Parameter matching and experiment of the combined cyclone separation and cylinder sieve cleaning system for rape combine harvester

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Abstract: Existing rape combine harvester with a cyclone separation cleaning device has the challenge that the loss rate and the cleaning rate increase and decrease simultaneously. A cleaning process route was proposed, which involves the cyclone separation cleaning device removing light and tiny impurities, and the cylinder sieve device removing coarse and long impurities such as pod shells and short stems. A novel cleaning system combining the cyclone separation cleaning device and cylinder sieve cleaning devices was designed. The ranges of the structure and operation parameters for each component were analyzed based on kinematics and dynamic analysis. A four-factor five-level quadratic orthogonal test was carried out, in which the loss rate and cleaning rate were taken as the evaluation indexes. The velocity at the suction port, the rotation speed of the cylinder sieve, the screw pitch of the spiral blade and the diameter of the sieve hole were taken as the influencing factors. The orthogonal test results showed that the cleaning system performed best at a rotation speed of the winnower is 600 r/min, an airflow velocity at the suction port is 18.25 m/s, a rotation speed of the cylinder sieve is 87 r/min, a screw pitch of the spiral blade is 440 mm and a diameter of the sieve hole is 4.48 mm. At this time, the loss rate of the cleaning system is 3.22%, and the cleaning rate is 95.67%. Compared to the conventional cyclone separation cleaning device, the loss rate is reduced by 2.17% and the cleaning rate is increased by 1.05%. This study can provide a reference for the optimal cleaning system design for rape combine harvesters.

Keywords: agricultural engineering, cleaning system, cyclone separation, cylinder sieve, rapeseed combine harvester
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1 Introduction

The existing rape combine harvester, which can complete the cutting, conveying, threshing, separation and cleaning at one time, has the characteristics of high mechanization and high efficiency. The cleaning system is crucial for a combine harvester, and its performance directly affects the quality of the combine harvester and subsequent storage and processing[1-3]. Currently, most rape combine harvesters are modified based on the wheat or rice combine harvesters. Mechanized rapeseed harvesting is realized by changing the screen and adjusting relevant parameters. However, these improved harvesters often suffer from a significant loss rate and a low cleaning rate[4,5]. Furthermore, 85% of the rapeseed planting area in China is located in the Yangtze River Basin. Most of the planting fields in this area are small plots of rice-oil rotation. Hence, the combine harvester needs to achieve the characteristics of compact structure and light weight. However, a combine harvester using the fan and vibrating screen has a large size and significant vibration[6]. It is essential to design a cleaning system that has a compact structure and excellent performance.

The cyclone separation cleaning device is a gas-solid two-phase separation device widely used in industry. It has the advantages of compact structure, slight vibration, easy adjustment and reliable operation. The research results show that the cyclone separation can be applied to small and medium-sized combine harvesters for rape, wheat, soybean and other crops[7-10]. Cyclone separation is effective in the cleaning operation of wheat, rice, and soybean, with a cleaning rate of up to 99% and a loss rate of less than 0.5%[11]. However, in rape cleaning using cyclone separation, the loss rate is generally greater than 5%, and the cleaning rate is lower than 94%. To improve the performance of cyclone separation, scholars researched the structure of the cyclone and the motion state of the threshing mixture in the cyclone[12-14]. Zhou et al.[15] designed a cyclone with an offset suction port and a cyclone separation system with a double grain elevator. Jin et al.[16] studied the influence of parameters on cleaning performance using high-speed photography. Ren et al.[17] established mathematical equations of motion for the structural parameters and trajectory parameters of the cyclone base on the theory of gas-solid two-phase flow. Huang et al.[18] analyzed the airflow field in the cyclone and the motion state between the material particles using the CFD-DEM coupling simulation method. Based on relevant research, the performance of the cyclone separation has been improved, but it still cannot meet the standard for rape combine harvester. This is because the components of rape threshed mixture include rapeseed, short stems, pod shells and light impurities. In rape cleaning, there is a specific cross interval between the suspension velocity of short stems and rapeseed. While ensuring a low loss rate, it is difficult to maintain a high

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cleaning rate.

A cylinder sieve has the advantages of simple structure, low vibration and noise, good wet separation performance and high reliability. Wu et al.[19,20] found that the cylinder sieve has good separation performance for the coarse and long stems in the threshing mixture. Meanwhile, Wan et al.[21,22] proposed a cleaning process route that combines the conical sieve and cyclone separation. During pre-screening, the screening efficiency is low due to many impurities in the threshing mixture. If the screening time is increased, the loss will be significant.

To address the problems, a cleaning process route is proposed, which involves using a cyclone separation device to remove light and tiny impurities from the threshed mixture, and a cylinder sieve cleaning device to screen the materials and remove coarse and long impurities. A cleaning system that combined cyclone separation and cylinder sieve has been designed. The parameters of the cyclone separation cleaning device and the cylinder sieve were determined based on the kinematics and dynamic analysis. The influence of critical parameters on the performance of the combined cyclone separation and cylinder sieve cleaning system, as well as the optimal parameter combination, was determined through a single-factor and quadratic orthogonal experiments. This study could provide a reference for improving the optimization of cleaning devices for rape combine harvesters.

2 Materials and methods

2.1 Main structure and working process of the combine harvester and cleaning system

The 4LYZ-4.0 rape combine harvester is a crawler-type combine harvester that is applied in Hilly and mountainous areas of China. The structure and parameters are presented in Figure 1 and Table 1. The combine harvester consists of a header, a shredding device, a longitudinal axial flow threshing and separation device, a cyclone separation cleaning device, a cylinder sieve device, a hydraulic system, a power chassis and other components.

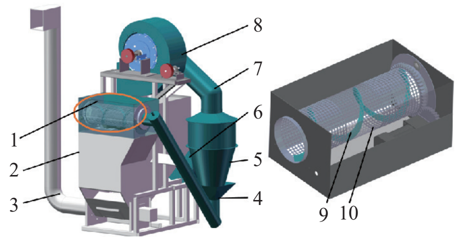
Figure 1 Overall structure of rape combine harvester

Table 1 Main parameters of rape combine harvester

Item	Parameters
Power/kW	72
Size (L×W×H)/(mm×mm×mm)	5000×2300×2800
Working width/mm	2000
Stubble height/mm	100-350
Feed rate/kg·s^{-1}	4.0

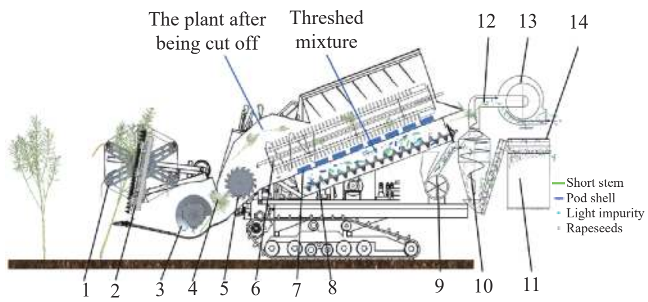
The structure of the combined cyclone separation and cylinder sieve cleaning system is shown in Figure 2. The cleaning system comprises a cyclone cleaning device and a cylinder sieve device. The cyclone cleaning device consists of a winnower, a cyclone, a fan, and a pipe. The cylinder sieve is primarily composed of a sieve with spiral blades.

