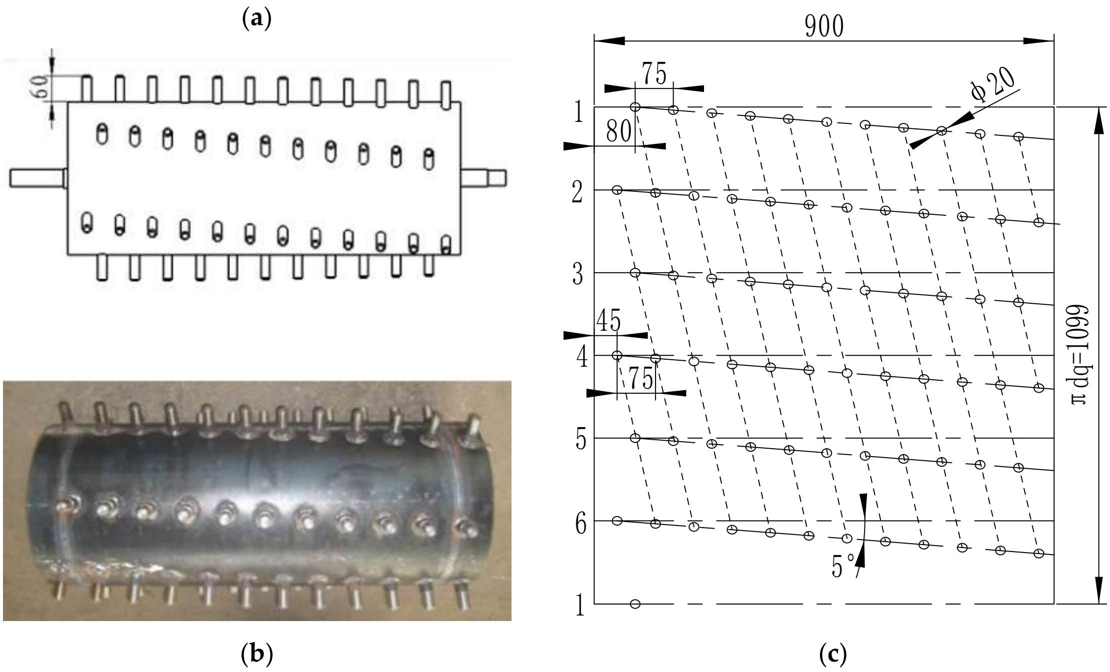


Figure 2. Tangential flow drum structure and column tooth arranged expanded view (magnified view). (**a**) The 3D model, (**b**) physical picture, (**c**) column teeth arranged expanded view.

Design of Transverse Axial Flow Threshing Drum

The transverse axial flow threshing drum is designed in two types. Type one is the column tooth plate-tooth mixed row threshing drum (TD1 for short), and type two is the fullcolumn tooth threshing drum (TD2 for short).The column teeth of TD1 have strong material grasping ability, striking, and combing functions. While the plate teeth have a good adaptability to the unevenly fed crop layer, and the rubbing effect is strong. The space-mixed column tooth-plate's tooth structure can increase the number of blows to the corn ear and the rubbing effect of the column teeth in the threshing chamber. As a result, sufficient threshing effect is generated between the ears, and the ears and the concave plate. This enhances the threshing separation effect so as to improve the adaptability to threshing operations. In structure, the transverse axial flow drum has three functional sections, e.g., threshing, sieving, and separating. In order to be threshed fully, a double annular baffle is designed in the second half of the stroke, which extends the residence time of the uncleaned material in the threshing chamber, so that the corn ear can be fully impacted, squeezed, and rubbed. The function of the partition on the right is to prevent the corn kernels from being discharged outwards and reduce the entrainment loss of the corn kernels. The structural form of TD1 and its column tooth plate's tooth arrangement are shown in Figure 3.

In order to study the threshing performance of TD1, this test was compared with the existing TD2 in the market. The threshing bench, operating parameters, and material properties of the comparison test were completely consistent. When carrying out the comparative test, TD1 and TD2 were installed on the test bench in turn. The TD2 structure is shown in Figure 4.

