EXPERIMENTAL STUDY ON NON-PLANAR SCREENING DEVICE FOR BUCKWHEAT THRESHING MATERIAL
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荞麦混合脱出物非平面筛分装置试验研究

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ABSTRACT
Structural and motion parameters of screen surface have an important impact on the screening quality. In order to reduce the loss rate and impurity rate of buckwheat threshing material in the screening process and improve the screening performance of the vibrating screen, the planar square hole sieve, round hole sieve, non-planar convex-column sieve, pit sieve, and wave sieve were designed. Screening test was conducted on buckwheat threshing material under different screen structure based on the discrete element method (DEM). The results showed that the screening effect of convex-column sieve was the best, followed by pit sieve, and they were better than the traditional planar sieve. In single factor screening test of convex-column sieve, the ratio and height of convex column have significant influence on screening performance. Convex column rate, convex column height in a certain range were advantageous for screening. The results can lay a foundation for the determination of optimal parameter of screen structure and motion, and also provide a theoretical basis for the design of screening and cleaning equipment for buckwheat.

ABSTRACT
筛面结构参数和运动参数对筛分质量有重要影响。为了进一步降低荞麦混合脱出物在筛分过程的损失率、含杂率，提高振动筛的筛分性能，本文设计了平面方孔筛、圆孔筛，非平面凸柱筛、凹坑筛、波浪筛，并基于离散元法进行了荞麦混合脱出物不同筛面结构下的筛分试验。结果表明：在振动参数相同的情况下，非平面凸柱筛面的筛分效果最好，凹坑筛面次之，但均优于传统的平面圆孔筛和方孔筛。在凸柱筛面筛分试验中，凸柱率和凸柱高度对筛分性能影响显著。凸柱率、凸柱高度在一定范围内对筛分有利。所得结论可为最优筛面结构和运动参数组合的确定奠定基础，同时，亦能为荞麦混合脱出物的筛分、清选装置的设计提供理论依据。

INTRODUCTION
Buckwheat has a high nutritional value and health function, recognized by FAO as a crop used for food and medicine *(FAO, 2014)*. The improvement of its yield and quality has been a concern at world level *(Germ M. et al., 2020)*. The planting area and yield in China rank second in the world. The demand for buckwheat is increasing year by year, but the corresponding development of industrialization and mechanization is slow. The existing harvesting machinery is challenging to meet the needs of buckwheat harvesting; significantly, the quality of the cleaning process should be enhanced *(Ji J. et al., 2016)*.

Buckwheat is an infinite raceme crop so that its growth and development are different from those of cereal crops. In harvesting process, the maturity of the same plant is not consistent, so it is difficult for the combine to harvest. Especially in the cleaning process, the threshing material of high moisture content can be easily accumulated on the sieve surface, and it is not easy to stratify and penetrate through the sieve, resulting in poor screening quality. Even an air-screen cleaning device broadly exploited in grain harvesting is difficult to accomplish an effective screening for buckwheat threshing material. The problems of high screening loss and impurity in buckwheat mechanical harvesting still exist, which seriously affects the economic benefits and restrict the growth of buckwheat industry.

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Generally, material screening is a complex random process. Many factors are affecting the material passing through the screen. The most critical factors are the material properties, structures, and kinematic parameters of the screening device *(Zhao Y. et al., 1999)*. At present, the vibrating screening device mostly adopts a crank connecting rod mechanism *(Li H. et al., 2011; Li J. et al., 1997).* The motion track of the sieve surface is single, easy to block, so it has poor adaptability to materials. Considering these problems, both homeland and abroad investigators have carried out much research on changing the motion form of the sieve body as well as the screening surface structure.

Regarding alternating the movement form of sieve, *Shen et al., (2012; 2011),* and *Wang et al., (2012),* had proposed and developed multi-dimensional parallel vibrating sieve with variable degrees of freedom, and carried out methodical research on the motion law and the screen motion trajectory. *Li et al., (2016),* examined the movement process of particles on the screening surface of a multi-dimensional vibrating sieve and stated that the four-dimensional vibrating sieve would have the best screening permeability.

