ANALYSIS AND OPTIMIZATION TEST OF OPERATION PROCESS OF CLEANING DEVICE OF CORN SEED HARVESTER

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玉米籽粒收获机清选装置作业机理分析与优化试验

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ABSTRACT

Aiming at the current problem of the high rate of impurity and loss in the cleaning device of corn seed harvesters in China, this paper took the cleaning device of 4YZL-6 self-propelled corn seed harvester as a sample and analyzed the movement law of the material on the sieve. Box-Behnken response surface experimental design theory was used for the orthogonal tests. Wind inlet angle, airflow velocity, and crank angular velocity were selected as influencing factors, and the impurity rate and loss rate as the evaluation index of operation quality. A regression mathematical model between each influencing factor and indicator was established, and the model was also integrated and optimized. The optimal parameter combination was obtained as follows: the wind inlet angle was 37.95°, the airflow velocity was 11.3 m/s, and the crank angular velocity was 4.1 r/s. The corresponding impurity rate was 0.87% and the loss rate was 0.34%. Verification tests were conducted on the optimization results, and the test results showed that under the optimal combination of parameters, the impurity rate was 0.89% and the loss rate was 0.35%. The relative errors of each evaluation index and its model prediction were 2.29% and 2.94%, respectively.

摘要

针对目前中国玉米籽粒收获机清选装置含杂率和损失率较高的问题，本文以4YZL-6自走式玉米籽粒收获机清选装置为例，分析了物料在筛子上的运动规律。采用Box-Behnken响应面试验设计理论，以入风角度、风速和曲柄角速度为影响因素，以含杂率和损失率为作业质量评价指标，进行三因素三水平正交试验。建立了各影响因素与指标之间的回归数学模型，同时对模型进行了综合优化。获得最优参数组合为：入风角度37.95°、风速11.3m/s、曲柄角速度4.1r/s，对应的含杂率为0.87%、损失率为0.34%。对优化结果进行验证试验，试验结果表明在最优参数组合下，含杂率为0.89%、损失率为0.35%，各评价指标与其模型预测值的相对误差分别为2.29%和2.94%。

INTRODUCTION

Impurity rate and loss rate are two important indicators of the operational performance of corn seed harvesters, which directly reflect the technical level of the harvester *(Wang et al., 2018; Xu et al., 2019)*. The cleaning device is one of the core components of the corn grain harvester, and its operation effect directly affects the harvesting quality of the whole machine *(Hou et al., 2019)*, so scholars at home and abroad have conducted a lot of research on it.

To improve the efficiency of sieving grain mixtures with flat seeds, sieves with size activators, which have a riffle appearance, were proposed *(Kharchenko et al., 2019)*. Some scholars determined the influence of the deck gap on the distribution of thrashing mass between cleaning and straw walker, keeping the degree of grain crushing limited with GOST *(Alexey et al., 2019)*. Some scholars analyzed the movement state of corn in the airflow field and designed a stepped sieve *(Wang et al., 2020)*. The sieve was designed with a step buffer zone, which allows the seeds to be temporarily retained in the step so that the loss rate was greatly reduced. In addition, some scholars studied the clogging law of the sieve and determined the desorption force of the clogged corn cob shaft on the sieve through experiments *(Cheng et al., 2021)*. Some scholars built a test platform for cleaning based on the cleaning system of the CASE-4099 corn seed harvester. The test platform used a new type of vertical adjustable wind divider and simulation to optimize the operating performance of the cleaning device *(Li et al., 2020)*.

Some scholars presented a mathematical model that characterizes the process of threshing and separation from the threshing machine with an axial flow of a thresher *(Vlădut et al., 2022)*. This study provided a reference for the analysis of corn threshing and separation processes.

The above research provides an important theoretical basis for the design and optimization of the parameters of the cleaning device of the corn seed harvester. However, fewer studies have been conducted to analyze the mechanism of the operating process of the cleaning device of the corn seed harvester. This paper took the cleaning device of 4YZL-6 self-propelled corn seed harvester as a sample and analyzed the movement law of the material on the sieve. A mathematical model between the operating parameters of the cleaning device and the cleaning effect was established through experiments conducted by the Box-Behnken central combination design method. Finally, the optimal combination of the operating parameters of the cleaning device of the corn seed harvester was obtained by optimization. This study can provide a reference for the selection and optimization of parameters for the cleaning device of corn seed harvester.