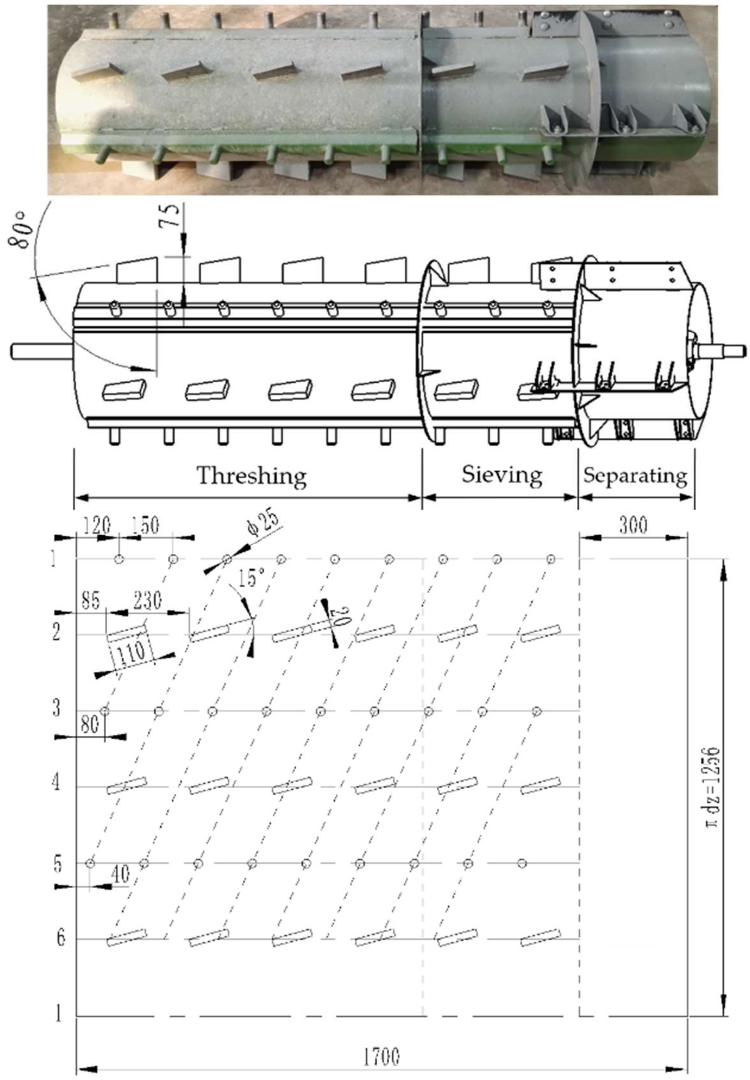


Figure 3. Transverse axial flow drum structure and the column tooth-plate's tooth arrangement (magnified view).

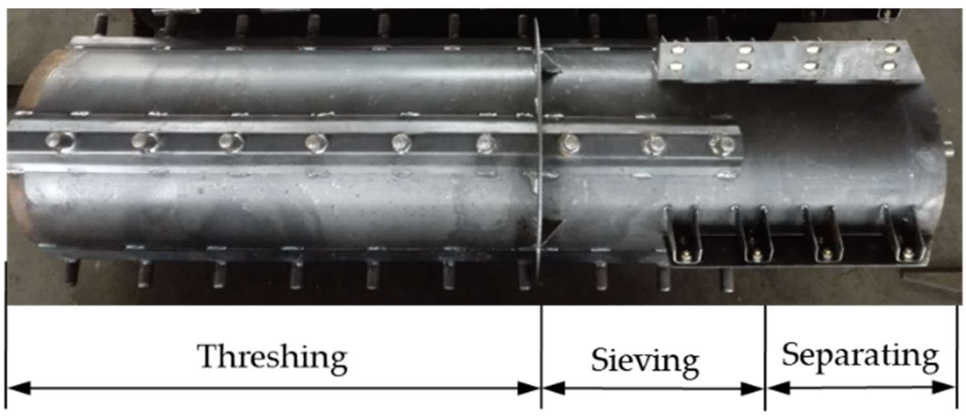


Figure 4. The fullcolumn tooth threshing drum (TD2 for short).

2.2.2. Design of Threshing Chamber

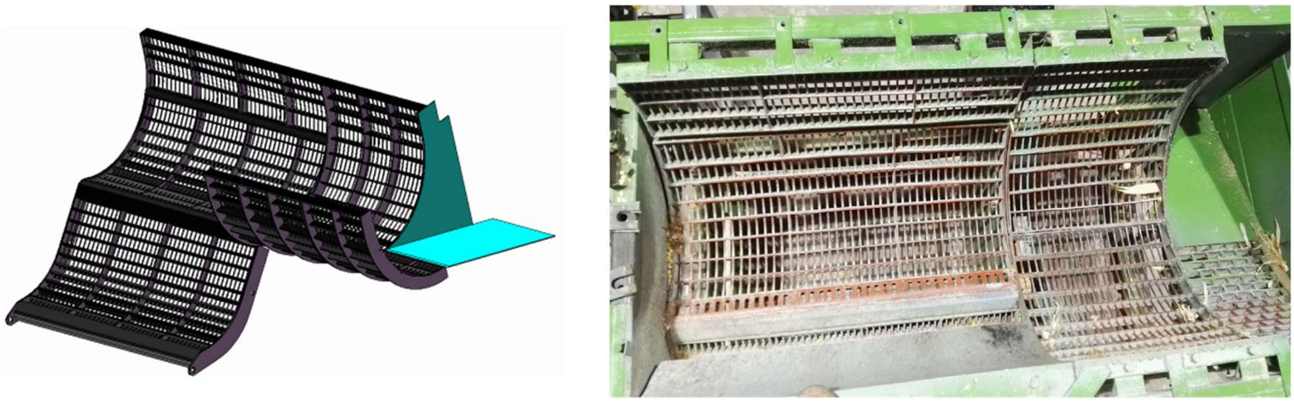
The threshing chamber is composed of the concave plate screen assembly and the upper cover. It is the main device for corn threshing and grain separation.

Design of Concave Plate Screen Assembly and Concave Sieve Components

In addition to completing the threshing operation with the drum, the concave plate screen also sieves the fallen grains. The removed grains can be separated from the threshing chamber as soon as possible to reduce or avoid the breakage caused by repeated beating and rubbing, and also to reduce the power consumption of the threshing system. Therefore, the effective passage of the concave screen has become one of the important contents of the design of the threshing chamber. The effective separation area of the concave plate sieve, that is, the sieve porosity, is the ratio of the total area of the sieve holes to the total area of the concave plate. Within a certain range, the larger the sieve porosity is, the better the separation effect.