Concerning research on the sieve structure, *Deng et al., (2013),* and *Li et al., (2016),* elaborated the design of non-planar sieve surface and its multi-dimensional penetration principle. Subsequently, they compared the screening performance of parallel vibrating sieve and traditional linear vibrating sieve by experiment. Both conventional planar and non-planar sieve surfaces were taken into account in their studies. The obtained results showed that the screening efficiency of the combination of parallel vibrating screen and non-planar sieve would be higher than that of the combination of straight and planar screens. *Cleary et al. (2009)*, simulated the operation of an industrial double-layer banana screen by DEM to examine the influence of energy transfer and absorption between particles on the screening efficiency. *Bellocp et al., (2017)*, proved that the rotary sieve would have a higher screening efficiency for materials with soft wet agglomeration such as millet.

The screening efficiency of the parallel vibrating sieve mentioned above has been improved, however, its structure is complex and the costs are high. Additionally, sieve of other forms applied to screening operation for coarse cereals has not been addressed in the literature. Herein, screening of buckwheat threshing material based on three kinds of non-planar sieves is planned to be examined, focusing on the sieving performance of convex-column sieve. The main aim is to reduce the loss rate and impurity rate in buckwheat-combined harvest cleaning, and thereby, a theoretical basis for the design of buckwheat combined harvester is established.

MATERIALS AND METHODS

Structural Design and Operation Principle

The structure model of the screening device has been presented in Fig.1. During the screening, the vibrating screen vibrated to and from under the drive of the vibrating mechanism. The buckwheat mixture came into the screen surface from the stepped shaking plate and moved backward. In the movement process, the grains in the mixture fell into the grain collecting box through the sieve, while the short stems moved to the outlet along the sieve and slid into the residual collecting box. The separation of grain and stem was realized, and the screening operation was completed.

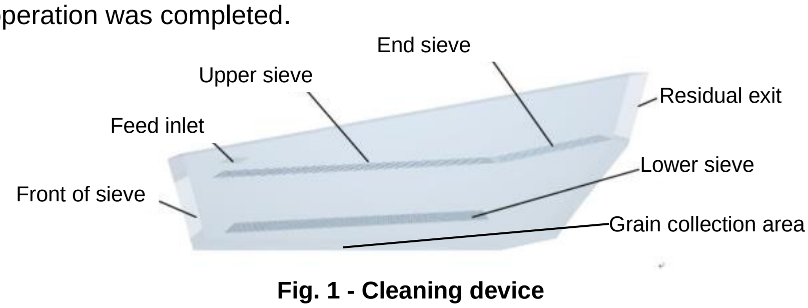


Fig. 1 - Cleaning device

Test materials

The understudy buckwheat threshing material (Heifeng No.1) consisted of test materials taken from the school experimental field. A complete feed combine harvester (XG788S) was exploited for harvesting. The harvested grains were obtained in the silo during the harvesting process, and the mixture was received under the threshing drum. It was found that the combine harvester could remove leaves, petals, dust, and other impurities effectively, however it was difficult to eliminate short stems. Therefore, this experiment only considered the separation of the mixture composed of grains and short stems.

Based on the material analyses, the weight ratio of the buckwheat grain and short stem in the mixture to be cleaned was 2.14:1. According to this ratio, the test materials were obtained (Fig. 2c).

