EXPERIMENTAI STUDY ON THE CLEANING PERFORMANCE OF BIONIC SCREEN BASED ON EARTHWORM MOTION CHARACTERISTICS

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基于蚯蚓运动特征的仿生筛清选性能试验研究

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ABSTRACT

As the feeding mass of the combine harvester continues to be increased, the accumulation of the maize mixture on the screen more serious leading to a reduction in the screening efficiency of the cleaning screen. The maize mixture on the screen was quickly transported backward through a bionic screen based on the movements characteristics of earthworms to reduce accumulation. However, the influence of the main operating parameters of this bionic screen on the cleaning performance was not clear, so the main operating parameters affecting the loss percentage and impurity percentage of maize grain in the cleaning device of bionic screen were simulated using CFD-DEM. Analysis of variance, regression and response surface were carried out on the test data, and parameter optimization was carried out to obtain the optimal parameter combinations: the concave depth of the screen surface was 25 mm, the installation angle of the screen surface was –5.5°, and the airflow velocity at the inlet of the cleaning device was 12.3 m/s. At this time, the loss percentage of maize grain was 1.56%, and the impurity percentage of maize grain was 1.85%, which satisfied the requirements of national standards. The experiment provides a reference and basis for the subsequent investigation of the screening mechanism of the bionic screen.

摘要

随着联合收获机喂入量越来越大，玉米脱出物在筛上的堆积越发严重导致清选筛筛分效率降低。基于蚯蚓运动特征的仿生筛能够将筛上玉米脱出物快速向后运移从而减少堆积。但是此仿生筛主要作业参数对清选性能的影响尚不明确，为此采用 CFD-DEM 耦合方法对影响仿生筛清选装置玉米籽粒损失率和含杂率的主要作业参数进行了仿真试验。对试验数据进行方差分析、回归分析和响应面分析，并进行参数优化得到较优的参数组合为：筛面下凹深度 25 mm，筛面安装倾角–5.5°，入口气流速度 12.3 m/s，此时，玉米籽粒损失率为 1.56%，籽粒含杂率为 1.85%，清选性能满足相关标椎要求。试验为后续仿生筛筛分机理的探究提供参考和依据。

INTRODUCTION

The mechanized harvesting of maize grain is a key link in the whole process of maize mechanization, which is of great significance to guarantee maize production and food security *(Buryanov et al., 2019; Zhao, 2023).* The cleaning device is a key component of a maize grain combine harvester, and its operation performance affects multiple indicators such as the loss percentage of maize grain and the impurity percentage of maize grain *(Wang et al., 2021).*

However, the feeding mass of maize grain harvesters continue to increase and has led to the accumulation of the maize mixture (a mixture of grains, stalks, and cobs that fall onto the vibrating screen after threshing by the threshing device) on the screen, which is a key problem that needs to be solved urgently for its improvement *(Vlădut et al., 2022)*. While the working width of the combine harvester and corn yields continue to increase, the feeding mass continues to be increased, so that the accumulation of maize mixture becomes more serious *(Ivan et al., 2015)*. Therefore, based on the principle of bionics *(Massah et al., 2020)*, the earthworm as a bionic prototype, and the movement characteristics of the earthworm and the operating principle of the cleaning screen were integrated. A bionic screen for maize cleaning based on the movement characteristics of earthworms has been designed to solve the accumulation of maize mixture on the screen under the large feeding mass with continuous feeding *(Wang et al., 2021)*. However, the influence of the main operating parameters of this bionic screen on its cleaning performance needs to be further explored.

The dispersion, layering, and screening of particles on the cleaning screen are directly affected by their operating parameters, so scholars have conducted in-depth research. *Ma et al.* constructed a variable amplitude vibrating screen based on a planar reciprocating vibrating screen, and the effect of the rotation angle of the front swing bar on the throwing and backward movement of particles in front of the screen was investigated *(Ma et al., 2015; Ma, 2017; Ma, 2020)*. *Kharchenko et al. (2019)* proposed a sieve with particle size activator to improve the efficiency of flat seed grain mixtures. *Mircea Costin et al., (2020)* designed a new constructive subassembly that would increase the performance of rotary sorters used for extracting various contaminants from seeds. *Li et al.* designed a stepped screen with a sliding finger structure arranged in a stepped pattern and with a certain angle at the end of each section, and the influence of the sliding finger angle on the accumulation of particles on the screen was analysed *(Li et al., 2022; Li, 2022)*.