The threshing chamber adopts a grid-type concave plate screen, the sieve rate is 40–70%, and the separation rate is as high as 75–90%. At the same time, the grid-type horizontal grid plate is about 10 mm higher than the screen bar. It cooperates with the roller to squeeze and rub the ear, and the threshing ability is stronger.

The concave plate screen welding components of the grain threshing chamber are assembled modularly, so that they can be replaced during various concave plate screen tests or other grain harvesting. The modular assembly effect of the concave plate screen components is shown in Figure 5.



(**a**) (**b**)

Figure 5. Concave plate sieve assembly. (**a**) The 3D model; (**b**) physical picture.

According to the design data, the sieve hole rate of the concave plate screen was calculated. The lowest sieve hole rate of the rear concave plate screen was 58.2%, the highest sieve hole rate of the tangential drum concave plate screen was 65.5%, and the overall average sieve hole rate was 63.5%, which enables the model to meet the technical requirements of harvesting machinery regulations [28], as shown in Table 3.

Table 3. Concave plate sieve porosity.

	Concave Screen Area (mm^2)	Sieve Area (mm^2)	Sieve Ratio (%)
Tangential flow drum concave plate sieve	463,529.6	303,732.3	65.5
Active concave plate sieve	411,492.9	267,628.1	65.0
Rear concave plate sieve	188,886.6	116,689.2	61.8
Middle concave plate sieve	271,304.2	168,394.5	62.1
Front concave plate sieve	167,685.6	97,620.2	58.2
Overall calculation	1,502,898.9	954,064.3	63.5

Design of the Threshing Chamber Upper Cover

The inner wall of the upper cover of the threshing chamber is designed with a spiral guide plate to ensure that the ear and husk mixture entering into the threshing chamber can move along the axial direction of the drum to prevent it from clogging. Theoretically, when the feeding speed is greater than the axial movement speed of the material along the deflector on the upper cover of the threshing chamber (i.e., the helical speed of the deflector relative to the transverse axial flow drum), material will clog in the threshing chamber. Therefore, the design must ensure that the threshing discharge speed of the material is greater than the feeding speed [28]. As calculated by the mass flow of the material per unit time, the feeding amount is not greater than the discharge amount, and then

$$\begin{cases} w_o \leq w_i \\ w_i = v_l m_v \\ v_l = v_z \tan \\ m_v = s_h \rho \end{cases} \Rightarrow \theta \geq \arctan \frac{w_i}{v_z s_h \rho} \tag{1}$$

In the formula, w_o is material feeding weight, kg/s; w_i is material discharge weight, kg/s; v_l is the speed of the material moving along the axial direction of the drum, m/s; v_z is drum peripheral velocity, m/s; m_v is material flow mass per unit length along the axial direction of the drum, kg/m; s_h is threshing chamber cross-section annular gap area, m^2; ρ is material density, kg/m^3; θ is deflector angle, °.

The density of the material discharged from the test is ρ = 75 kg/m^3. In order to ensure that the range of the design angle is applicable, the peripheral velocity of the transverse axial flow drum is conservatively calculated according to the minimum design peripheral velocity, which is v_z = 14.4 m/s; after calculation, the annular gap area of the cross-section of the threshing chamber is 0.035 m^2, and the material feeding amount is designed according to the maximum feeding amount w = 12.12 kg/s. The minimum guide angle of the deflector without material clogging can be obtained as

$$\theta \geq \arctan \frac{w_i}{v_z s_h \rho} = 3.8^o$$

The angle of the deflector at the end should not be less than the minimum deflector angle of 3.8°, which is designed to be 5°, and the maximum angle of the deflector at the starting end is designed to be 25°; the number of deflectors is 9, and the interval between each deflector is 150~250 mm. The design result of the upper cover of the threshing chamber is shown in Figure 6.

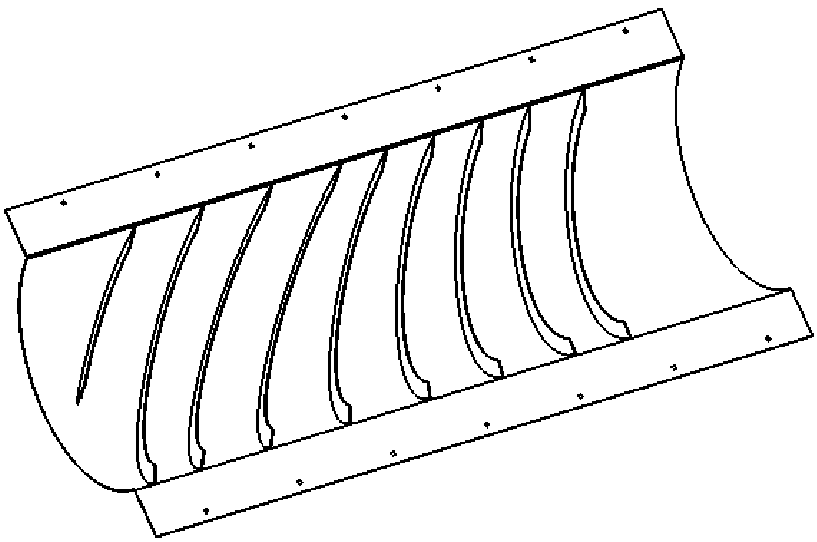


Figure 6. Threshing room upper cover structure.