MATERIALS AND METHODS

Structure and working principle

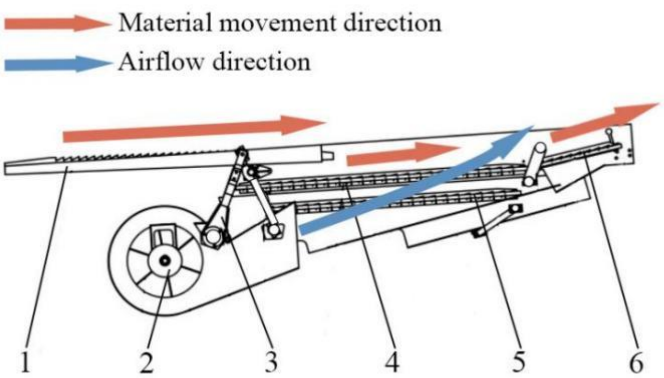


Fig. 1 – Structural diagram of the cleaning device

1.Shaking plate; 2. Centrifugal fan; 3. Crank-link mechanism; 4. Upper sieve；5. Lower sieve; 6. Tail Sieve

As shown in Fig. 1, the cleaning device of the corn seed harvester is mainly composed of shaking plate, centrifugal fan, crank-link mechanism, upper sieve, lower sieve, and tail sieve. In which, the shaking plate feeds the threshed material to the cleaning device by reciprocating motion. The role of the centrifugal fan is to provide the airflow required for clearing operation and to blow and transport the material during screening by using the difference in physical properties to accelerate the dispersion of the material on the sieve. The crank-link mechanism causes the sieve to perform a planar reciprocating motion, the function of which is to continuously throw and transport the material on the sieve backward. The upper sieve and the lower sieve make use of the size difference between the materials to make the seeds pass through the sieve while the miscellaneous residue is discharged from the tail sieve to realize the separation of corn seeds and miscellaneous residue.

Analysis of the operating mechanism of the cleaning device

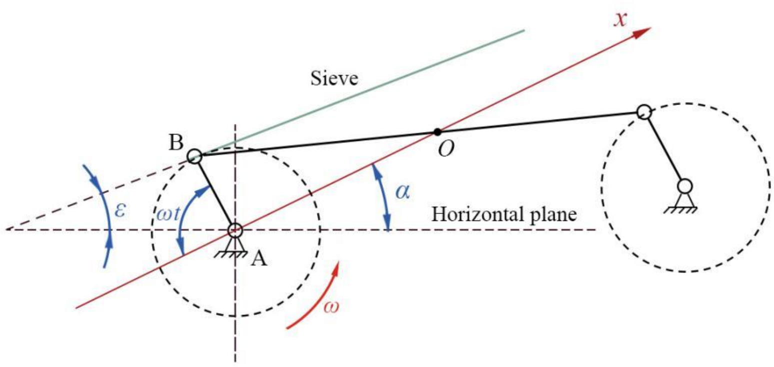


Fig. 2 – Analysis of sieve movement

The cleaning device takes advantage of the difference in suspension speed between corn kernels and redundant debris to achieve separation through high-speed airflow *(Tong et al., 2016; Hou et al., 2020)*. The separation process of the material is mainly carried out on the screen and therefore requires a detailed analysis of the movement process. In this study, the sieve is powered by a crank-link mechanism, and the schematic diagram of its motion is shown in Fig. 2. In the figure, the angle between the sieve and the horizontal plane is ε, the radius of the crank AB is r, and the angular velocity of the crank AB is ω. The crank *AB* rotation center *A* is the coordinate origin, the midpoint of the sieve is *O*. *AO* is the positive direction of the *x*-axis, and the angle between the *x*-axis and the horizontal plane is α. The length of the crank *AB* is much smaller than the length of the connecting rod, and the sieve is supported by a parallel four-bar mechanism, so the movement pattern of each point on the sieve is the same, which can be regarded as the reciprocating linear motion of the sieve along the *OB* direction *(Feng, 2022; Han, 2020)*.