Numerical simulation is an effective method to study complex problems as the experimental process and results are fully visualized and the relevant details of the experiment can be effectively analysed. In the field of agricultural engineering, the computational fluid dynamics and discrete element method (CFD-DEM) coupling method is commonly used to numerically simulate the gas-solid two-phase flow motion of agricultural materials. *Xu et al., (2020),* simulated the screening process of rice mixture using CFD-DEM, and a mathematical model was established to extract the particle centre velocity and dispersion of the rice mixture. *Yuan et al. (2019),* simulated the screening process of rice mixture in a fan-inner cylinder using CFD-DEM, and the influence of the working and structural parameters of the cylinder screen on the particle movement and cleaning performance was analysed. *Feng et al., (2021),* tracked the motion of particles through CFD-DEM, and the influence of the centroid position on the screening behaviour during collision between particles and screen holes was studied.

Based on this, the simulation experiment of the cleaning performance of the bionic screen was conducted through CFD-DEM, with the concave depth of the bionic screen surface, the installation angle of the screen surface, and the airflow direction angle as test factors, with the loss percentage of maize grain and the impurity percentage of maize grain as test indicators. The influence of the main operating parameters of the bionic screen on its cleaning performance was explored, and parameter optimization was carried out to obtain the optimal parameter combination of the bionic screen. The experiment provides a reference and basis for the subsequent investigation of the screening mechanism of bionic screen.

MATERIALS AND METHODS

Structure of bionic screen based on earthworm motion characteristics

The structure of the bionic screen is shown in Fig. 1, which mainly consists of a frame, cam drive mechanism, and screen plate. The side plates are fixed to the front and rear sides of the frame symmetrically, and the driveshaft is fixed on the side plates through the bearing seat. Cam drive mechanisms are installed at the front and rear ends of the driveshaft, respectively, and the screen plate is driven by the pin shaft hinged with the cam driving mechanism. The biomimetic principle and design basis of this bionic screen could be found in the preliminary research results of the project (*Wang et al., 2021*).

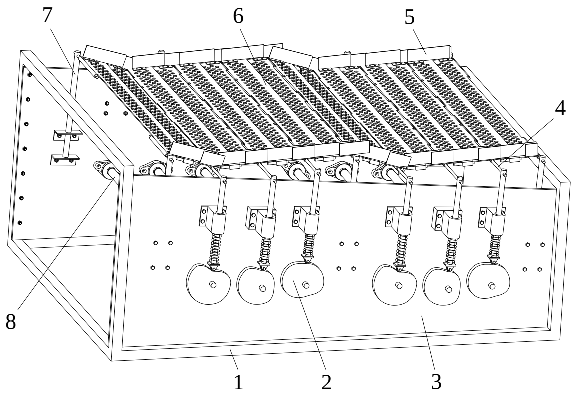


Fig. 1 - Structure diagram of bionic screen

1 - frame; 2 - cam drive mechanism; 3 - side plate; 4 - pin shaft; 5 - baffle; 6 - screen plate; 7 - support rod; 8 - driveshaft

Working principle of bionic screen

During the movement of the bionic screen, the screen surface is concave and reaches the lowest point. At this time, the screen surface becomes "V-shaped", and the screen surface was divided into four postures according to the different concave positions.

The screen surface is continuously changed from attitude 0 to attitude 3 by means of the interplay between the cam drive mechanisms. During operation, the fan is installed at the front of the bionic screen. The maize mixture is initially stratified and dispersed by the fan's airflow during the process of falling from the oscillation grain pan. The maize mixture is fed to the front of the bionic screen, then gathers at the lowest point of the bionic screen surface, and gradually migrates backward with the bionic screen surface to avoid accumulation. The follower is driven by the rotating cam to move up and down. Simultaneously, the combinations of the screen plate are driven by the followers to achieve continuous conversion between concave bending and flattening. The maize mixture falling on the bionic screen surface is thrown up, shaken, and loosened, so that the impurities and the grains are gradually stratified and dispersed on the screen surface.