3. Results and Discussion

This part comprehensively studies the threshing separation system by analyzing the threshing capacities of the tangential flow threshing drum and the axial flow threshing drum, the threshing law of each functional section, and the comparison of the threshing and breakage rates of the two transverse axial flow threshing drums TD1 and TD2. This will provide the basis for the optimal design of the threshing system with low damage and high efficiency.

The threshing bench test was replaced with the transverse axial flow drums TD1 and TD2 to carry out the research. The threshing gap value at the entrance is generally smaller than the average diameter of the ear; it is convenient to squeeze and rub the ear during the feeding process, so that the bracts and leaves are loose and, as a result, the seeds also become loosened. The outlet gap is equal to half of the diameter of the shaft core, which is convenient for the discharge of bracts and broken shaft cores. According to the statistical results of the biological characters of the Qiaoyu 8 ear in Table 1, the threshing gap is set to 40 and 12 mm for the inlet and outlet, respectively, with a maximum threshing gap ratio of 3.3, which conforms to the technical specifications of the grain harvesting machinery.

According to the calibration results in Table 1, the procedure was to set the linear speed of the feeding conveyor belt according to the test feed amount. The test was carried out within the moisture content range of 22–32%, whereas the moisture content of each test should differby 2%. The threshing test was carried out according to the single factor test plan; each test was repeated twice, and the feeding amount was 50 kg each time. The collection effect of the grain collection box in the corn threshing test is shown in Figure 7. The total amount of threshed material in each small grid and sample was weighed, and the grain breakage rate in each small grid was countedthree times and the average value taken. Then the moisture content after being threshed three times was taken, and the average value was taken. At the same time, the power consumption of the threshing test was recorded through the host computer software. The test data of the entire process are thus recorded in detail for further analysis. A large number of experiments showed that the threshing grains are mainly in the tangential flow area A and the axial flow area B; C1 and C2 have fewer grains, and C3 also has fewer grains, so the experimental analysis focused on the areas A and B as the research objects.

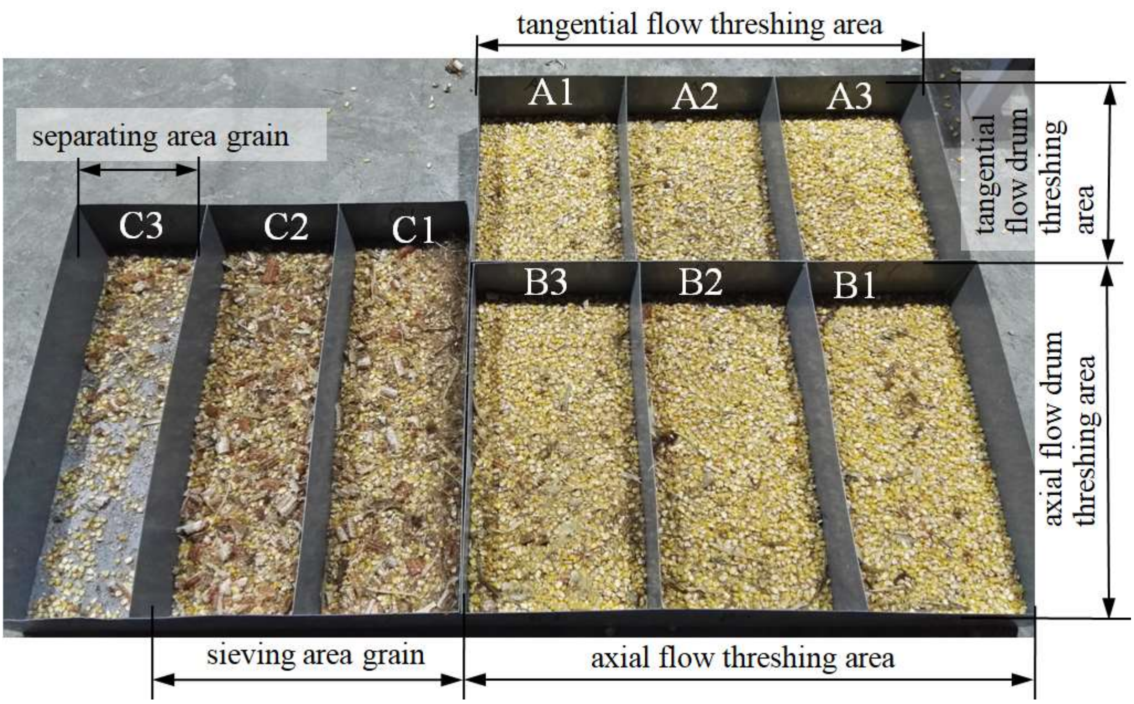


Figure 7. Threshing grain collection.