The rapeseed plants are cut by the cutter and the reel, and transported to the shredding device by the re-cutting conveyor. The rape is further chopped by the shredding device under the forced conveying action of the auxiliary feeding roller, and the rape forms a material flow of 100-300 mm. The material is fed radially at the top to the longitudinal axial flow threshing and separating device by the throwing action of the shredding device. The longitudinal axial flow threshing and separation device threshes and separates the rape. The rape threshed mixture consisting of rapeseed, pod shells, short stems and light impurity is passed through the screen. The rape threshed mixture is thrown to the cyclone at a certain initial speed by the winnower. In the cyclone, most tiny and light impurities are separated from the fan outlet under the coercion of the rising airflow, while the rapeseed and a small number of impurities fall from the grain outlet. The material at the outlet is rapeseed containing impurities. The impurities mainly include long and coarse impurities such as pod shells and short stems. The rapeseed containing impurities is lifted by the conveying auger into the cylinder sieve located at the upper of the grain tank. During the rotation of the cylinder sieve, the spiral blade makes the material move axially, and the rapeseed falls into the grain tank through the sieve holes, while the impurities are separated. The working process of the combine harvester is shown in Figure 3.



1. Cylinder sieve 2. Tank 3. Grain unloading device 4. Conveying auger 5. Cyclone 6. Winnower 7. Pipe 8. Fan 9. Spiral blade 10. Sieve

Figure 2 Structure of the combined cyclone separation and cylinder sieve cleaning system



1. Reel 2. Cutting device 3. Re-cutting conveyor 4. Feeding roller 5. Shredding device 6. Longitudinal axial flow threshing drum 7. Concave sieve 8. Threshed mixture conveyor 9. Winnower 10. Cyclone 11. Grain tank 12. Pipe 13. Fan 14. Cylinder sieve

Figure 3 Schematic diagram of working process for rape combine harvester

2.2 Main parameters of cleaning system

The feeding rate is the key parameter of the combine harvester, and the feed rate of the combine harvester is 4 kg/s. The harvest index refers to the ratio of the dry matter mass of the economic yield to the dry matter mass of the biological yield when the crop is harvested, the feeding rate of the combine harvester is related to its size. The average harvest index value of rape grown in China is 25%[23]. The rape and rapeseed moisture content during the harvest period is about 70% and 40%, respectively. The comprehensive calculation shows that the rapeseed account for 14.30% of the overall biomass during the harvest period. The rapeseed generation rate was 0.57 kg/s while the feeding rate of the combine harvester was 4 kg/s. The pre-test showed that the rapeseed accounted for about 50% of the total mass of the rape threshed mixture, the generation rate of the rape threshed mixture was 1.14 kg/s[24].

2.2.1 Cyclone separation cleaning device

The cyclone separation cleaning device primarily utilizes the disparity in suspension velocities among each component of the rape threshed mixture. The winnower conveys materials by throwing them through the rotating impeller blade. The production efficiency Q_y should exceed the feeding rate of the rape threshed mixture. The rotation speed of the winnower n_y must not be lower than 585.62 r/min, as calculated by Equation (1)[25]. The diameter of the winnower was 0.35 m.

$$Q_y = 30 n_y m_y \gamma \eta a_y^2 b_y \tan\varphi / 3600 \geq 1.14 \text{ kg/s} \tag{1}$$

where, a_y is the height of impeller blade, the value was 0.10 m; b_y is the width of the impeller blade, the value was 0.06 m; m_y is the number of the impeller blades, the value was 6; γ is the volumetric mass of material, the value was 360 kg/m^3; η is the efficiency coefficient, the value was 0.3; φ is the natural rest angle, the value was 31°.

The rape threshed mixture is composed of rapeseed, pod shells, short stems and light impurities. The suspension velocity of rapeseed, pod shells, short stems and light impurities are 7.4-9.4 m/s, 2.4-3.2 m/s, 6.3-11.2 m/s, and 1.1-3.2 m/s, respectively[26]. There is a crossover interval between the suspension velocity of the short stem and rapeseed. Therefore, the cyclone separation is difficult to screen the impurities in the rape threshing mixture at one time. The cyclone separation device is mainly used to remove the light and tiny impurities in the rape threshed mixture. The light and tiny impurities are pod shells and light impurities. The pod shells account for about 26% of the rape threshing mixture, and the light impurities account for about 10% of the rape threshing mixture. The mass of the light and tiny impurities accounts for 36% of the rape threshing mixture. The short stems account for about 14% of the rape threshing mixture[24].

The cyclone comprises an upper cone section, a lower cone section and a middle straight cylinder section. Bolts connect the three sections tightly, and the middle connecting part is sealed with a rubber gasket. The upper cone section is connected to the fan through the pipe, the middle straight cylinder section is connected to the winnower and the lower cone section is connected to the grain lifting auger. The cyclone separation cleaning device is designed to remove 40% of the impurities from the rape threshing mixture. The structural parameters of the cyclone are closely related to the feeding rate. It is clear that the feeding rate of the cyclone is 1.14 kg/s. The impurities separation rate Q_z of the cyclone separation cleaning device is 0.456 kg/s. The minimum air volume V_0=0.543 m^3/s is calculated by Equation (2)[25].

$$V_0 = Q_z / \mu\rho \tag{2}$$

where, V_0 is the minimum air volume, m^3/s; ρ is the density of air, here ρ = 1.2 kg/m^3; μ is the mixing concentration ratio of impurity-carrying airflow, here μ = 0.7.