Experimental materials

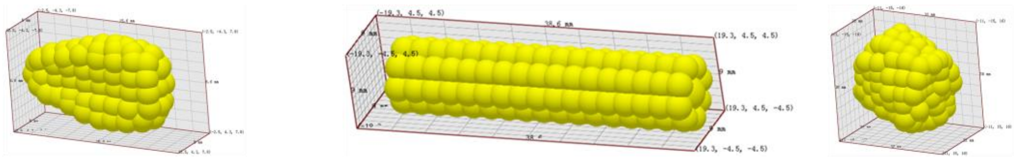
The Xianda 205 maize variety was used in the experiment. In the maize mixture, grains, stalks and cobs each account for 73.34%, 17.56%, and 9.10%, with moisture content ranging from 27.41% to 28.65%, 37.22% to 38.01% and 57.09% to 58.22%, respectively.

Foundation of model of bionic screen cleaning device

The length of the cleaning device is 1779 mm, the height is 500 mm, and the width is 105 mm *(Yuan et al., 2022; Yuan, 2020)*. The height of the airflow inlet is 380 mm, and the height of the impurity outlet is 280 mm. The screen body is a round hole screen with a diameter of 15 mm. The length of the screen surface is 1500 mm.

Foundation of particle model of maize mixture

The three-dimensional modelling of simulated particles was carried out for each component of the maize mixture, and this contour was used as the basis for filling the spheres. To ensure accurate contouring of maize mixture while ensuring the computational speed of the computer *(Zhang et al., 2020; Wang, 2020)*, the radius of the modelled spheres was selected as 1 mm. The simulation model of the maize mixture after the modelling was shown in Fig. 2.



(a) - Maize grain of cone-shape (b) - Maize stalk (c) - Maize cob

Fig. 2 - Simulation models of maize mixture

Setting of simulation parameters

The standard *k-ε* turbulence model was selected in Fluent, and the type of solver was set to pressure based unsteady state. The Hertz-Mindlin (no-slip) model was selected in EDEM. The angle of the air outlet of the fan was 25°, and the rotational speed of the cams were 90 r/min. The equations of motion of the screens were extracted by ADAMS, and the non-simple harmonic motion of the bionic screen was added to EDEM through API (Application Programming Interface). The numerical simulation experiment of bionic screen was conducted through CFD-DEM-API coupling. The moisture contents of maize grains, stalks and cobs was 27.91%, 37.62%, and 57.09%, respectively, and the parameters of mechanical properties of each component of the maize mixture are shown in Table 1 *(Wang et al., 2018; Wang, 2015)*.

Table 1

Mechanical properties of materials

Material	Density [kg/m^3]	Shear modulus [MPa]	Poisson ratio
Maize grain	1190	127	0.40
Maize stalk	150	100	0.42
Maize cob	650	109	0.45
Screen surface (steel)	7800	700	0.30

The parameters of properties interaction for each component of maize mixture are shown in Table 2 *(Wang et al., 2018; Wang, 2015)*.

Table 2

Interaction properties of materials

Attributes of contact	Grain-Grain	Grain-Stalk	Grain-Cob	Grain-Screen (steel)	Stalk-Stalk	Stalk-Cob	Stalk-Screen (steel)	Cob-Cob	Cob-Screen (steel)
Recovery coefficient of collision	0.44	0.35	0.28	0.61	0.26	0.29	0.43	0.27	0.39
Rolling friction coefficient	0.06	0.01	0.01	0.03	0.01	0.01	0.01	0.01	0.01
Static friction coefficient	0.50	0.32	0.73	0.53	0.32	0.47	0.45	0.97	0.43

Setting of particle factors

The particle factor is set above the oscillation grain pan, and the feeding mass of maize mixture is 7 kg/s. The feeding mass of maize mixture is 0.6338 kg/s after equal conversion based on the screen width of the simulation model and continued to feed for 3 s. The specific feeding mass of maize mixture is shown in Table 3.

Table 3

Feeding mass of different components of maize mixture

Component	Category	Number of particles [unit]	Total number of particles [unit]	Mass [kg]	Total mass [kg]
Maize grain	**Cone**	2835	4282	1.0424	1.3994
	Spherical	973		0.2119	
	Rectangle	474		0.1451	
Maize stalk	**28 mm[a] cylinder**	573	2142	0.0458	0.3360
	36 mm cylinder	789		0.1088	
	44 mm cylinder	468		0.1012	
	52 mm cylinder	312		0.0802	
Maize cob	**1/4 cylinder**	1374	1554	0.0840	0.1661
	1/2 cylinder	105		0.0344	
	Whole cylinder	75		0.0477	
Total			7978		1.9015

Note: [a] 28 mm, 36 mm, 44 mm, and 52 mm are the length of the cylinder.