Thus, the acceleration a at any point on the sieve can be represented as follows：

$$a = r\omega^2 \cos \omega t \tag{1}$$

As shown in Fig. 3, when the material is moving along the sieve, the forces acting on the material include the inertial force μ, gravity mg, the normal reaction force N of the sieve, the frictional force f and the airflow thrust P.

The inertial force μ is as follows:

$$\mu = mr\omega^2 \cos \omega t \tag{2}$$

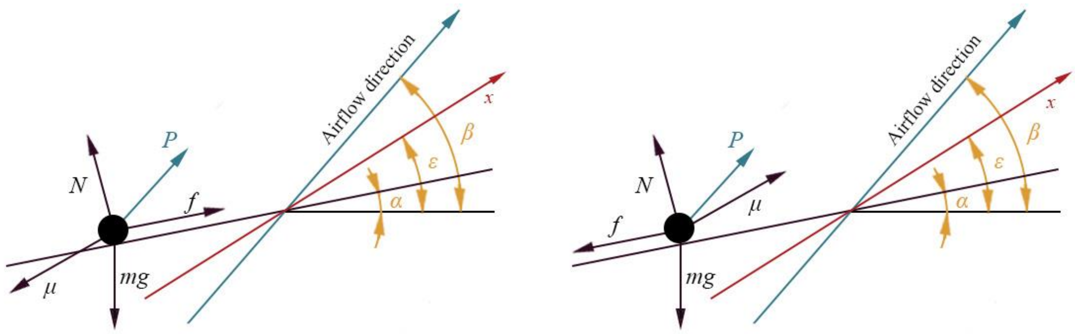
The frictional force f is as follows:

$$f = N \cdot tg\phi \tag{3}$$

According to the gas-solid two-phase flow separation theory *(Li et al., 2022; Ren et al., 2022)*, the airflow thrust P is as follows：

$$P = \frac{1}{2} CA\rho_s v_s^2 \tag{4}$$

Where, μ is the inertia force, N; m is the mass of the material, kg; f is the friction force, N; N is the normal reaction force of the sieve, N; φ is the friction angle between the material and the sieve, (°); P is the airflow thrust, N; C is the material resistance coefficient; A is the material windward area, m^2; ρ_s is the material density, kg/m^3; v_s is the airflow velocity, m/s.



(a) a＞0 **(b) a＜0**

Fig. 3 – Sketch of material movement

Material slides forward along the sieve

As shown in Fig. 3a, the material and the sieve surface move together, when ωt is in the interval from 0 to π/2 and 3 π/2 to 2π, the acceleration a is positive, the inertia force μ is negative, and the material has the tendency to slide forward along the sieve surface *(Wang, 2022)*. At this point, the material is subjected to the following forces:

$$\begin{cases} N = \mu \sin(\varepsilon - \alpha) + mg \cos\alpha - P\sin(\beta - \alpha) \\ f = \mu \cos(\varepsilon - \alpha) + mg \sin\alpha - P\cos(\beta - \alpha) \end{cases} \tag{5}$$

From Eqs. (2) to (5), it is obtained that:

$$mr\omega^2 \cos\omega t(\varepsilon - \alpha + \varphi) = mg \sin(\varphi - \alpha) + \frac{1}{2} CA\rho_s v_s^2 \cos(\beta - \alpha + \varphi) \tag{6}$$

The airflow thrust P is determined by the material resistance coefficient C, the windward area of materials A, the density of material ρ_s, and the airflow velocity v_s. So, for the convenience of expression, δ is taken as the adjustment coefficient, and the adjustment coefficient δ varies with the change of airflow thrust P and satisfies the following equation.

$$\frac{1}{2} CA\rho_s v_s^2 \cos(\beta - \alpha + \varphi) = (\delta - 1) mg \sin(\varphi - \alpha) \tag{7}$$

Substituting Equation (7) into Equation (6):

$$\frac{r\omega^2}{g} \cos\omega t = \frac{\delta \sin(\varphi - \alpha)}{\cos(\varepsilon - \alpha + \varphi)} \tag{8}$$