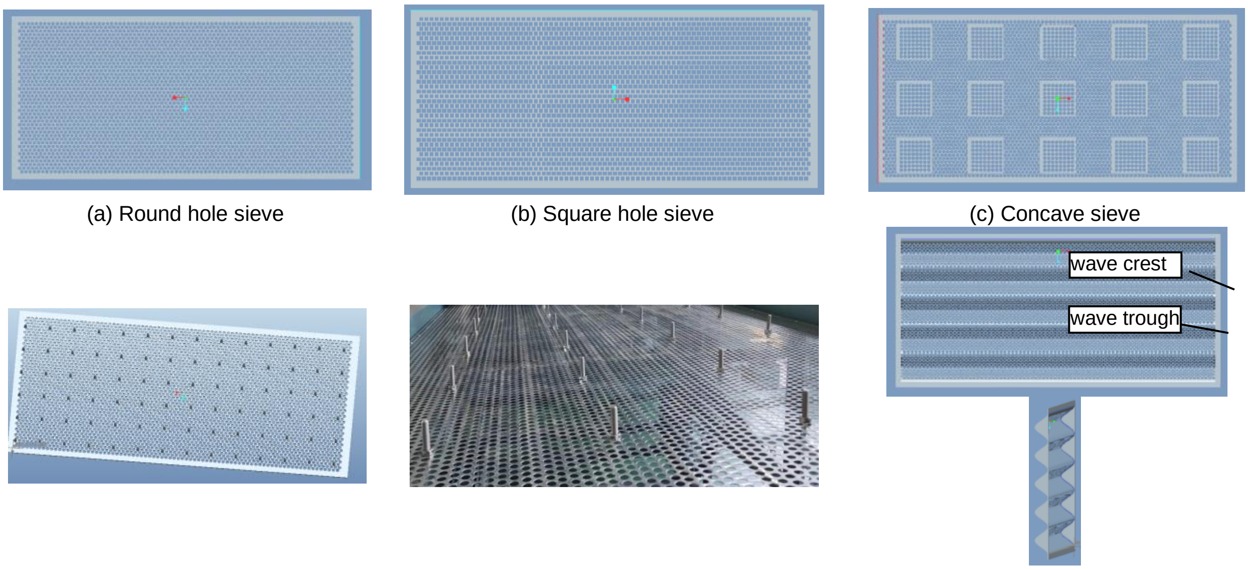
In the mixture, the water content of buckwheat grains was 17.68%, and the grain density was 2540 kg/m^3, while the water content of stems was 61.11%, and the density was 570 kg/m^3. The grains and stems are shown in Fig. 2(a), 2(b). The buckwheat grains had triangular pyramid shape, and the shape of short stems was elliptical cylinder. By measurement and statistical analysis, the average dimension of the buckwheat grains was 5.90 mm in height, 3.94, 3.92, and 3.93 mm in three bottom edges. The average sizes of the stems in length, width, and thickness were 79.0, 2.95, and 2.77 mm, respectively.

(a)Buckwheat grain (b) Short stems (c) Buckwheat threshing material

Fig. 2 - Test materials

The sieve structure

In this test, the upper sieve was designed. The round hole sieve (RS) and the square hole sieve (SS) were of planar punching screening surface. Three kinds of non-planar sieve surfaces (convex-column, pit, and wave sieves) were taken into account. According to the specifications of the testbed, Pro/E was employed to design the sieves. The screen frame was made from stainless steel with dimensions 1600×860 mm, its surrounding was covered with a 15 mm edge, and the screen surface's thickness was 2 mm. Let us consider the triaxial dimensions of the buckwheat grains would be less than 8 mm. By this view, the hole size of the upper sieve was controlled to be 8 mm in diameter or length, and the opening rate would be 62%. The lower sieve adopted a round hole sieve of 6 mm diameter. The screen models of the round and square hole sieves have been presented in Fig. 3(a) and 3(b).



(a) Round hole sieve (b) Square hole sieve (c) Concave sieve

(d) Convex-column sieve (e) Object of convex-column sieve (f) Wave sieve

Fig. 3 - Physical models of vibrating screen

The non-planar convex-column sieve

The non-plane convex-column sieve (CCS) was composed of a flat baseplate (i.e., a round hole screen), convex columns, and a screen frame. The convex columns (bolts of M8) were arrayed on the baseplate and fixed by nuts through the screen holes. The layout of the convex columns would have a specific impact on the screening operation; hence, the convex column ratio and the height were commonly exploited to characterize the convex-column screen structure. The convex-column ratio (ρ) was defined as the ratio of the total number of convex columns to the total number of sieve holes:

$$\rho = M/N \times 100\% \quad (1)$$

where: M was the number of convex columns and N was the total number of sieve holes. The convex column height represented the length of the bolt higher than the screen surface, denoted by h.