To ensure that the impurities can be smoothly removed, the airflow velocity at the suction port shall be greater than the maximum suspension velocity of the impurity. Therefore, the airflow velocity at the suction port v_x shall be at least 11.2 m/s. Taking into account the enhancement in airflow velocity resulting from the reduction in diameter at the suction port in comparison to the straight section. The airflow velocity v_x at the suction port is calculated as 17 m/s. The diameter of the suction port D_x=0.202 m is calculated by Equation (3). Considering the connection between the suction port and the pipe, the inner diameter of the pipe D_p is taken as 0.2 m, and the wall thickness of the cyclone is taken as 2 mm. Thus, the diameter of the suction port D_x is 0.196 m.

$$D_x = \sqrt{\frac{4V_0}{\pi v_x}} \tag{3}$$

The airflow field in the cyclone is divided into the upward airflow in the central column area and the spiral downward airflow at the periphery. The upward airflow velocity in the central column area needs to be greater than the suspension velocity of light and tiny impurities, but less than the rapeseed suspension velocity to avoid the rapeseed being carried away. Thus, the value of upward airflow velocity v_n of the central column area should be less than 7.4 m/s, and v_n=7 m/s is used for calculation. The velocity of spiral downward airflow at the periphery needs to be greater than the suspension velocity of the light and tiny impurities. Thus, the spiral downward airflow velocity v_w at the periphery should be greater than 3.2 m/s, and v_w=3.3 m/s is used for calculation. The diameter of the middle straight cylinder D_z=0.408 m is calculated by Equation (4). The value of D_z is 0.41 m.

$$D_z = \sqrt{\frac{V_0 - \frac{\pi}{4} D_x^2 (v_n - v_w)}{\frac{\pi}{4} v_w}} \tag{4}$$

The airflow enters the cyclone through the grain outlet and feed inlet. The airflow volume through the grain outlet V_c and the feed inlet V_j should be equal to V_0.

$$\begin{cases} V_0 = V_c + V_p \\ V_c = 0.25 v_c \pi D_c^2 \\ V_j = abv_j \end{cases} \tag{5}$$

where, V_c is the airflow volume through the grain outlet, m^3/s; v_c is the airflow velocity at the grain outlet, m/s; V_p is the airflow volume through the feed inlet, m^3/s; D_c is the diameter of grain outlet, m; a is the height of the feed inlet, here a = 0.15 m; b is the width of the feed inlet, here b = 0.15 m; v_j is the airflow velocity at grain feed inlet, m/s. When the rotating speed of the winnower is 580-780 r/min and the airflow velocity at the suction port is 0 m/s. Measured by an anemometer, the airflow velocity at the grain feed inlet is 4.6-6.8 m/s. Considering that the airflow field in the cyclone separator is influenced by the velocity of the inlet airflow, the value v_j is taken as 7 m/s for calculation.

The airflow velocity at the grain outlet should be greater than the suspension velocity of tiny and light impurities and less than the suspension velocity of rapeseed. Thus, the airflow velocity at the grain outlet can be 7 m/s. Since the cross-sectional area of airflow decreases, the airflow velocity increases sharply at the grain outlet. The airflow velocity at the grain outlet v_c is selected as 10 m/s. D_c=0.222 m is calculated by Equation (5). The value of D_c is 0.22 m.

The total pressure of the fan p_a includes the dynamic pressure in the pipe p_d, static pressure in the pipe p_j, the localized pressure loss p_f and the cyclonic pressure loss p_x in the cyclone[27].

$$p_a = p_d + p_j + p_f + p_x \tag{6}$$

The pipe is connected to the suction port. Thus, the diameter of the pipe D_p is 200 mm. The airflow velocity at the pipe v_g=17.28 m/s, and the dynamic pressure in the pipe p_d=179.16 Pa was calculated by Equation (7).

$$\begin{cases} v_g = \dfrac{4V_0}{\pi D_p^2} \\ p_d = 0.5\rho v_g^2 \end{cases} \tag{7}$$

The static pressure in the pipe p_j=931.63 Pa was calculated by Equation (8).

$$\begin{cases} p_j = p_{j1} + p_{j2} + p_{j3} = 9.81\left(\dfrac{\xi l \rho v_g^2}{2\gamma g} + \dfrac{\psi \rho v_g^2}{2g} + \dfrac{\lambda \rho v_g^2}{2g}\right) \\ \psi = 3\left[0.131 + 0.163\left(D_p/R\right)^{3.5}\right]\dfrac{\theta}{90} \end{cases} \tag{8}$$

where, p_{j1} is the pressure loss throughout the pipe, Pa; p_{j2} is the local pressure loss, Pa; p_{j3} is the pressure loss of inlet and outlet, Pa; ξ is the coefficient of airflow friction, the value is 0.25; l is the length of the pipe, the value is 1.5 m; γ is the hydraulic diameter, the value is 0.20 m; ψ is the resistance coefficient of the pipeline to airflow; λ is the resistance coefficient of the outlet and inlet to airflow, the value is 0.6; R is the radius of the pipe corner, the value is 0.128 m; θ is the angle of the pipe corner, the value is 90°.

The value of cyclonic pressure loss p_x=199.69 Pa was calculated by Equation (9).

$$\begin{cases} \dfrac{2p_x}{\rho v_p^2} = 1 + 2q^2\left[\dfrac{2(D_z - b)}{D_x} - 1\right] + 2\left(\dfrac{4ab}{\pi D_x^2}\right)^2 \\ q = \dfrac{-\left[\dfrac{D_x}{2(D_z - b)}\right]^{0.5} + \left[\dfrac{D_x}{2(D_z - b)} + \dfrac{4A_R G}{ab}\right]^{0.5}}{2A_R G/(ab)} \end{cases} \tag{9}$$

where, v_p is the airflow velocity at the cyclone inlet, m/s. After determining the structural parameters of the cyclone, when the airflow velocity at the suction port is 17.28 m/s, the rotating speed of winnower is the 580-780 r/min. Measured by an anemometer, the airflow velocity at the inlet of the cyclone is 6.50-8.50 m/s. The airflow velocity at the inlet of the cyclone separator is calculated as 7.00 m/s; A_R is the area of cyclone separation cylinder inner wall, the value is 0.85 m^2; G is the inner wall friction coefficient of the cyclone, the value is 0.005.

The cyclone is a multi-sectional combination type with different diameters in different sections. There are pressure losses in the airflow entering different sections. The structure and parameters of the cyclone separator are shown in Figure 4. There is a gradual expansion pressure loss p_{f1} and a tapering pressure loss p_{f2}. Bernoulli's equation gives the gradual expansion pressure loss of the airflow p_{f1} through plane 1.

$$\begin{cases} p_{f1} = k\left[A_1/\left(0.25\pi D_c^2\right) - 1\right]^2 \dfrac{\rho v_1^2}{2g} \\ k = 1.025 + 2.5\left(\dfrac{D_1}{D_c}\right)^2 \times 10^{-3} + 0.8D_c \times 10^{-3} \\ v_1 = \dfrac{4V_c}{\pi D_z^2} \end{cases} \tag{10}$$

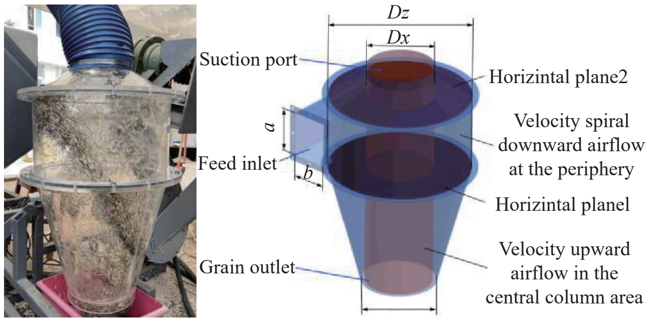
where, A_1 is the area of plane 1.