3.1. Comparative Analysis of Threshing Volume between Tangential Flow and Axial Flow

In order to study the threshing operation load of the three partitions:the tangential flow threshing area A, axial flow threshing area B, and separation and impurity removal C, the weight of the previous threshing material in the three partitions was, respectively, taken and the average value was calculated. The average weight proportions of the threshing material in the three zones A, B, and C of drum TD1 were 41.9, 44.5, and 13.6%, respectively, and the same for drum TD2 were 42.4, 44.5, and 13.1%, respectively (Figure 8). The author's experiments showed that the threshing weight of each functional section of drum TD1 and drum TD2 was equivalent, and there was no significant difference. Therefore, when improving the efficiency of threshing machinery in the future, tangential flow and axial flow should be considered equally.

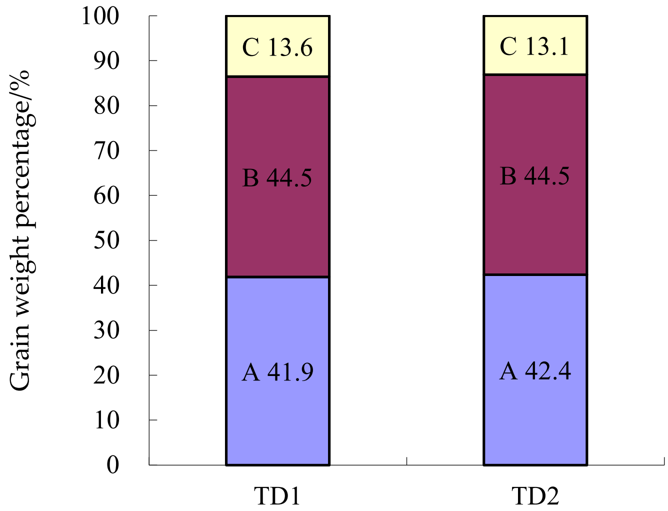


Figure 8. Threshing amount statistical comparison in different sections of two types of drums.

3.2. Threshing Separation Rule of Each Section

At different water content intervals, there was a certain relationship between the threshing amount of each section of the threshing system and the water content (Figure 9). The drums TD1 and TD2 showed relatively similar trends. The test results show that when the moisture content was lower than 28%, the threshing amount of the tangential flow was closer to that of the transverse axial flow. Under this condition, the average difference was within 1%, and the threshing capacity of the tangential flow drum and the B section of the axial flow drum were almost the same. With the increase in the moisture content of the corn material, in the tangential flow, the mass proportion of the threshing material decreased obviously but increased slowly in the transverse axial flow, and the threshing material in the separation area C of the transverse axial flow also showed an increasing trend synchronously. When the moisture content was higher than 28%, the threshing ability of the tangential flow was obviously weaker than that of the transverse axial flow, and the difference between the threshing amount of the transverse axial flow and the tangential flow of drum TD1 was significantly larger than that of drum TD2. This shows that the threshing ability and adaptability of the cylindrical tooth plate's tooth mixed arrangement structure of drum TD1 to the corn ear with a higher moisture content are higher than those of drum TD2 full column tooth arrangement structure.

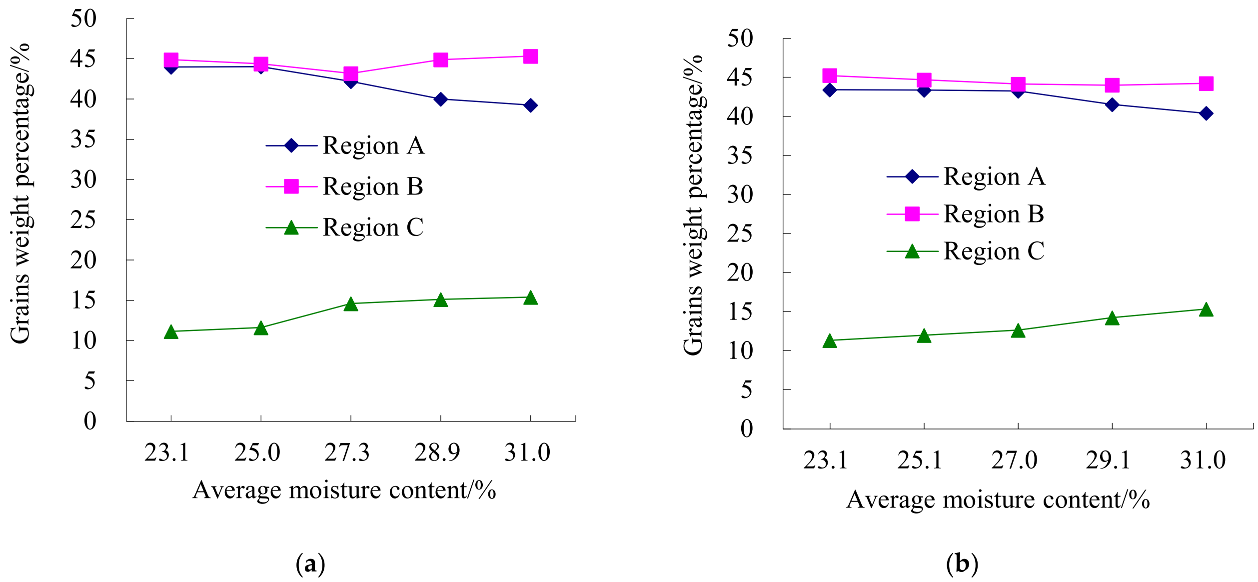


Figure 9. The relationship between threshing grain amount and moisture content in each section. (**a**) TD1; (**b**) TD2.