According to the pre-test results, the convex-column ratio was about 1.0% (one convex column was arranged with 18 holes and 9 holes in order along the length and width directions of the sieve), and the convex-column height was 23 mm. The simulation model as well as the physical drawings were also demonstrated in Fig. 3(d), 3(e).

The non-plane concave sieve

The concave sieve (CS) was a screen with an array of square pits processed on the square hole sieve. In the present scrutiny, 15 square pits of side length 180 mm and of depth 10 mm were designed on the square hole sieve to form a concave screen surface. The simulation model had been shown in Fig. 3(c).

The non-planar wave sieve

The longitudinal section of the wave sieve (WS) was wavy, usually formed by bending a round hole screen with an appropriate width. It formed a curvy surface with five crests and five troughs of radius 30 mm. The simulation model was presented in Fig. 3(f).

Screening performance evaluation

The screening loss rate (S) and the grain impurity rate (H) are usually used as evaluation indexes for screening performance. In the simulation experiment, the grain quantity was counted by using grid cell group instead of grain collecting box and miscellaneous collecting box, and the particle quality was calculated indirectly. The screening loss rate (S) and the grain impurity rate (H) were defined by:

$$S = m_a / (m_a + m_b) \times 100\% \quad (2)$$

$$H = m_c / (m_c + m_b) \times 100\% \quad (3)$$

Where: m_a was the weight of grains discharged from the residual outlet, g. m_b represented the weight of grains under the sieve, g. m_c denoted the weight of stem under the sieve, g.

Methods of DEM simulation tests

Simulation model and parameter setting

The simulation models (Fig.4) for the buckwheat grains and stems were established in EDEM 2.7 according to the material dimensions given in "Test materials". Hertz-Mindlin (no-slip) contact model was implemented, which had been successfully exploited in grain screening and cleaning *(Li Y. et al., 2007; Wu Z. et al., 2019; Li J. et al., 2013).* The simulation parameters were determined by combining the results of the discrete element simulation of agricultural materials at homeland and abroad and the parameters of stainless steel *(Fan R. et al., 2021; Hou H., 2019; Sun J., 2019; Keppler I. et al., 2012; Boac J., 2010).* (See Table 1)

(a) Buckwheat grain (b) Stem

Fig. 4 - Models of simulation

Table 1

Simulation parameters and values

Parameters	Values	Parameters	Values
Poisson's ratio of buckwheat	0.290	Restitution coefficient of buckwheat-buckwheat	0.260
Poisson's ratio of stem	0.400	Restitution coefficient of stem-screen	0.360
Poisson's ratio of screen	0.300	Coefficient of static friction of buckwheat-buckwheat	0.482
Shear modulus of buckwheat [MPa]	34.325	Coefficient of static friction of buckwheat-stem	0.611
Shear modulus of stem [MPa]	5.500	Coefficient of static friction of buckwheat-screen	0.446
Shear modulus of screen [MPa]	70000	Coefficient of static friction of stem-stem	0.600
Density of buckwheat [kg/m^3]	2540	Coefficient of static friction of stem- screen	0.500
Density of stem [kg/m^3]	570	Coefficient of rolling friction of buckwheat-buckwheat	0.290
Density of screen [kg/m^3]	7800	Coefficient of rolling friction of buckwheat-stem	0.505
Restitution coefficient of stem-stem	0.160	Coefficient of rolling friction of buckwheat-screen	0.235
Restitution coefficient of buckwheat-stem	0.220	Coefficient of rolling friction of stem-stem	0.460
Restitution coefficient of buckwheat-screen	0.500	Coefficient of rolling friction of stem-screen	0.300

Sieving simulation test for different sieve surface types

The established models were imported into EDEM2.7 one by one. The material properties, contact parameters, and motion parameters were added. Let us set the surface inclination angle to 5°, screen surface amplitude to 25 mm, vibration direction angle to 6°, and vibration frequency to 3.33 Hz (corresponding crank speed 200 r/min). When the feeding amount rate was set to 0.5 kg/s, the production rate of grains and stems in order were 0.34 and 0.16 kg/s. According to the motion of the stepped shaking plate, the speeds of the material that went into the screen were determined (the horizontal and the vertical sub-speed were 0.433 and 0.25 m/s, respectively). The particle generation and the simulation times in order were 1 s and 5 s. Fig. 5 presents the screening simulation process of the convex-column sieve.