The value p_{f1}=4.32 Pa was calculated by Equation (10). Similarly, the tapering pressure loss p_{f2}=14.06 Pa can be obtained by Equation (11).

$$\begin{cases} p_{f2} = k\left[A_2/\left(0.25\pi D_x^2\right) - 1\right]^2 \dfrac{\rho v_2^2}{2g} \\ k = 1.025 + 2.5\left(\dfrac{D_z}{D_x}\right)^2 \times 10^{-3} + 0.8D_x \times 10^{-3} \\ v_2 = \dfrac{4V_0}{\pi D_z^2} \end{cases} \tag{11}$$

where, A_2 is the area of plane 2.

Therefore, the total pressure p_a is 1328.86 Pa. The airflow volume is 1954.80 m^3/s.

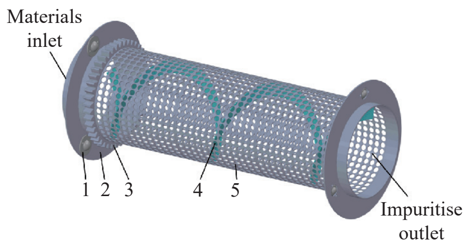


Note: a is the height of thefeed inlet, m; b is the width of the feed inlet, m; D_z is the diameterof the middle straight cylinder, m; D_x is the diameter of the suction port, m.

Figure 4 Structure and physical picture of the cyclone separator

2.2.2 Cylinder sieve cleaning device

The cylinder sieve is a cylindrical component with holes on the surface and a spiral blade on the inner wall. One end of the cylinder sieve is connected to the outlet of the grain lifter, and the other end is the impurities outlet. The cylinder sieve device is hung and fixed onto the grain tank. The retaining ring with the universal ball on the cylinder sieve realizes the axial fixation of the sieve. The universal ball can reduce the dry friction during the rotary motion of the cylinder sieve. The structural diagram of cylinder sieve assembly is shown in Figure 5.



1. Universal ball 2. Axial fixed retaining ring 3. Drive gear 4. Spiral blade 5. Sieve

Figure 5 Structural diagram of cylinder sieve assembly

Considering the size of the cleaning system and the requirement of the cylinder sieve. The diameter of the cylinder sieve D_g is determined as 200 mm. Furthermore, it is generally recommended to maintain a length-to-diameter ratio of 2-5 for the cylinder sieve[28]. In this study, the ratio value is 3, and the length of cylinder sieve L is 600 mm. The rapeseed is nearly spherical. The cylinder sieve uses circular holes. The diameter of rapeseed was distributed between 1.42 mm and 2.96 mm. The diameter of the sieve hole D_k should be greater than 3 mm. In addition, the sieving curve of rapeseed containing impurities was determined by sieving pre-test, and the results showed that the sieving effect was poor when the sieve hole was more significant than 7 mm. The size of the sieve hole is selected at 3-7 mm.

The rotation speed of the cylinder sieve has a significantly impact on the quality of sieving, as it affects the movement of materials in different states. When the material movement state is shown in Figure 6, the material in the sieve alternates repeatedly from the inner layer to the outer layer. The movement of the materials reaches turbulent condition, which is conducive to the process of seed permeability sieve[29].

In this condition, the force of the material in the sieve is analyzed. Without taking into account the material interaction, the material in the cylinder is simplified to one point. The material in the cylinder sieve is mainly subjected to gravity, friction force, support force and centrifugal force. Figure 6 depicts the forces on the material inside the cylindrical sieve in the vertical axis plane. The material is lifted to point A and thrown out to produce a cascades phenomenon. At this time, the centrifugal force is equal to the gravity and the radial force. When the material moves to point B, the rotation speed of the cylinder sieve is the maximum critical rotation speed. The angle θ between gravity and support force is 0, and the inner wall of the drum support force on the material is 0.

$$\begin{cases} m_z r\omega^2 \leq m_z g\cos\theta \\ \omega = 2\pi n/60 \end{cases} \tag{12}$$

where, ω is the angular velocity of cylinder sieve, rad/s; m_z is the quality of materials; r is the radius of the cylinder sieve, m; n is the rotation speed of cylinder sieve, r/min (n≤94.58 r/min).

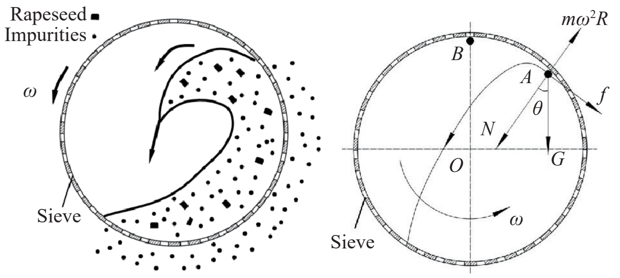


Figure 6 Movement state of materials in cylinder sieve and mechanical analysis of materials

The spiral blade can transport material to avoid blockage. The conveying efficiency Q_g should satisfy the following Equation (13).

$$Q_g = 47D_g^2 t_g n\psi\gamma C \geq 2.67\ \text{t/h} \tag{13}$$

where, t_g is the screw pitch of the spiral blade, m; C is the inclined conveying coefficient, the value is 1; ψ is the filling coefficient, the value is 0.35; γ is the volume mass of rapeseed containing impurities[30], 0.86 t/m³.

The minimum value of the screw pitch of the spiral blade is $0.8D_g$[25]. The minimum rotation speed of the cylinder sieve is 29.49 r/min. The rotation speed range is 29.49-94.58 r/min.

The cylinder sieve is horizontally installed. The spiral blades are responsible for move the material axially. The screw pitch of the spiral blades must meet the requirements for conveying and separating performance. To meet the separation performance requirements, it is essential to ensure that the rapeseed center of gravity moves promptly below the sieve surface as they move on the sieve. It means that the time t_2 required to move a sieve hole is greater than the time t_1 required for the rapeseed center of gravity to move below the inner plane of the sieve. The trajectory of rapeseed in the sieve is shown in Figure 7.

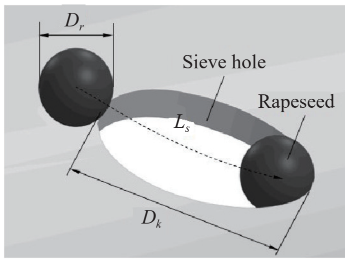
$$\begin{cases} t_1 \leq t_2 \\ L_s = V_a t_2 \\ D_r = g t_1^2 \\ V_a = \sqrt{V_z^2 + V_t^2} \end{cases} \tag{14}$$

where, L_s is the actual distance that the rapeseed move within the sieve by one sieve hole length, m; V_a is the actual movement speed of rapeseed, m/s; D_r is the diameter of the rapeseed, m; V_z is the axial velocity of material, m/s; V_t is the circumferential velocity of matierial, m/s.