Since ωt is in the interval 0 to π/2 and 3π /2 to 2π, cosωt ≤1. Therefore, to make the material slide forward along the sieve, the following formula needs to be satisfied:

$$\frac{r\omega^2}{g} > \frac{\delta \sin(\varphi - \alpha)}{\cos(\varepsilon - \alpha + \varphi)} \tag{9}$$

Material slides backwards along the sieve

When ωt in π/2 ~ 3π/2 interval, the acceleration a is negative, the inertia force μ is positive, and the material has the tendency to slide backward along the sieve (as shown in Fig. 3b). By analogy with equations (5) to (9), the material has to meet the following to slide backward along the sieve.

$$\frac{r\omega^2}{g} > \frac{\delta \sin(\varphi + \alpha)}{\cos(\varepsilon - \alpha - \varphi)} \tag{10}$$

Material thrown off the sieve surface

In the cleaning operation, it is necessary to keep the seeds from leaving the sieve surface. The material is moving by inertia force, when the inertia force μ is along the positive direction of the x-axis, the acceleration a is negative, with the increase of $r\omega^2$, the normal reaction force N decreases, the material has the tendency to be thrown away from the sieve surface *(Si, 2017; Zheng, 2020)*. As shown in Fig.4, the sign of the material being thrown away from the sieve surface is N = 0.

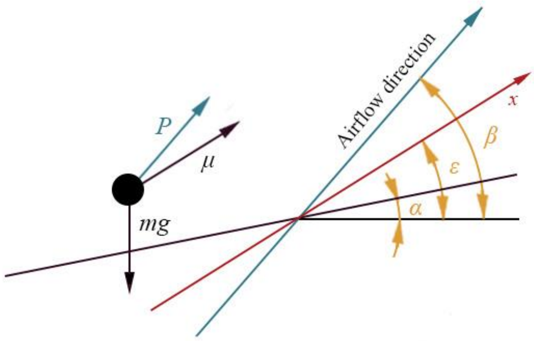


Fig. 4 – Sketch of material movement

At this time, the material is subjected to the following forces:

$$N = mg \cos\alpha - \mu \sin(\varepsilon - \alpha) - \frac{1}{2} CA\rho_s v_s^2 \sin(\beta - \alpha) \tag{11}$$

Taking θ as the adjustment coefficient, the adjustment coefficient θ varies with the airflow thrust P and satisfies the following equation:

$$\frac{1}{2}CA\rho_s v_s^2 \sin(\beta-\alpha)=(1-\theta)mg\sin\alpha \tag{12}$$

When the material is thrown away from the sieve, N = 0. The following equations can be obtained by analogy from equations (5) to (9).

$$\frac{r\omega^2}{g}>\frac{\theta\cos\alpha}{\sin(\varepsilon-\alpha)} \tag{13}$$

In order to make full use of the area of the sieve for separation, and make the corn seeds have more chances to fall into the sieve holes, it is necessary to ensure that the material slides up or down along the sieve, while the distance sliding down is greater than the distance sliding up, and is not thrown away from the sieve surface *(Chai et al, 2021; Mu et al, 2020)*.

The following formula needs to be satisfied:

$$\frac{\theta\cos\alpha}{\sin(\varepsilon-\alpha)}>\frac{r\omega^2}{g}>\frac{\delta\sin(\varphi-\alpha)}{\cos(\varepsilon-\alpha+\varphi)}>\frac{\delta\sin(\varphi+\alpha)}{\cos(\varepsilon-\alpha-\varphi)} \tag{14}$$

From the above analysis, the main factors affecting the effect of cleaning are the sieve and the centrifugal fan. Among them, the crank angular velocity affects the magnitude of the inertial and frictional forces. Airflow velocity and wind inlet angle affect the size of airflow resistance. The following orthogonal tests and response surface analysis were conducted on the effects of the three factors, wind inlet angle, airflow velocity and crank angular velocity, on the scavenging effect to determine the optimal combination of parameters.

Experimental design

Based on the analysis of the operating mechanism of the cleaning device of corn seed harvester, wind inlet angle A, airflow velocity B and crank angular velocity C were selected as the test factors. The experiment was conducted using Box-Behnken central combination design method with orthogonal test. The test factors and levels are shown in Table 1.