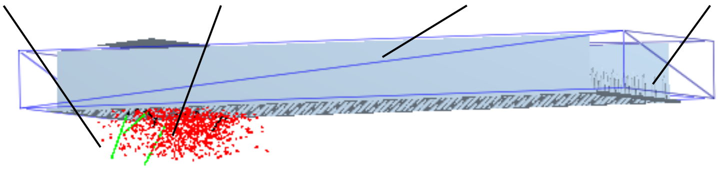


Fig. 5 - Screening simulation process of convex-column sieve

Simulation test of single factor screening based on convex-column sieve

The screening tests were performed according to Table 2. The factors and levels were preliminarily determined by production practice. For instance, the convex-column ratio was determined by pre-test results. The empirical values of other three factors were selected to make the screening process proceed smoothly and had the slightest influence on the dependent variables. The test procedure and other parameters were the same as the sieving simulation test of different screen surfaces in the previous section.

Table 2

Factors and levels of screening test of convex-column sieve surface

No.	Convex-column ratio / (%)	Convex-column height / (mm)	Amplitude / (mm)	Vibration frequency / (r/min)
1	0.267, 1.000, 1.714, 2.500, 3.286	23	25	200
2	1.000	3, 13, 23, 33, 43	25	200
3	1.000	23	15, 20, 25, 30, 35	200
4	1.000	23	25	160, 180, 200, 220, 240

RESULTS

Simulation tests of various sieve surfaces

The screening test results of buckwheat threshing material for five types of screening surface are provided in Fig. 7.

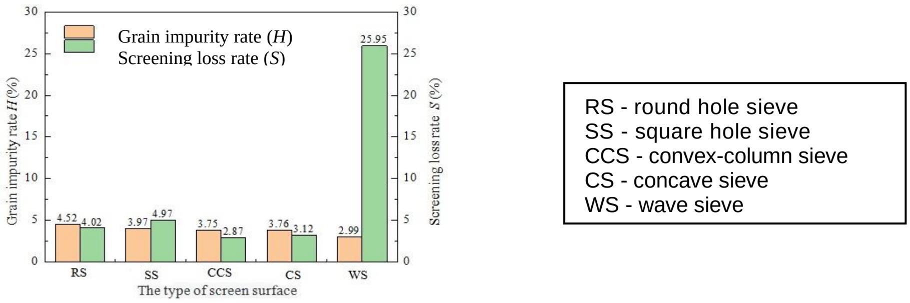


Fig. 7 - Simulation results of five screening surface types

In the figure, we can see that the wave sieve had a smaller impurity rate but the largest loss rate. The impurity rate and loss rate of convex column sieve and pit screen were smaller, they were smaller than the round and square hole screen. On the whole, the screening performance of a non-planar sieve (except wave sieve) would be obviously better than that of a planar sieve under the current test conditions. It is worth mentioning that the wave sieve had a larger loss rate, as high as 25.95%, while the convex-column and the pit sieves had a lower loss and impurity rate. For the case of wave sieve, the stems were primarily concentrated in the trough of the wave sieve, which blocked the sieve holes. As a result, the grains in the trough could not pass through the sieve and mixed in the stems, flowing out of the cleaning chamber and resulting in a considerable loss rate. During pit sieve operation, the whole sieve box evolved into a large screen box composed of several small shallow sieve boxes, which could provide three directions (up and down, front and back, left and right) for materials to pass through the screen, that was, the sieve had three-dimensional sieve penetration *(Shen H. et al., 2012)*.