For the drum TD1, the proportion of the threshing material in each moisture content interval is shown in Figure 10. When the average moisture content was 25%, the difference between the threshing amount of the tangential flow and the threshing amount of the transverse axial flow was only 0.4%.As the moisture content of the material increased, the proportion of the threshing material in the tangential flow decreased, and the proportion of the threshing material in the transverse axial flow increased. The test shows that the threshing capacity of the tangential flow drum and the transverse axial flow drum was almost the same under the moisture content of 28%. When the moisture content was higher than 28%, the threshing capacity of the tangential flow drum was obviously weaker than that of the transverse axial flow drum. Combined with the material characteristics of the corn ear, it was found that when the moisture content was lower than 28%, the gap between the rows of the ear and the ring increased significantly with the decrease in the moisture content. This indicates that the dehydration of the grain led to the shrinkage of the grain volume and the weakening of the mutual agglomeration between the grains [29], reduced threshing difficulty.

In another test, the three grain collection areas A, B, and C were divided into 7 × 5 grids axially–radially, the weight of the materials in each small grid was counted, and MATLAB was used to draw a spatial surface map of the distribution of the threshing matter. The map is presented in Figure 11, and it was observed that in zone A, the material was threshed tangentially and pushed into the transverse axial flow threshing chamber. Due to the helical action of the column teeth, the amount of threshing in the 1st to the 7th grids in the axial direction was slightly increased. In the transverse axial flow threshing zone B, along the direction of the material's axial movement, the distribution of the grains from the 1st to the 7th grids did not change significantly. However, the material takes the axis as the symmetry line and is roughly symmetrically distributed along the radial direction. In the next threshing and separation zone C, the material distribution changed very significantly, and the axial direction decreased rapidly. The grains were screened in large quantities in the previous axial region; the grains entrained by the bracts were finally intercepted in the impurity removal area. In the end, the distribution of grains in the C3 area was very small, and the entrainment loss was significantly reduced.

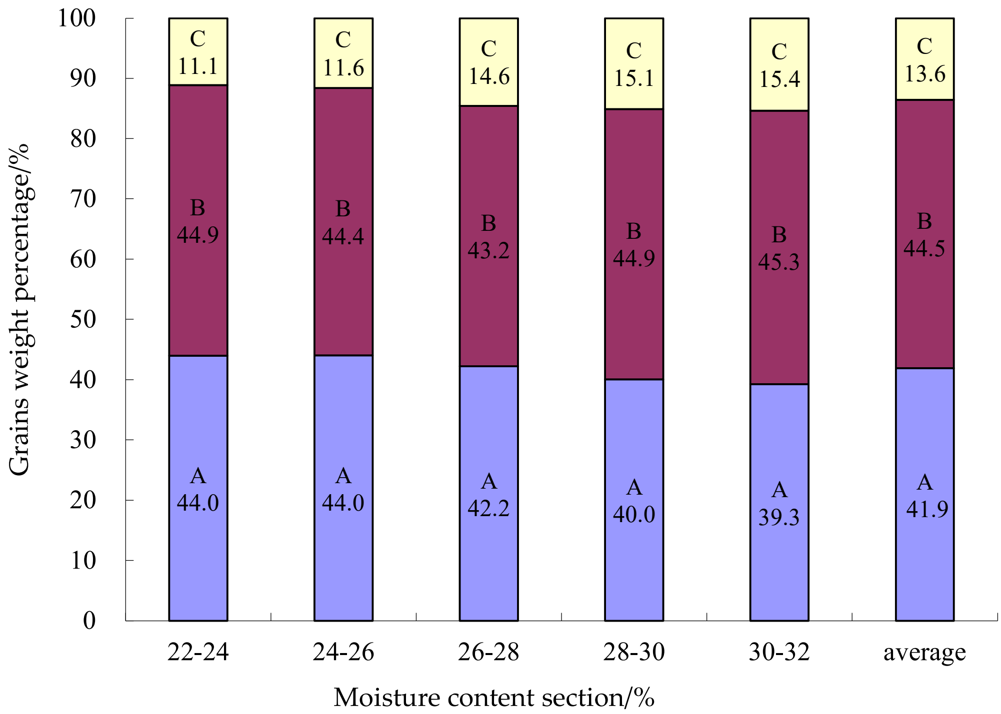


Figure 10. The proportion of threshing material in each moisture content section of the drum TD1.

The experimental study shows that in the threshing process of the transverse axial flow drum, the action time of the material in the threshing system is about 2–3 s. By that time the material in the transverse axial flow threshing chamber has been beaten, turned over, and squeezed many times; the action time is long and the threshing is relatively sufficient. During the threshing of the tangential flow drum, the action time of the material in the A zone is only 0.021–0.029 s according to the theoretical calculation. The corn ear is instantly threshed by high-speed blowing and impact squeezing with the concave plate screen, and the action time is short. For the ears with a higher moisture content, this is obviously not effective for threshing. The tangential flow drum throws more material into the transverse axial flow threshing chamber, causing a large amount of material to lag, increasing the risk of clogging.