Table 1

Experimental factors and levels

levels	Factors		
	Wind inlet angle A	Airflow velocity B	Crank angular velocity C
	[°]	[m/s]	[r/s]
-1	30	8	4
0	40	12	6
1	50	16	8

As shown in Fig. 5, the test was conducted in Zibo City, Shandong Province, and the harvested corn variety was Zhengdan 958. The physical characteristics at harvest were as follows: the average moisture content of harvested seeds was 32.6%, the average moisture content of stalks was 91.2%, the average moisture content of fruit stalks was 52%, and the mass weight of 100 grains was 39-48 g.

Fig. 5 – Test site

As shown in Fig. 6, the test machine was 4YZL-6 self-propelled corn seed harvester, the size of the machine was 8800×4180×3850 mm, the rated power was 147 kW, and the number of harvested rows was 6. The implement forward speed was 2 km/h, and the flow of material was 60 kg/h. The maximum air volume of the fan of the cleaning device was 10 m^3/s. The amount of corn offcuts fed that the sieve can bear per unit area was 1.5~2.5 kg/(s·m^2). The cleaning device is shown in Fig. 7.

Fig. 6 – Self-propelled corn grain harvester

Fig. 7 – Cleaning device

The testing instruments include: tape measure, SN-DHS-20A intelligent moisture tester, electronic stopwatch, electronic balance, TEST0410-2 anemometer, Testo 465 optical tachometer and 3G3JZ-A4007 transducer. The test was conducted according to GB /T 21961-2008 *Test Methods for Corn Harvesting Machinery*. The speed of the harvester was 2.5 km/h during the test, and the average value was taken after each group of tests was repeated three times. Random samples were taken from the grain bins after the test, no less than 2000 g each time, and impurities were selected and weighed. The entire mixture was also collected in the assay area and the seeds were weighed according to the same method. Calculate the impurity rate Y_1 and loss rate Y_2 according to the following equation *(Chen et al. 2019; Geng et al., 2021)*.

Impurity rate Y_1:

$$Y_1 = \frac{w_1}{w_2 + w_1} \times 100\% \tag{15}$$

Loss rate Y_2:

$$Y_2 = \frac{w_3}{w_3 + w_4} \times 100\% \tag{16}$$

where, w_1 is the mass of impurities in the grain box sample, g; w_2 is the mass of seeds in the grain box sample, g; w_3 is the mass of seeds in the sample in the measurement area, g; w_4 is the mass of impurities in the sample in the measurement area, g.

RESULTS AND ANALYSIS

As shown in Table 2, the test protocol consisted of 17 sets of tests, and each set of tests was repeated three times to take the average value as the test results.

Table 2

The experiment results

Test number	Wind inlet [°]	Airflow velocity [m/s]	Crank angular [r/s]	Impurity rate %	Loss rate %
1	-1	-1	0	1.19	0.88
2	1	-1	0	1.31	0.73
3	-1	1	0	1.28	1.03
4	1	1	0	1.31	1.23
5	-1	0	-1	1.04	0.47
6	1	0	-1	1.27	0.49
7	-1	0	1	1.11	1.58
8	1	0	1	0.97	1.85
9	0	-1	-1	1.01	0.32
10	0	1	-1	1.05	0.67
11	0	-1	1	0.90	1.39
12	0	1	1	0.89	2.11
13	0	0	0	0.95	0.71
14	0	0	0	0.87	0.73
15	0	0	0	0.86	0.66
16	0	0	0	0.91	0.68
17	0	0	0	0.87	0.58

Analysis of variance

According to the test results in Table 2, ANOVA is performed on the impurity rate and loss rate. The non-significant items are excluded, and the results are shown in Table 3.