According to the kinematic analysis of the material on the spiral blade, the actual velocity of material V_a can be decomposed into axial velocity V_z and circumferential velocity V_t[31].

$$\begin{cases} V_t = \dfrac{t_g n\left(\dfrac{t_g}{2\pi r} + \mu\right)}{60\left[1 + \left(\dfrac{t_g}{2\pi r}\right)^2\right]} \\ V_z = \dfrac{t_g n\left(1 - \mu\dfrac{t_g}{2\pi r}\right)}{60\left[1 + \left(\dfrac{t_g}{2\pi r}\right)^2\right]} \end{cases} \tag{15}$$

where, μ is the friction coefficient between material and the spiral blade, the value is 0.5.



Note: D_r is the diameter of the rapeseed, m; L_s is the actual distance that the rapeseed move within the sieve by one sieve hole length, m; D_k is the diameter of the sieve hole, m.

Figure 7 Trajectory of rapeseed on the cylinder sieve

The time for the rapeseed to move distance L_s on the sieve needs to be greater than the time for the rapeseed to move the radius of rapeseed r_z in the radial direction along with the sieve. When the rotation speed of the cylinder sieve and the diameter of the sieve hole is the smallest, the screw pitch of the spiral blade can take the maximum value. The screw pitch of the spiral blade t_g should be smaller than 440 mm as calculated by Equations (14) and (15). In summary, the value of screw pitch of spiral blades t_g is 160-440 mm.

2.2.3 Bench test

A bench test is conducted on a key components test bench for a combine harvester to clarify the impact of parameters on cleaning performance and identify the optimal parameters. The test bench includes a console, a conveyor belt, a header, a threshing and separation device, a cyclone cleaning device, a cylinder sieve, a control detection system and a high-speed photography, as shown in Figure 8. The parameters of test bench can be adjusted through the console, the operating parameters can be monitored online, and the high-speed photography can be used to observe the material movement track in the threshing and cleaning system.

The material used in the experiment was Huayouza 62 planted by the rapeseed direct seeder. The rape was re-hydrated before the test. The moisture content is 60%-70%. The indexes used to evaluate the cleaning system for the rape combine harvester are the loss rate η_1 and the cleaning rate η_2. The mass of rapeseed under the cylinder sieve is m_1, the mass of rapeseed in the outlet of the fan is m_2, the mass of rapeseed in the outlet of the cylinder sieve is m_3 and the mass of impurities under the cylinder sieve is m_4.

$$\begin{cases} \eta_1 = \dfrac{m_2 + m_3}{m_1 + m_2 + m_3} \\ \eta_2 = \dfrac{m_4}{m_1 + m_4} \end{cases} \tag{16}$$

Factors affecting the performance of the cleaning system include the rotation speed of the winnower, the airflow velocity at the suction port, the rotation speed of the cylinder sieve, the screw pitch of the spiral blade and the diameter of the sieve hole. The rotation speed of the winnower impacts the initial velocity of the material entering the cyclone and the airflow volume at the inlet, thereby influencing the performance of the cyclone. Based on the calculation results, the rotational speed of the winnower should be more significant than 585.62 r/min. The relevant results show that a higher rotational speed can easily cause a sizeable centrifugal force on the materials. The materials are difficult to get close to the high-speed airflow area, resulting in a low cleaning rate[9]. When the rotating speed of the winnower is 500-700 r/min, the cleaning performance is optimal. Therefore, when the rotating speed of the winnower is 585-700 r/min, the initial velocity of the material entering the cyclone and the inlet airflow volume change slightly. The rotating speed of the winnower was selected as 600 r/min for subsequent tests.

The airflow velocity at the suction port A, the rotation speed of the cylinder sieve B, the pitch of the spiral blade C and the diameter of the sieve hole D were taken as factors. The range of each factors are 13-21 mm, 30-94 r/min, 160-440 mm, and 3-7 mm, respectively. A single factor text determined the range of levels for each factor in a four-factor five-level quadratic orthogonal test, and the impact of each factor on the evaluation index was also clarified. The optimal combined parameters were determined based on the results of the quadratic orthogonal test. Each experiment was performed 3 times.