Design of test

Based on the theoretical analysis and design process in the early stage, the factors that affect the cleaning performance of the bionic screen were obtained, including the concave depth of the screen surface, the cam rotation speed, the installation angle of the screen surface, the airflow velocity at the inlet of the cleaning device, and the airflow direction angle. The effective adjustment ranges for each factor are 25.0~75.0 mm, 60~120 r/min, -1.5°~-5.5°, 9.6~14.4 m/s, and 20.0°~30.0°, respectively. The significant factors were removed based on pre-experiments *(Wang et al., 2022; Wang, 2021)*. The concave depth of the screen surface x_1, the installation angle of the screen surface x_2, and the airflow velocity at the inlet of the cleaning device x_3 were selected as factors. The loss percentage of maize grain y_1 and the impurity percentage of maize grain y_2 were selected as indicators, and a three-factor, five-level quadratic orthogonal rotation combination experiment was designed. The median of each factor is used as the zero level of the experiment, and the coding of the experimental factors is shown in Table 4.

Table 4

Experimental factors and models

Level	Factor: The concave depth of the screen surface x_1 [mm]	The installation angle of the screen surface x_2 [°]	The airflow velocity at the inlet of the cleaning device x_3 [m/s]
1.682	75.0	–5.5	14.4
1	62.5	–4.5	13.2

Level	Factor The concave depth of the screen surface x_1 [mm]	The installation angle of the screen surface x_2 [°]	The airflow velocity at the inlet of the cleaning device x_3 [m/s]
0	50.0	–3.5	12.0
–1	37.5	–2.5	10.8
–1.682	25.0	–1.5	9.6

The total mass of feeding grain into the cleaning device was calculated by the proportion of maize grain to the maize mixture before simulation. At the end of the simulation experiment, the material under the screen and the quality of the grain were extracted, respectively. The loss percentage of maize grain and the impurity percentage of maize grain were calculated using equations (1) and (2), and each group of experiments was repeated 3 times to obtain the average value.

$$S_L = \frac{W_L}{W_Z} \times 100\% \tag{1}$$

$$Z_z = \frac{W_{za}}{W_h} \times 100\% \tag{2}$$

S_L - loss percentage of maize grain [%];
W_L - mass of maize grain lost [g];
W_Z - mass of all maize grain [g];
Z_z - impurity percentage of maize grain [%];
W_{za} - mass of impurities [g];
W_h - mass of sample (mixture of maize grain and impurities) [g].

RESULTS

Test results

The coupled CFD-DEM simulation of the maize mixture is shown in Fig. 3. In the figure, the yellow material is maize grains, the green material is maize stalks and the red material is maize cobs.

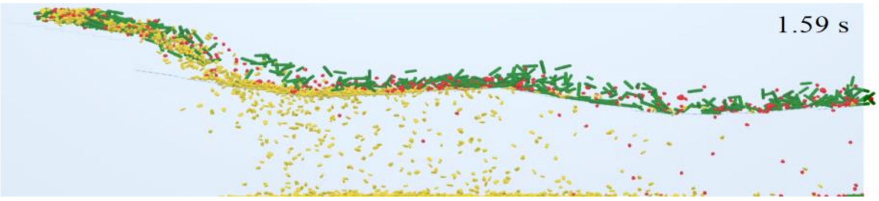


Fig. 3 - CFD-DEM coupled simulation of maize mixture

The results of the three-factor five-level quadratic orthogonal rotation combination test are shown in Table 5.