The regression equations of the impurity rate and loss rate are shown in Eqs. (17) to (18).

$$Y_1 = 0.89 + 0.03A - 0.063C - 0.093AC + 0.26A^2 + 0.12B^2 - 0.052C^2 \tag{17}$$

$$Y_2 = 0.67 + 0.22B + 0.62C + 0.095BC + 0.13A^2 + 0.16B^2 + 0.29C^2 \tag{18}$$

As can be seen from Table 3, the *P*-values for both the impurity rate and loss rate models were <0.01, indicating that the regression model was highly significant. Their coefficients of determination R^2 are 0.9848 and 0.9896, respectively, indicating that the changes in response values can be explained by models Y_1 and Y_2. The *P*-values of the model misfit terms for the impurity rate and loss rate were 0.8525 and 0.1561, respectively, which were greater than 0.05, indicating that the error generated by the test was small and the model was reasonable, and model Y_1 and Y_2 could be used to predict the trends of the impurity rate and loss rate.

Table 3

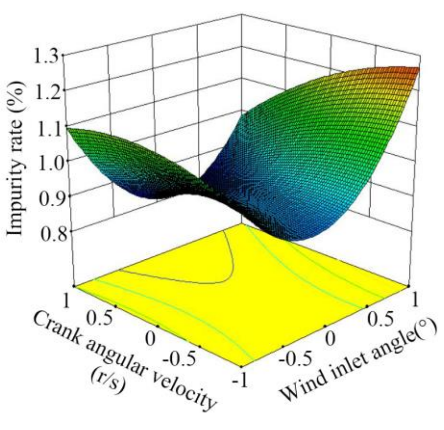
Variance analysis results of impurity removal rate

Source	Y_1					Y_2				
	Sum of Squares	DF	Mean Square	F Value	P Value	Sum of Squares	DF	Mean Square	F Value	P Value
Model	0.44	9	0.49	50.41	<0.0001	4.18	9	2.29	73.72	<0.0001
A	7.2×10^{-3}	1	7.2×10^{-3}	7.43	0.0295	0.041	1	0.041	2.29	0.1737
B	1.8×10^{-3}	1	1.8×10^{-3}	1.86	0.2150	0.37	1	0.37	59.38	0.0001
C	0.031	1	0.031	32.26	0.0008	3.11	1	3.11	493.99	<0.0001
AB	2×10^{-3}	1	2×10^{-3}	2.09	0.1914	0.031	1	0.031	4.86	0.0633
AC	0.34	1	0.34	35.34	0.0006	0.016	1	0.016	2.48	0.1593
BC	6.2×10^{-4}	1	6.2×10^{-4}	0.65	0.4482	0.036	1	0.036	5.73	0.0479
A^2	0.28	1	0.28	288.8	<0.0001	0.076	1	0.076	12.00	0.0105
B^2	0.063	1	0.063	65.50	<0.0001	0.11	1	0.11	17.43	0.0042
C^2	1.1×10^{-2}	1	1.1×10^{-2}	11.87	0.0108	0.36	1	0.36	56.78	0.0001
Residual	6.8×10^{-3}	7	9.7×10^{-3}			0.044	7	0.0063	3.03	
Lack of Fit	1.1×10^{-3}	3	3.7×10^{-3}	0.26	0.8525	0.031	3	0.010	73.72	0.1561
Pure Error	5.7×10^{-2}	4	1.42×10^{-3}			0.013	4	0.003		
Cor Total	0.45	16				4.22	16			

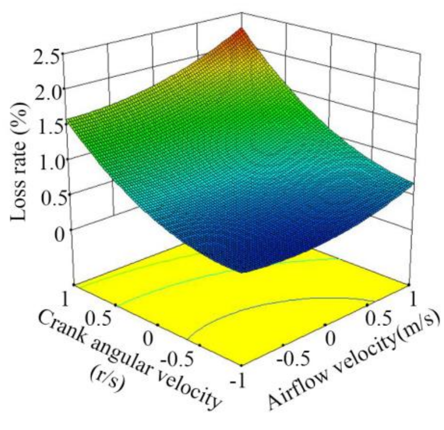
Note: P < 0.01 (extremely significant), 0.01 <P < 0.05 (significant).

Analysis of response Surface

From the analysis of variance of each index in Table 3, it can be seen that the interaction term that has a significant effect on the impurity rate is *AC*, and the interaction term that has a significant effect on the loss rate is *BC*, and the interaction of each factor is shown in Fig. 8.