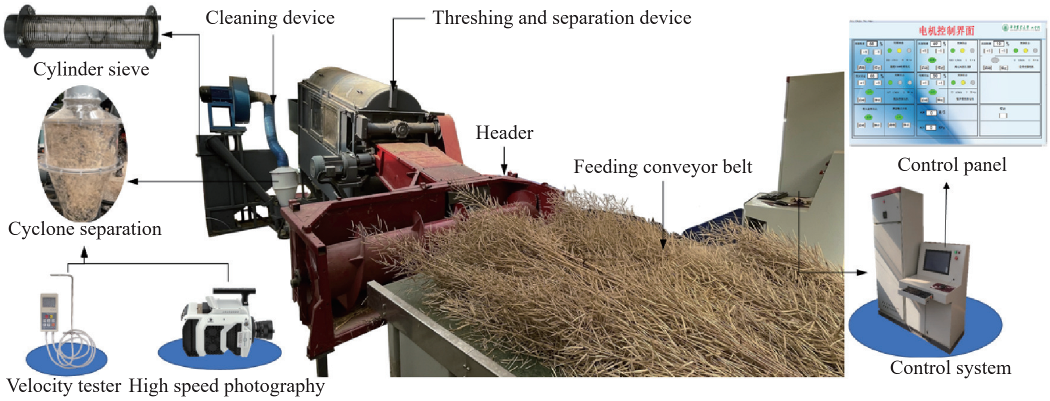


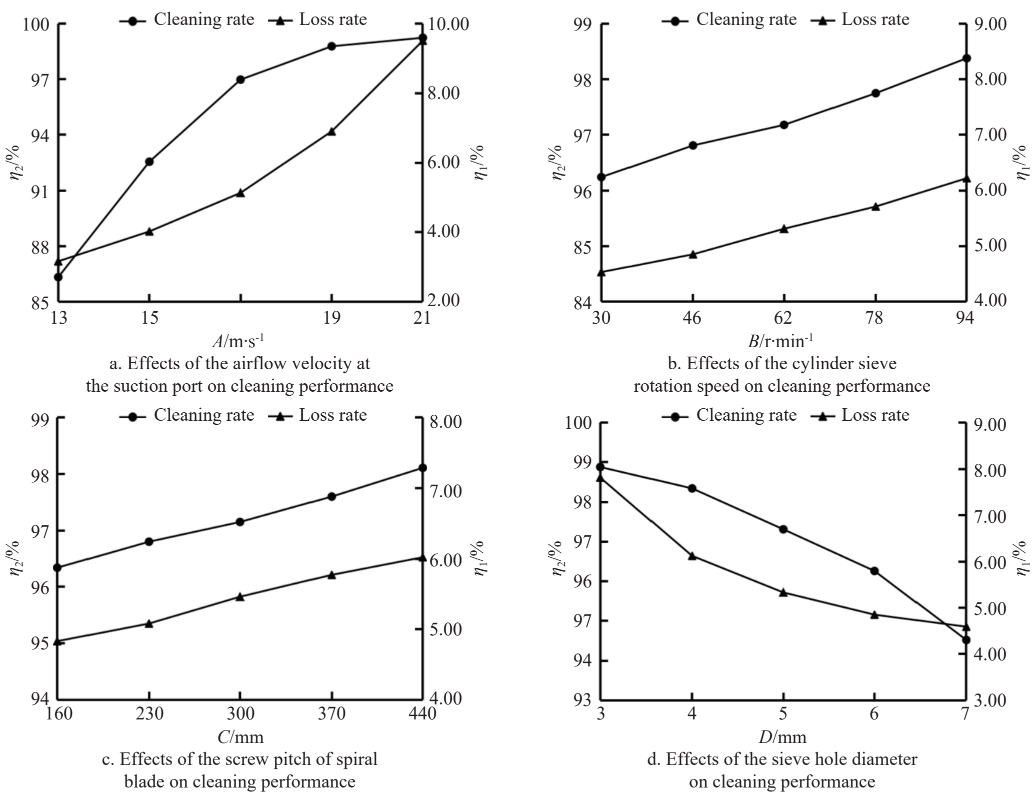
Figure 8 Key components test bench for combine harvester

3 Results and discussion

3.1 Effect of parameters on the cleaning system

3.1.1 The airflow velocity at the suction port

The airflow velocity at the suction port is a critical parameter of the cyclone separation cleaning device, which significantly impacts the airflow field in the cyclone. As the airflow velocity at the suction port increases, the loss rate caused by cyclone cleaning gradually increases. When the airflow velocity at the suction port exceeds 19 m/s, the loss rate increases sharply because the updraft velocity in the cyclone exceeds the rapeseed suspension velocity. The cleaning rate gradually increases with the airflow velocity at the suction port. In addition, when the airflow velocity at the suction port is 13-15 m/s, the loss rate of the cyclone separation is low. However, the ability of the cyclone to separate light and tiny impurities is weak, which results in a large workload on the cylinder sieve cleaning device. As a result, the cleaning rate of the combined cleaning system is low. The influence of the airflow velocity at the suction port on the cleaning system is shown in Figure 9a.



a. Effects of the airflow velocity at the suction port on cleaning performance

b. Effects of the cylinder sieve rotation speed on cleaning performance

c. Effects of the screw pitch of spiral blade on cleaning performance

d. Effects of the sieve hole diameter on cleaning performance

Figure 9 Influences of various factors on the loss rate η_1 and cleaning rate η_2

3.1.2 Rotation speed of the cylinder sieve

The cleaning rate and loss rates of the cleaning system demonstrate an upward trend with an increase in the rotation speed of the cylinder sieve. With an increase in the rotation speed of the cylinder sieve, the axial conveying speed of the material accelerates. This acceleration leads to insufficient time for the rapeseed to pass through the sieve, resulting in an elevated loss rate. Simultaneously, the size of impurities is larger than the rapeseed, the screening probability of impurities is smaller than rapeseed. Thus, the cleaning rate is also increase. When the rotation speed of the cylinder sieve is low, the axial movement speed of the material decreases, this leads to an increase in the material's retention time within the cylinder sieve, resulting in a higher probability of both rapeseed and impurities being screened. At this time, the loss rate and the cleaning rate of the cylinder sieve gradually decreases.

3.1.3 The screw pitch of the spiral blade

The cleaning rate and loss rate exhibit an upward trend with an increase in the screw pitch of the spiral blade. This result is similar to the effect of increasing the rotating speed of the cylinder sieve. The main reason for this is that the axial speed of the material increases with the increase of the screw pitch of the spiral blade, which affects the residence time.

3.1.4 Diameter of the sieve hole

As the size of the sieve holes increases, the cleaning rate and loss rate gradually decrease. This is because as the sieve holes become larger, the probability of rapeseed and impurities passing through the screen increases.

3.2 The optimal parameter combination of the cleaning system

The quadratic orthogonal test was conducted to determine the optimal parameter combination. The levels of the factors and results are listed in Tables 2 and 3. The loss rate η_1 and the cleaning rate η_2 were chosen as the evaluation indexes.

Table 2 Factors and levels of experiment

Levels	Factors			
	A/m·s^{-1}	B/r·min^{-1}	C/mm	D/mm
Upper asterisk arm (2)	13	30	160	3
Upper level (1)	15	46	230	4
Zero level (0)	17	62	300	5
Lower level (–1)	19	78	370	6
Lower asterisk arm (–2)	21	94	440	7

According to the analysis of the variance of the loss rate η_1 in Table 4, the primary and secondary order of the influence of factors, as well as their interaction on the loss rate, can be determined by examining the intersection of factors. The order of influence is as follows: D, A, B, C, D^2, AB, AC, BC, and A^2. The effects are extremely significant (p<0.01) and other factors are not significant (p>0.05). Furthermore, the lack of fit (p=0.1517), which is also not significant, proves that no other factors are affecting the test index. The test results were analyzed by using Design-expert 8.6. Multiple regression fitting is performed for each test index and the insignificant factors are eliminated. The regression equation of each factor level on the loss rate was obtained.

$$\eta_1 = 12.550 - 0.595A + 0.064B + 0.016C - 1.614D - 0.009AB - 0.002AC + 0.0002BC + 0.038A^2 + 0.263D^2 \quad (17)$$

According to the analysis of the variance of the cleaning rate η_2 in Table 5, the primary and secondary order of the influence of factors, as well as their interaction on the cleaning rate, can be determined by examining the intersection of factors. The order of influence is as follows: A, D, A^2, B, C, D^2, BC, AB, and AC. The effects are highly significant (p<0.01), and other factors are not significant (p>0.05). The lack of fit (p=0.0816), which is also not significant, proves that no other factors are affecting the test index. The test results are analyzed by using Design-expert 8.6. Multiple regression fitting is performed for each test index, and the insignificant factors are eliminated. The regression equation of each factor level on the cleaning rate was obtained.

$$\eta_2 = 83.83 + 2.280A - 0.220B - 0.0466C + 3.598D + 0.007AB + 0.001AC + 0.0003BC - 0.130A^2 - 0.272D^2 \quad (18)$$

To determine the optimal parameters for the combined cyclone separation and cylinder sieve cleaning system, the two regression models are solved using the optimization module in Design-Expert 8.6. The parameter optimization equation and constraints are shown in Equation (18).