Table 5

Design scheme and the result of quadratic regression rotation combination

Number	The concave depth of the screen surface x_1 [mm]	The installation angle of the screen surface x_2 [°]	The airflow velocity at the inlet of the cleaning device x_3 [m/s]	The loss percentage of maize grain y_1 [%]	Standard deviation	The impurity percentage of maize grain y_2 [%]	Standard deviation
1	–1 (37.5)	–1 (–2.5)	–1 (10.8)	0.87	0.11	4.09	0.30
2	1 (62.5)	–1 (–2.5)	–1 (10.8)	1.28	0.13	2.96	0.26
3	–1 (37.5)	1 (–4.5)	–1 (10.8)	1.66	0.22	2.51	0.19
4	1 (62.5)	1 (–4.5)	–1 (10.8)	3.02	0.14	1.53	0.22
5	–1 (37.5)	–1 (–2.5)	1 (13.2)	2.12	0.20	2.06	0.18

6	1 (62.5)	–1 (–2.5)	1 (13.2)	2.37	0.18	2.17	0.26
7	–1 (37.5)	1 (–4.5)	1 (13.2)	2.74	0.15	1.82	0.15
8	1 (62.5)	1 (–4.5)	1 (13.2)	2.93	0.21	1.74	0.17
9	–1.68 (25.0)	0 (–3.5)	0 (12.0)	0.65	0.08	3.01	0.34
10	1.68 (75.0)	0 (–3.5)	0 (12.0)	1.51	0.12	2.16	0.23
11	0 (50.0)	–1.68 (–1.5)	0 (12.0)	0.62	0.09	3.54	0.35
12	0 (50.0)	1.68 (–5.5)	0 (12.0)	1.95	0.23	2.46	0.24
13	0 (50.0)	0 (–3.5)	–1.68 (9.6)	2.69	0.24	3.5	0.26
14	0 (50.0)	0 (–3.5)	1.68 (14.4)	4.48	0.32	0.95	0.09
15	0 (50.0)	0 (–3.5)	0 (12.0)	1.28	0.06	3.15	0.21
16	0 (50.0)	0 (–3.5)	0 (12.0)	1.15	0.08	2.98	0.26
17	0 (50.0)	0 (–3.5)	0 (12.0)	0.97	0.11	3.13	0.22
18	0 (50.0)	0 (–3.5)	0 (12.0)	1.11	0.10	2.89	0.19
19	0 (50.0)	0 (–3.5)	0 (12.0)	0.82	0.08	3.34	0.27
20	0 (50.0)	0 (–3.5)	0 (12.0)	1.26	0.11	2.65	0.19
21	0 (50.0)	0 (–3.5)	0 (12.0)	0.89	0.08	3.62	0.29
22	0 (50.0)	0 (–3.5)	0 (12.0)	0.73	0.12	3.46	0.29
23	0 (50.0)	0 (–3.5)	0 (12.0)	1.07	0.17	2.89	0.25

Analysis and discussion of the results

The results were analysed by ANOVA using Design-Expert 8.0 software to test their significance. The regression equations of the loss percentage of maize grain and the impurity percentage of maize grain were obtained based on regression analysis, and the influence of the interaction terms on the experimental indexes were analysed by response surface.

The loss percentage of maize grain

(1) Variance and regression analysis

The results of ANOVA for loss percentage of maize grain are shown in Table 6, and the experimental model was highly significant (p<0.01). The effect of concave depth of the screen surface x_1, the installation angle of the screen surface x_2 and the airflow velocity at the inlet of the cleaning device x_3 on the loss percentage of maize grain were highly significant (p<0.01). The interaction terms of concave depth of the bionic screen surface with airflow velocity at the inlet of the cleaning device x_1x_3, installation angle of the screen surface with airflow velocity at the inlet of the cleaning device x_2x_3, and the quadratic term of airflow velocity x_3^2 were significant on the loss percentage of maize grain (p<0.05). The rest of the terms were not significant. The order of the effect of each factor on the loss percentage of maize grain was x_3, x_2, x_1.