For the tangential flow–transverse axial flow threshing system, most grain harvesting studies put more emphasis on the structure and threshing function of the transverse axial flow drum, as well as the feeding function of the tangential flow drum, while ignoring the threshing function of the tangential flow drum. It is, therefore, considered that at the moment when the ear is fed, the shear flow drum does not play much of a role in threshing. Through experimental tests, the tangential flow drum has not only a feeding function, but the mass proportion of its threshing material reaches more than 40%. Therefore, when optimizing the structural design of the threshing system of the tangential flow–transverse axial flow type, both the tangential flow and the transverse axial flow should be paid equal attention to effectively reduce the grain breakage rate and improve the quality of the harvesting operations.

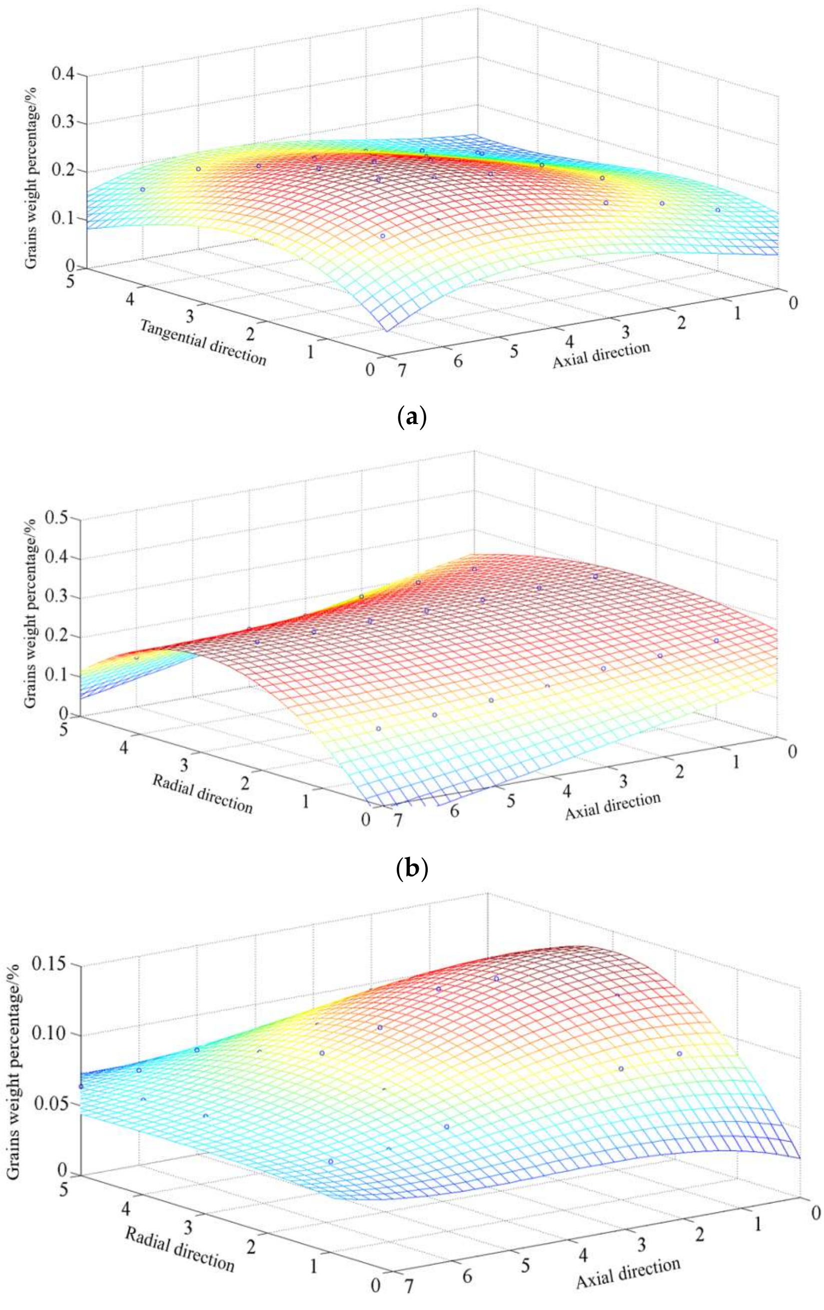


Figure 11. Threshing flow distribution variation law quadratic response surface. (**a**) Tangential flow threshing zone A; (**b**) transverse axial flow threshing zone B; (**c**) transverse axial flow threshing zone C.

3.3. Comparison of the Breakage Rate between Drum TD1 and TD2

The comparative analysis of drum TD1 and drum TD2 takes the threshing performance of the respective B sections as the object. Comparing the influence of the change in the material's moisture content on the breakage rate under the line speed of each group, the test comparison analysis is shown in Figure 12. On the whole, the grain breakage rate of drum TD1 and drum TD2 increased rapidly with the increase in the moisture content. When the TD1 line speed of the drum was 15.84–18.72 m/s, and the moisture content was 22–26% in the threshing test, the grain breakage rate was less than 5%. The result complies with the mechanized grain harvesting standard stipulated by the national standard (Figure 12a). Among the results, when the threshing breakage rate was in the range of 24–26%, that moisture content was the lowest. This shows an obvious inflection point, and at the speed of 17.28 m/s, the breakage rate was 1.5%, which is the lowest value in the threshing test. When the moisture content was 26–28%, the grain breakage rate was about 5%, which is basically close to the national standard. However, at times, when the moisture content was higher than 28%, the grain breakage rate increased rapidly with the increase in the moisture content. Thus, breaking the national standard and reducing the adaptability of the grain harvesting. Under the rotating speed of 20.16–21.60 m/s, covering the whole moisture content range of the threshing test, the grain breakage rate was basically above 6%, and it showed a sharp increasing trend with the increase inthe moisture content, which completely fails to meet the national standard requirements for grain harvesting.