$$\begin{cases} \min \eta_1(A,B,C,D) \\ \max \eta_2(A,B,C,D) \\ 13 \le A \le 21 \\ 30 \le B \le 94 \\ 160 \le C \le 440 \\ 3 \le D \le 7 \end{cases} \quad (19)$$

Table 3 Results of quadratic orthogonal test

Text	Experiment factors				Response index	
	A	B	C	D	η_1	η_2
1	–1	–1	–1	–1	6.23	98.25
2	1	–1	–1	–1	5.85	94.66
3	–1	1	–1	–1	5.38	96.25
4	1	1	–1	–1	3.85	93.5
5	–1	–1	1	–1	5.64	96.49
6	1	–1	1	–1	4.03	93.63
7	–1	1	1	–1	5.32	95.73
8	1	1	1	–1	2.83	93.78
9	–1	–1	–1	1	8.52	99.76
10	1	–1	–1	1	7.92	96.5
11	–1	1	–1	1	7.70	98.12
12	1	1	–1	1	5.91	95.21
13	–1	–1	1	1	7.82	98.33
14	1	–1	1	1	6.23	95.5
15	–1	1	1	1	7.82	97.29
16	1	1	1	1	5.09	95.72
17	–2	0	0	0	7.00	98.88
18	2	0	0	0	4.32	92.05
19	0	–2	0	0	6.15	98.32
20	0	2	0	0	4.48	96.21
21	0	0	–2	0	5.83	98.02
22	0	0	2	0	4.82	96.37
23	0	0	0	–2	4.49	94.72
24	0	0	0	2	7.71	98.18
25	0	0	0	0	5.62	97.45
26	0	0	0	0	5.48	97.11
27	0	0	0	0	5.55	97.36
28	0	0	0	0	5.12	97.2
29	0	0	0	0	5.47	97.39
30	0	0	0	0	5.05	96.92
31	0	0	0	0	5.29	97.43
32	0	0	0	0	5.59	97.12
33	0	0	0	0	5.03	97.64
34	0	0	0	0	4.95	96.97
35	0	0	0	0	5.68	96.92
36	0	0	0	0	5.03	97.56

According to the results of Equation (18), the combined cyclone separation and cylinder sieve cleaning system performs better when the rotation speed of the winnower is 600 r/min, the airflow velocity at the suction port is 18.25 m/s, the rotation speed of the cylinder sieve is 87 r/min, the screw pitch of the spiral blade is 440 mm and the diameter of the sieve hole is 4.48 mm. The performance of the combined cyclone separation and cylinder sieve cleaning system is better. Finally, the model predicts that the loss rate is 3.07% and the cleaning rate is 95.36%. When these parameters were used for the bench verification test, the results showed that the cleaning system loss rate and cleaning rate were 3.22% and 95.67%, respectively. Compared to the cyclone cleaning system, the loss rate of the combined cyclone separation and cylinder sieve cleaning system is reduced by 2.17%, and the cleaning rate is increased by 1.05%[24].

Table 4 Variance analysis of the loss rate

Variance source	Sun of squares	Degree of freedom	Mean of square	F value	P value
Model	52.80	9	5.87	53.13	<0.0001**
A	13.62	1	13.62	123.35	<0.0001**
B	5.68	1	5.68	51.48	<0.0001**
C	3.08	1	3.08	27.91	<0.0001**
D	24.64	1	24.64	223.19	<0.0001**
AB	1.19	1	1.19	10.76	0.0030**
AC	1.06	1	1.06	9.61	0.0046**
BC	0.57	1	0.57	5.16	0.0316**
A^2	0.75	1	0.75	6.76	0.0152*
D^2	2.21	1	2.21	20.00	0.0001**
Residual	2.87	26	0.11		
Lack of fit	2.06	15	0.14	1.86	0.1517
Cor total	55.68	35			

Table 5 Variance analysis of the cleaning rate

Variance source	Sun of squares	Degree of freedom	Mean of square	*F* value	*p* value
Model	93.52	9	10.39	94.34	<0.0001**
A	52.16	1	52.16	473.52	<0.0001**
B	5.74	1	5.74	52.14	<0.0001**
C	3.44	1	3.44	31.19	<0.0001**
D	18.48	1	18.48	167.78	<0.0001**
AB	0.71	1	0.71	6.41	<0.0178*
AC	0.68	1	0.68	6.18	<0.0197*
BC	1.36	1	1.36	12.32	<0.0017**
A^2	8.60	1	8.60	78.05	<0.0001**
D^2	2.37	1	2.37	21.51	<0.0001**
Residual	2.86	26	0.11		
Lack of fit	2.18	15	0.15	2.32	0.0816
Cor total	96.39	35			

4 Conclusions

In this research, a cleaning process route is proposed, in which the cyclone separation cleaning device is used to remove the light and tiny impurities in the threshed mixture, and the cylinder sieve device is used to remove the coarse and long impurities. The combined cyclone separation and cylinder sieve cleaning system is designed and manufactured. The Single-factor and quadratic orthogonal tests were conducted.

1) Compared to the conventional cyclone separating cleaning system for rape combine harvester, the combined cyclone separation cleaning device and cylinder sieve cleaning device can help reduce the loss rate and increase the cleaning rate. Specifically, the loss rate of the combined cyclone separation and cylinder sieve cleaning system is reduced by 2.17% and the cleaning rate is increased by 1.05%. These results can provide a reference for designing cleaning system structures.

2) The results of theoretical analysis and the single-factor experiments shows that the suitable parameter range of the airflow velocity at the suction port, the rotation speed of the cylinder sieve, the pitch of the spiral blade and the diameter of the sieve hole are: 13-21 m/s, 30-94 r/min, 160-440 mm and 3-7 mm, respectively.

3) A four-factor five-level quadratic orthogonal test determines the optimal parameter combination. When the rotation speed of the winnower, the airflow velocity at the suction port, the rotation speed of the cylinder sieve, the screw pitch of the spiral blade and the diameter of the sieve hole are set to 600 r/min, 18.25 m/s, 87 r/min, 440 mm, and 4.48 mm, respectively. The combined cyclone separation and cylinder sieve cleaning system performs better. Under these conditions, the loss rate and the cleaning rate of the combined cyclone separation cleaning device and cylinder sieve device are 3.22% and 95.67%, respectively.

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[References]

[1] Xu L Z, Li Y, Li Y M, Chai X Y, Qiu J. Research progress on cleaning technology and device of grain combine harvester. Transactions of the CSAM, 2019; 50(10): 1–16. (in Chinese)

[2] Fan C L, Cui T, Zhang D X, Yang L, Tian C C, Zhong X J. Design and experiment of double-layered reverse cleaning device for axial flow combine harvester. Transactions of the CSAM, 2018; 49(S1): 239–248. (in Chinese)

[3] Badretdinov I, Mudarisov S, Lukmanov R, Permyakov V, Nasyrov R. Mathematical modeling and research of the work of the grain combine harvester cleaning system. Computers and Electronics in Agriculture, 2019; 165: 104966.