Table 6

ANOVA results for the loss percentage of maize grain

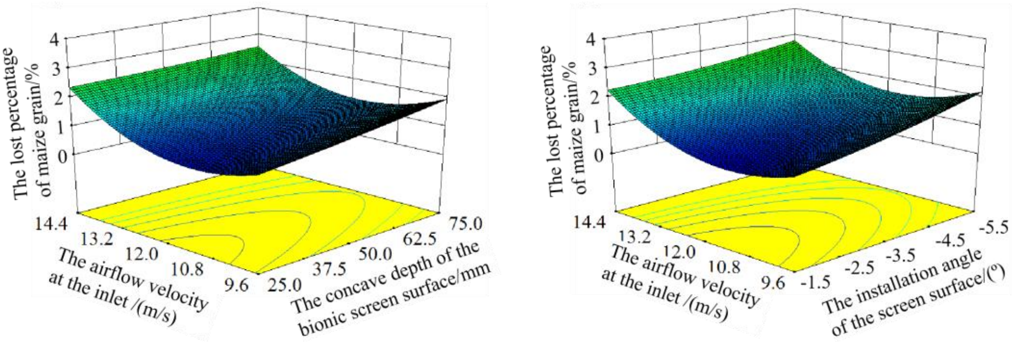
Source of variance	Sum of squares	df	Mean square	*F*-Value	*p*-Value
Model	20.68	9	2.30	59.06	<0.0001
x_1	0.98	1	0.98	25.16	0.0002
x_2	2.59	1	2.59	66.55	<0.0001
x_3	2.94	1	2.94	75.65	<0.0001
x_1x_2	0.099	1	0.099	2.54	0.1347
x_1x_3	0.22	1	0.22	5.68	0.0331
x_2x_3	0.23	1	0.23	5.85	0.0309
x_1^2	0.019	1	0.019	0.48	0.4989
x_2^2	0.18	1	0.18	4.67	0.0500
x_3^2	13.45	1	13.45	345.69	<0.0001
Residual	0.51	13	0.039		
Lack of fit	0.21	5	0.042	1.14	0.4118
Error	0.30	8	0.037		
Sum	21.19	22			

From Table 6, the lack of fit of the model was not significant (p>0.05), and the regression model was established. The insignificant terms were removed to obtain the regression equation of each factor on the loss percentage of maize grain as shown in equation (3).

$$y_1 = 1.03 + 0.27x_1 + 0.44x_2 + 0.46x_3 - 0.17x_1x_3 - 0.17x_2x_3 + 0.92x_3^2 \left(R^2 = 0.9761\right) \quad (3)$$

(2) Analysis of the response surface of the interaction term

When the installation angle of the screen surface is –3.5°, there is an interaction between the concave depth of the bionic screen surface and the airflow velocity at the inlet of the cleaning device, as shown in Fig. 4(a). Under the condition of an airflow velocity at the inlet of the cleaning device, the loss percentage of maize grain increases with the increase of the concave depth of the bionic screen surface. The reason is that with the increase of the concave depth of the bionic screen, the horizontal velocity of the grains increases, and the probability of the grains passing through the screen gradually decreases, resulting in a gradual increase in the loss percentage of maize grain. Under the condition of a concave depth of the bionic screen surface, the loss percentage of maize grain first decreased and then increased with the increase of the inlet air velocity. The reason is that the airflow velocity at the inlet of the cleaning device affects the separation and migration of maize mixture along the screen surface. When the inlet airflow velocity is too small, the grains and impurities cannot be effectively separated, and the grains cannot be fully contacted with the screen surface, resulting in a high the loss percentage of maize grain.



(a) - $y_1(x_1, 0, x_3)$ (b) - $y_1(0, x_2, x_3)$

Fig. 4 - Response surface of effects of various factors on loss percentage of maize grain

When the concave depth of the screen surface is 50.0 mm, there is an interaction between the installation angle of the screen surface and the airflow velocity at the inlet of the cleaning device, as shown in Fig. 4(b). Under the condition of airflow velocity at the inlet of the cleaning device, the loss percentage of maize grain increases with the increase of the installation angle of the screen surface. The reason is that with the increase of the installation angle of the screen surface, the horizontal velocity of the grain gradually increases, and the probability of its penetration through the screen decreases, resulting in a gradual increase in the loss percentage of maize grain. Under the condition of installation angle of the screen surface, the loss percentage of maize grain first decreased and then increased with the increase of the inlet airflow velocity. The reason is that the grains and impurities cannot be effectively separated when the inlet airflow velocity is low. When the inlet airflow velocity is too high, the grains move backwards faster. In both cases, the probability of the grains passing through the screen is reduced.

The impurity percentage of maize grain

(1) Variance and regression analysis

The results of ANOVA for impurity percentage of maize grain are shown in Table 7, and the experimental model was highly significant (p<0.01). The effect of concave depth of the screen surface x_1, the installation angle of the screen surface x_2 and the airflow velocity at the inlet of the cleaning device x_3 on the impurity percentage of maize grain were highly significant (p<0.01). The interaction terms of concave depth of the bionic screen surface with airflow velocity at the inlet of the cleaning device x_1x_3, installation angle of the screen surface with airflow velocity at the inlet of the cleaning device x_2x_3, the quadratic term of concave depth of the bionic screen surface x_1^2, and the quadratic term of airflow velocity x_3^2 on the impurity percentage of maize grain were significant (p<0.05). The rest of the terms were not significant. The order of the effect of each factor on the impurity percentage of maize grain was x_3, x_2, x_1.