This structure indirectly lead to the growth of the effective screening area, resulting in a significant reduction of the congestion of the screen; however, it is challenging to design, process, and it is not economical.

In the operation of the convex-column sieve, although the effective screening area was reduced by the convex columns, it loosened and prevented the accumulation of crops with high moisture content during screening. Particularly in the sieve's forepart, the convex column's loose effect was significant since the materials can be easily stratified, not simply blocked, and the screening effect was good.

Single-factor tests based on the convex-column sieve

The screening test results of convex-column screen under single-factor are shown in Fig.8-11. According to Fig. 8, by increasing the convex-column ratio, the screening loss firstly decreased and then grew. Additionally, the grain impurity rate increased considerably for the convex-column ratio in the range of 0.267%~2.5% and slightly lessens when the convex-column ratio varied from 2.5% to 3.286%. For the case of the convex column ratio equal to 2.5%, the maximum impurity rate and the minimum loss rate in order were 3.9% and 2.64%.

In the simulation process, it is found that the loosening effect of the convex column on the material became weak as the convex column ratio increased, and the grains easily mixed in the stems with the screen to push back and out of the cleaning room, resulting in growing losses.

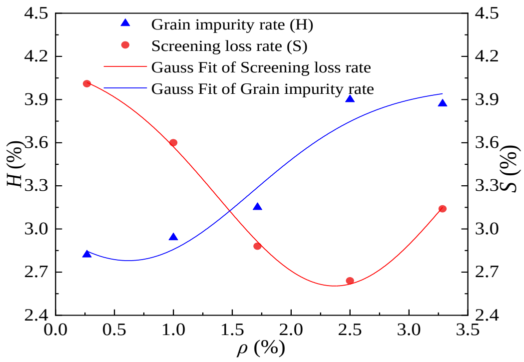


Fig. 8 - Loss and impurity rates under different convex-column ratio

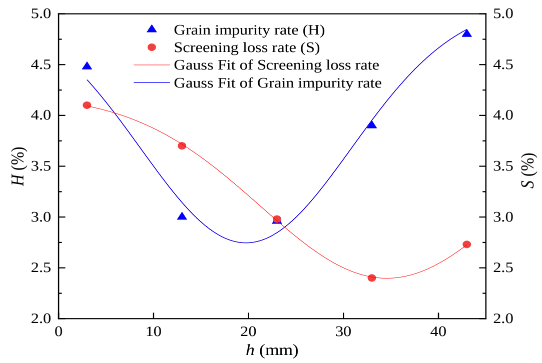


Fig. 9 - Loss rate and impurity rate under different convex-column height

Based on Fig.9, when the height of the convex column was equal to 3 mm, the impurity rate and the loss rate would be 4.48% and 4.10%, respectively, and the screening effect was close to that of the round hole sieve. When the convex column height was 3 mm, the loose effect on the material was not noticeable, and the convex-column sieve was similar to the punching sieve. A short-term accumulation of mixed materials was observed during the simulation when they fell on the vibrating screen. Some stems passed through the sieve due to the applied vibration, while some grains moved to the end sieve under the sieve pushing and fell into the impurity collecting box, causing losses. As a result, the rates of both impurities and losses were high. By growing the convex-column height, the material layer is loose in the height direction, and the material is stratified and screened better; therefore, the amount of loss is reduced, and the impurity became slightly high.

However, when the height increases to a specific range, the movement resistance of the material would increase, and some parts of stems would penetrate the sieve pore openings, growing the impurity yield. At the same time, a tiny part of the grain mix in the stem and finally enter into the impurity collecting box with the stem, resulting in a slight rise of the loss.

As can be seen from Fig.10, when the amplitude varied from 15 mm to 35 mm, both loss and impurity rates decreased in the first branch and then increased as the amplitude magnified. For the case of amplitude equal to 25 mm, the impurity and loss rates were small.

By increasing the vibration amplitude, the movement amplitude of the material on the sieve surface increased as well, and the material would be in a better motion state. The grain went through the sieve holes, the stem moved to the end of the sieve, went into the impurity collection box; therefore, the rates of both impurities and losses would be low.