(a) Y_1=(A, 0, C)



(b) Y_2=(0, B, C)

Fig. 8 – Response surface

Fig. 8a shows the effect of the interaction between the inlet wind angle and the crank angular velocity on the impurity rate when the wind velocity is fixed at 0 level. From the figure, it can be seen that the impurity rate decreases with the inlet wind angle and then rises rapidly. This is because when the inlet wind angle is too small, the angle between the airflow thrust and the sieve is too small, which will cause the debris to stick to the sieve surface, and it is difficult to blow the debris to the back of the sieve through the airflow. When the inlet wind angle is too large, the angle between the airflow thrust and the sieve is too small, which will cause the airflow to blow the debris upward. When the debris hits the shell of the cleaning device, the debris will fall back to the sieve surface and it is difficult to exclude the sieve from the device.

Fig. 8b shows the effect of the interaction between the airflow velocity and the crank angle velocity on the loss rate when the inlet wind angle is fixed at the 0 level. It can be seen from the figure that the loss rate increases with the increase of the crank angle velocity and the airflow velocity. This is because when the airflow velocity is larger, the airflow thrust is also larger and the corn kernels with slightly lighter mass will be thrown off the sieve surface. When the crank angle velocity is larger, the frequency of sieve vibration will be larger, and the corn seeds will be thrown away from the sieve surface more easily.

Parameter optimization and validation

To achieve the best harvesting performance of the scavenging unit, minimum impurity and loss rates are required. Parameter optimization was performed using Design-Expert 10.0 software with the objective function and the objective constraints and variable intervals shown in equation (19).

$$\begin{cases} \min\ y_1(A,B,C) \\ \min\ y_2(A,B,C) \\ \\ s.t.\begin{cases} 30° < A < 50° \\ 8m/s < B < 16m/s \\ 4r/s < C < 6r/s \end{cases} \end{cases} \tag{19}$$

The multi-objective optimization solution of each parameter was performed by Design-Expert10.0, and the optimized results were obtained as follows: the wind inlet angle was 37.95°, the airflow velocity was 11.3 m/s, the crank angular velocity was 4.1 r/s, corresponding to the impurity rate of 0.87% and loss rate of 0.34%.

Table 4

Test results of optimized parameter combination

Items	Impurity rate Y_1 /(%)	Loss rate Y_2 /(%)
Predicted value of model	0.87	0.34
Value of validation test	0.89	0.35
Relative error	2.29	2.94

To verify the accuracy of the model predictions of each indicator, a validation test was conducted in Zibo City, Shandong Province, in September 2022. The optimal combination of parameters obtained from the previous paper was used for the operational parameters, and three sets of parallel tests were designed, and the test results are shown in Table 4. Under the condition of optimal parameter combination, the impurity content of model verification test was 0.87% and the loss rate was 0.34%. The relative errors of each evaluation index and its model predicted value were 2.29% and 2.94%, which were less than 5%, and the parameter optimization results were reliable.

CONCLUSIONS

In this paper, the operating mechanism of the cleaning device of the corn seed harvester was studied. And the optimal operating parameters of the 4YZL-6 self-propelled corn seed harvester cleaning device were derived from the experiment. The specific conclusions drawn from this study are as follows:

1. The principle analysis of the cleaning operation and the force analysis of the operating process were carried out. The factors influencing the cleaning effect are the wind inlet angle, airflow velocity and crank angle velocity.

2. Field trials were conducted using the Box-Behnken test protocol. Wind inlet angle, airflow velocity and crank angle velocity were used as influencing factors, and impurity rate and loss rate were used as evaluation indicators. The optimization model of cleaning device parameters was established by ANOVA and response surface analysis, excluding the insignificant term. The optimal combination of parameters was obtained: the wind inlet angle was 37.95°, the airflow velocity was 11.3 m/s, and the crank angle velocity was 4.1 r/s. The corresponding impurity rate was 0.87% and loss rate was 0.34%.

3. Validation tests were conducted for the optimal parameter combinations. The results of the field validation tests were as follows: the impurity rate was 0.89% and the loss rate was 0.35%, and the relative errors of each index and the model predicted values were less than 5%.

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