[4] Wang L J, Feng X, Wu Z C, Li R, Cui Y Q, Li Y B. Design and test of stepped vibrating screen with cross air for maize harvester. Transactions of the CSAM, 2018; 49(10): 115–123. (in Chinese)

[5] Jin C Q, Li Q L, Ni Y L, Wang T E, Yin X. Experimental study on double air outlet multi-ducts cleaning device of wheat combine harvester. Transactions of the CSAE, 2018; 36(10): 26–34. (in Chinese)

[6] Jiang T, Zhang M, Guan Z H, Mu S L, Wu C Y, Wang G, et al. Simulation and analysis of the pneumatic recovery for side-cutting loss of combine harvesters with CFD-DEM coupling approach. Int J Agric & Biol Eng, 2022; 15(2): 117–126.

[7] Dai F, Song X F, Guo W J, Zhao W Y, Zhang F W, Zhang S L. Simulation and test on separating cleaning process of flax threshing material based on gas-solid coupling theory. Int J Agric & Biol Eng, 2020; 13(1): 73–81.

[8] Dai F, Song X F, Shi R J, Zhao W Y, Guo W J, Zhang Y. Migration law of flax threshing materials in double channel air-and-screen separating cleaner. Int J Agric & Biol Eng, 2021; 14(3): 92–102.

[9] Liao Q X, Wan X Y, Li H T, Ji M Y, Wang H. Design and experiment on cyclone separating cleaning system for rape combine harvester. Transactions of the CSAE, 2015; 31(14): 24–31. (in Chinese)

[10] Dai F, Zhao W Y, Liu G C, Zhang S L, Shi R J, Wei B. Design and experiment of separating and cleaning machine for flax threshing material. Transactions of the CSAM, 2019; 50(8): 140–147. (in Chinese)

[11] Shi Q X, Ma M, Yan W H, Zhou H, Yuan H J, Li Y H. Two-stage winnower cyclone separating cleaning system performance testing and optimization. Transactions of the CSAM, 2014; 45(11): 124–128. (in Chinese)

[12] Yao Y, Huang W, Wu Y, Zhang Y, Zhang M, Lyu J. Effects of the inlet duct length on the flow field and performance of a cyclone separator with a contracted inlet duct. Powder Technology, 2021; 393(11): 12–22.

[13] Safikhani H, Shams M, Dashti S. Numerical simulation of square cyclones in small sizes. Advanced Powder Technology, 2011; 22: 359–365.

[14] An I H, Lee C H, Lim J H, Lee H Y, Yook S J. Development of a miniature cyclone separator operating at low Reynolds numbers as a pre-separator for portable black carbon monitors. Advanced Powder Technology, 2021; 32: 4779–4787.

[15] Zhou X J, Yuan H J, Yan W H, Shi Q X, Ma M, Li Y H. Performance experiment on cyclone separating device based on off-centered inlet scoop. Transactions of the CSAE, 2014; 45(8): 80–85, 159. (in Chinese)

[16] Jin X, Du X W, Gan B X, Ji J T, Dong X, Wang G X. Cleaning performance experiment of cyclone separating system in miniature combine harvester. Transactions of the CSAM, 2016; 47(5): 99–105. (in Chinese)

[17] Ren S G, Xie F P, Wang X S, Liu D W, Li X, Chen L Y. Gas-solid two-phase separation operation mechanism for 4LZ-0. 8 rice combine harvester cleaning device. Transactions of the CSAE, 2015; 31(12): 16–22. (in Chinese)

[18] Huang A N, Ito K, Fukasawa T, Fukui K, Kuo H P. Effects of particle mass loading on the hydrodynamics and separation efficiency of a cyclone separator. Journal of the Taiwan Institute of Chemical Engineers, 2018; 90: 60–67.

[19] Wu S Y, Zhao J W, Guo Y H. An approach to the performance of the squirrel-cage sieve cleaning unit. Transactions of the CSAM, 1987; 18(1): 92–99. (in Chinese)

[20] Yuan J B, Wu C Y, Li H, Qi X D, Xiao X X, Shi X X. Movement rules and screening characteristics of rice-threshed mixture separation through a cylinder sieve. Computers and Electronics in Agriculture, 2018; 154: 320–329.

[21] Wan X Y, Shu C X, Xu X, Yuan J C, Li H T, Liao Q X. Design and experiment on cylinder sieve with different rotational speed in cleaning system for rape combine harvesters. Transactions of the CSAE, 2018; 34(14): 27–35. (in Chinese)

[22] Wan X Y, Liao Q X, Xu Y, Yuan J C, Li H T. Design and evaluation of cyclone separation cleaning devices using a conical sieve for rape combine harvesters. Apply Engineering in Agriculture. 2018; 34(4): 677–686.

[23] Li G N, Lu K, Jian H J, Liang Y, Lu J. H, Peng L, et al. Research advances on harvest index of Brassica napus L. Chinese Journal of Oil Crop Science, 2018; 40(5): 640–648. (in Chinese)

[24] Yuan J C, Wang C, He K, Wan X Y, Liao Q X. Effect of components mass ratio under sieve on cleaning system performance for rape combine harvester. Journal of Jilin University (Engineering and technology Edition), 2021; 51(5): 1897–1907. (in Chinese)

[25] China Academy of Agricultural Mechanization Science. Manual for design of agricultural machinery. Beijing: Agricultural Science and Technology Press, 2007; 1885p. (in Chinese)

[26] Liao Q X, Chen L, Li H T, Han C Y, Liu M F. Cleaning unit test-bed of extraction components for rape combine harvester. Transactions of the CSAM, 2013; 44(10): 80–85, 79. (in Chinese)

[27] Chi Y, Li M F, Yang Y B, Sui A B, Chi Y J. Cyclone device collecting eggshell membranes and eggshells separately from eggshells mixture. Trans. Transactions of the CSAM, 2019; 50(8): 339–350. (in Chinese)

[28] Liu X F, Zheng X, Ding Y S. Food machinery. Wuhan: Hubei Science and Technology Press, 2002. (in Chinese)

[29] Boateng A A, Barr P V. Modelling of particle mixing and segregation in the transverse plane of a rotary kiln. Chemical Engineering Science, 1996; 51(17): 4167–4181.

[30] Lei W, Wang R L, Wang L Y, Yuan F, Meng L J, Xing M L, et al. Genome-wide association study of seed density and its related traits in *Brassica napus* L. Acta Agron. Sinica, 2021; 47(11): 2099–2110.

[31] Yin Z J, Sun J, Chen B, Zhang W L. Study on transportation mechanism of open screw conveyors and design of parameters. Mining and Processing Equipment, 2010; 38(11): 66–71. (in Chinese)