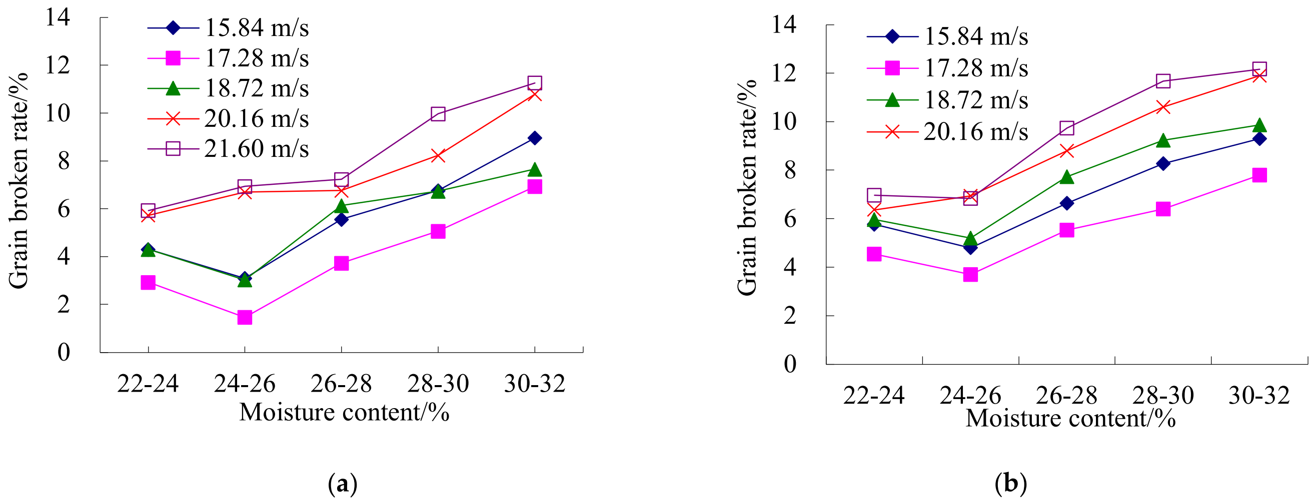


Figure 12. The relationship between the moisture content and grain broken rate under various drum peripheral velocity conditions. (**a**) TD1; (**b**) TD2.

The relationship between the breakage rate and moisture content of drum TD2 in zone B was similar to that of drum TD1, as shown in Figure 12b. However, its grain breakage rate in the corresponding moisture content interval and at peripheral velocity was higher than that of drum TD1. The optimal working moisture content range was 24–26%, the optimal drum peripheral speed was only 17.28 m/s, and the lowest grain breakage rate was 3.7%. If the influencing factors fluctuate, the grain breakage rate will easily exceed the national standard, and the threshing adaptability of drum TD2 is much lower than that of drum TD1.

4. Conclusions

In this paper, a corn threshing bench test was designed, and the rule of threshing separation between tangential flow and transverse axial flow was studied. The threshing performance of the column tooth plate-tooth mixed row threshing drum (TD1) and the full column tooth threshing drum (TD2) were compared and analyzed, and the following conclusions were drawn:

(1) The mass ratio of TD1 and TD2 drum threshing materials shows that the three-stage structure design of transverse axial flow drum threshing, screening, and impurity removal is reasonable, and the contradiction between the long threshing stroke and the compact drum structure has been balanced. This segmented structure can effectively compensate for the short threshing stroke of the transverse axial flow type.

(2) Through experimental tests, the tangential flow drum has not only a feeding function, but the mass proportion of its threshing material reaches more than 40%. Therefore, when optimizing the structural design of the threshing system of the tangential flow–transverse axial flow type, both the tangential flow and the transverse axial

flow should be paid equal attention to effectively reduce the grain breakage rate and improve the quality of the harvesting operations.

(3) The moisture content of the material has a certain influence on the threshing capacity of the tangential flow and transverse axial flow drums, and the proportion of threshing material in the tangential drum decreases with the increase in the moisture content. When the moisture content is below 28%, the threshing amount of the tangential flow drum is almost the same as the threshing mass of the transverse axial flow drum threshing screen (area B). When the moisture content is higher than 28%, the proportion of threshing material in the tangential flow drum decreases significantly.

(4) The control experiment showed that under the same conditions, the threshing ability and adaptability of drum TD1 to corn ears with a higher moisture content (>28%) were higher than those of drum TD2. Compared with drum TD2, drum TD1 has a wider range of moisture content and peripheral velocity in terms of the grain breakage rate that meets the national standard.

(5) Within the range of all test moisture content and test drum peripheral velocity, the minimum grain breakage rate of drum TD2 was 3.7% and that of drum TD1 was 1.5%. Thus, a reduction of 59.5% in the grain breakage rate was achieved by drum TD1.

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