When the amplitude continued to increase, the movement range of the material on the sieve surface was getting bigger and bigger. The grains jumped to the end of the sieve and jumped out of the cleaning chamber, while parts of the short stem fell into the collecting box through the sieve due to the vibration effect; hence, the grain loss rate increased significantly while the impurity rate slightly grew.

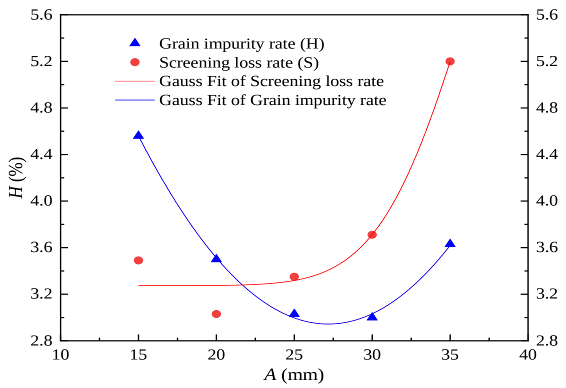


Fig. 10 - Loss rate and impurity content under different amplitude

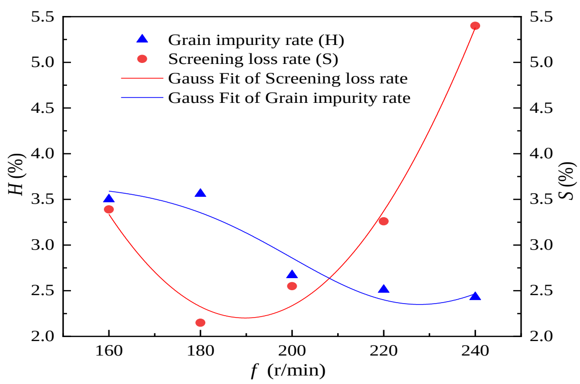


Fig. 11 - Loss rate and impurity rate under different frequency

During the screening process based on the plotted results in Fig. 11, by an increase of the vibrating screen frequency from 160 r/min to 240 r/min, the plot of the grain impurity rate demonstrated a decreasing branch after a slight increase, while the grain loss first decreased and then increased.

For the case of vibration frequency equal to 160 r/min, a considerable loss rate was detectable. This was mainly because of the fact that the smaller frequency resulted in fewer grain beat on the sieve surface and a lower chance of passage through the sieve. By increasing the vibration frequency, the collision times of materials and sieve surface increased. Hence, the probability of sieve penetration increased, the loss rate decreased, while the impurity rate would slightly increase. With the further increase of frequency, the movement of the material on the sieve surface would intensify; that is, the retention time of the stem on the sieve surface would lessen, and the short stem cannot easily penetrate the sieve pores, so the impurity rate would continuously reduce. Nevertheless, buckwheat grains moved faster and faster to the end of the sieve, leading to the loss of grains directly, and thereby, the loss rate rose sharply.

CONCLUSIONS

(1) The performance of the non-planar sieve (excluding wave sieve) was generally better than that of the planar circular hole sieve and square hole sieve under the same motion parameters. The screening effect of non-planar convex column sieve was the best, its impurity rate and loss rate were 3.75%, 2.87%, respectively, followed by the pit sieve, its impurity rate and loss rate were 3.76%, 3.12%, respectively.

(2) The convex-column height, convex-column ratio, vibration frequency, and amplitude all had a certain influence on the quality of screening operation. The convex-column ratio and height significantly influenced the screening performance, and they were of high benefit to the sieving in a particular range. For the sieving of buckwheat threshing material at the harvest stage, the appropriate ranges of the height and the convex-column ratio in order were 13~33 mm and 1.0%~2.5%.

(3) As the moisture content of the mixture decreased in the test, the sieving performance of the convex-column sieve would lessen and even hinder the screening of materials. The moisture content range of the material associated with the superior screening performance of the convex-column sieve is still required to be determined through further tests.

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