Table 7

ANOVA results for the impurity percentage of maize grain

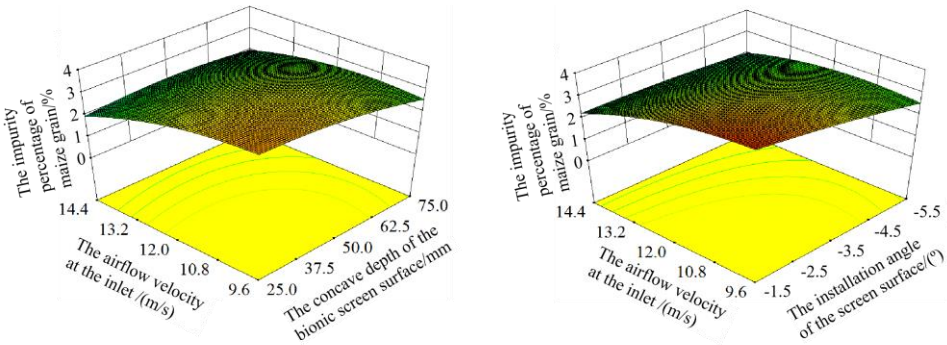
Source of variance	Sum of squares	df	Mean square	*F*-Value	*p*-Value
Model	11.63	9	1.29	12.18	<0.0001
x_1	0.90	1	0.90	8.50	0.0120
x_2	2.21	1	2.21	20.85	0.0005
x_3	4.22	1	4.22	39.75	<0.0001
x_1x_2	0.0002	1	0.0002	0.0019	0.9660
x_1x_3	0.57	1	0.57	5.40	0.0370
x_2x_3	0.68	1	0.68	6.45	0.0246
x_1^2	0.87	1	0.87	8.22	0.0132
x_2^2	0.12	1	0.12	1.15	0.3036
x_3^2	2.08	1	2.08	19.58	0.0007
Residual	1.38	13	0.11		
Lack of fit	0.62	5	0.12	1.30	0.3529
Error	0.76	8	0.095		
Sum	13.01	22			

From Table 7, the lack of fit of the model was not significant (p>0.05), and the regression model was established. The insignificant terms were removed to obtain the regression equation of each factor on the impurity percentage of maize grain as shown in equation (4).

$$y_2 = 3.13 - 0.26x_1 - 0.4x_2 - 0.56x_3 + 0.27x_1x_3 + 0.29x_2x_3 - 0.088x_2^2 - 0.36x_3^2 \left(R^2 = 0.8940\right) \tag{4}$$

(2) Analysis of the response surface of the interaction term

When the installation angle of the screen surface is –3.5°, there is an interaction between the concave depth of the bionic screen surface and the airflow velocity at the inlet of the cleaning device, as shown in Fig. 5(a). Under the condition of airflow velocity at the inlet of the cleaning device, the impurity percentage of maize grain decreases with the increase of the concave depth of the bionic screen surface. The reason is that with the increase of the concave depth of the bionic screen surface, the horizontal velocity of maize stalk and cob gradually increases, and the probability of impurities remaining through the screen decreases, resulting in a gradual decrease in the impurity percentage of maize grain. Under the condition of concave depth of the bionic screen surface, the impurity percentage of maize grain gradually decreased with the increase of the airflow velocity at the inlet of the cleaning device. The reason is that with the increase of the airflow velocity at the inlet of the cleaning device, the separation effect of grains and impurities along the screen surface is better, so that the backward migration speed of impurities is faster and faster, so that the impurity percentage of maize grain gradually decreases.



(a) - $y_2(x_1, 0, x_3)$ (b) - $y_2(0, x_2, x_3)$

Fig. 5 - Response surface of effects of various factors on impurity percentage of maize grain

When the concave depth of the screen surface is 50.0 mm, there is an interaction between the installation angle of the screen surface and the airflow velocity at the inlet of the cleaning device, as shown in Fig. 5(b). Under the condition of airflow velocity at the inlet of the cleaning device, the impurity percentage of maize grain decreases with the increase of the installation angle of the screen surface. The reason is that with the increase of the installation angle of the screen surface, the horizontal speed of the impurities gradually increases, so that the impurity percentage of maize grain gradually decreases.

Under the condition of installation angle of the screen surface, the impurity percentage of maize grain decreased gradually with the airflow velocity at the inlet of the cleaning device. The reason is that with the increase of the airflow velocity at the inlet of the cleaning device, the impurities migrate backward on the screen faster and faster, so that the impurity percentage of maize grain gradually decreases.

Optimization of parameters

To obtain the best cleaning performance of the bionic screen, the multi-objective optimization algorithm of the Design-Expert 8.0 software was used to optimize the structural parameters and operating parameters of the bionic screen based on the multi-factor experiments. The objectives and constraints are as follows:

$$\begin{cases} \min\ y_1 \\ \min\ y_2 \\ 25\text{mm} \le x_1 \le 75\text{mm} \\ -1.5° \le x_2 \le -5.5° \\ 9.6\text{m/s} \le x_3 \le 14.4\text{m/s} \end{cases} \tag{5}$$

Optimization results: when the concave depth of the screen surface is 25 mm, the installation inclination angle of the screen surface is –5.5°, and the inlet airflow velocity is 12.3 m/s, the loss percentage of maize grain is 1.56%, and the impurity percentage of maize grain is 1.85%, which are all in line with the standard requirements *(GB/T 21962, 2020; NY/T 1355, 2007)*.

Verification test of bench

The bench of the bionic screen cleaning device is shown in Fig. 6. The bench test is carried out to verify the results of the simulation test with the optimization results of the simulation test as the operation parameters.

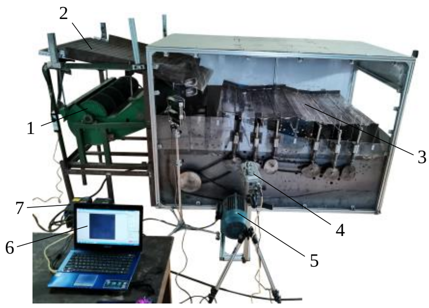


Fig. 6 - Cleaning device of bionic screen

1 - fan; 2 - oscillation grain pan; 3 - bionic screen; 4 - high-speed camera; 5 - motor; 6 - computer; 7 - frequency converter.

Before the test, the maize mixture were evenly spread on the oscillation grain pan, and 21 kg of maize mixture were continuously fed in 3 s to ensure that the feeding mass of maize mixture was 7 kg/s. The loss percentage of maize grain and the impurity percentage of maize grain were calculated, and each group of experiments was repeated 5 times to obtain the average value. The average value of the loss percentage of maize grain was 1.64%, and the average value of the impurity percentage of maize grain was 1.86%. The maximum relative error between the measured values and the numerical simulation results does not exceed 5.13%, which is within the acceptable range. The accuracy of the numerical simulation was proven.

CONCLUSIONS

The main operating parameters that affect the loss percentage and impurity percentage of maize grain in the cleaning device of bionic screen were simulated using CFD-DEM. Analysis of variance, regression and response surface were carried out on the test data, and the optimal parameter combination was obtained.

(1) The effects of the concave depth of the bionic screen surface x_1, the installation angle of the screen surface x_2, and the airflow velocity at the inlet of the cleaning device x_3 on the loss percentage of maize grain and the impurity percentage of maize grain were analysed by the variance and interaction term response surface method. The order of the effect on the loss percentage and impurity percentage of maize grain was x_3, x_2, x_1.

(2) The parameters of the bionic screen were optimized and its optimal combination of parameters was obtained as follows: the concave depth of the screen surface was 25 mm, the installation inclination angle of the screen surface was –5.5°, and the inlet airflow velocity was 12.3 m/s. At this time, the loss percentage of maize grain was 1.56%, and the impurity percentage of maize grain was 1.85%, which are all in line with the standard requirements.

(3) The validation experiment was conducted by the bench of bionic screen cleaning device, the average value of the loss percentage of maize grain of the bionic screen cleaning device was 1.64%, and the average value of the impurity percentage of maize grain was 1.86%. The maximum relative error between the measured values and the numerical simulation results does not exceed 5.13%, and the accuracy of the numerical simulation was proven.

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