Constructive and regime parameters of horizontal impact crusher of grain materials

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Abstract. In order to ensure the best digestibility of feed, all the nutrients included in their composition should be given to animals in crushed form. Particle size of feed is different for all species and age categories of animals. The most common “shock” crushers give up to 30% of the dust fraction and up to 20% of the underground one. Nowadays, impact and centrifugal-rotor grain crushers that use a “slice-chipping” are the most effective ones. The small-sized horizontal impact crusher, which constructive and technological scheme of grinding is fixed in the patents of the Russian Federation, was made for carrying out experiments. The quality of the grinding process was assessed by three different indicators (the degree of grinding, the grinding module and the actual effectiveness of the process). Data on joint and separate grinding of wheat, barley, oats and corn were obtained. The conducted multifactorial experiment showed that the proposed design of the impact crusher allows obtaining up to 98% of the finished product balanced by the particle size at specific energy costs up to 2 WH/kg and productivity up to 260 kg/h. The most rational design and operating parameters of the horizontal impact crusher for various types of grinding were established on the basis of existing standards, zootechnical requirements and the latest scientific research. The developed horizontal impact crusher can be used instead of the widely used small-sized hammer mills, since, in comparison with them, its specific energy consumption is reduced to 50%.

1. Introduction

The agro-industrial complex including agriculture and the food industry which one of subsections is production of feed for animals - the most important sector of the economy of the Russian Federation. The contribution of this sector to the gross national product is up to 20%, of which 15% are in agriculture and 3% in the food industry [1, 2].

To ensure the best digestibility of feed, all nutrients included in their composition should be given to animals in processed form. The main operations of animal feed preparation are cleaning, grinding, dosing and mixing [1, 3].

Grinding creates the conditions for the implementation of all subsequent technological operations. Its implementation accounts for up to 75% of energy and 45% of labor costs. The absence of whole and underground particles, low content of dust fractions and aligned granulometric composition of the crushed grain material not only provide an increase in animal productivity, but also are a criterion for evaluating the efficiency of grinding devices [1, 4].
Particle size of feed is different for all species and age categories of animals. For example, table 1 summarizes the requirements of the national standards of the Russian Federation, which apply to feed grits obtained by grinding feed components to particles of a given size and intended for feeding farm animals [5].

**Table 1.** Indicators controlling granulometric composition (quality) of feed grits according to GOST R standard 54379-2011 at a humidity of not more than 13.5...14.5%.

| Species of animals          | Grit size ratio and permissible deviation (sieve residue) for the lower (min) and upper (max) values of the range |
|----------------------------|-------------------------------------------------------------------------------------------------------------|
|                            | norm - min…max, mm | Norm deviation min…max, % |
| Poultry                    | 1...4               | 18...5            |
| Cattle and small cattle    | 1...5               | 18...0            |
| Pigs                       | 1...5               | 18...10           |
| Fish                       | 1...2               | 3...10            |
| Fur animals, rabbits and nutria | 1...5               | 18...0            |

Modern researches do not always correspond to existing zootechnics rules and applicable standards. Thus, according to scientists from the United States (Kansas state University) [6], the size of feed particles for pigs is within 500 - 900 microns, i.e. 0.5 - 0.9 mm, and according to Russian State Standard GOST R 54379-2011 standard, the same feed should not contain more than 18% of particles less than 1 mm of the total mass.

To obtain the finished product, different principles of destruction are used in grinding grain material machines (crushers): compression, shear, abrasion, impact, cutting and others. The application of a particular principle has a significant impact on the energy intensity of the process and the particle size distribution of the finished product [1].

For example, hammer and impact-centrifugal crushers are widely used in feed preparation lines, which provide a given module of grinding grain depending on the age category of animals and birds. During their operation, the content of the dust fraction increases up to 30% with fine grinding, and underground up to 20% with coarse, which reduces the quality of the finished product and increases the specific energy consumption of the grinding process [7].

It is possible to predict the size of the particles obtained in the process of grinding the material when cutting (chipping). When splitting and breaking, the shape of the particles is unstable, but uniform in size, in other cases, for example, in shock, the separation of the material into parts obtained particles of different sizes and shapes. For this reason, the most effective in recent years are impact and centrifugal-rotor grain crushers using chipping or cutting at the heart of the grinding process [1, 7, 8].

Experimental determination of design-mode parameters of horizontal impact crusher of grain materials aims to obtain optimal performance of the grain size distribution of the finished feed in accordance with modern research scientists, zootechnic requirements and state standards.

2. Materials and methods

For carrying out experimental tests, the experimental small-sized horizontal impact crusher, which design is protected by patents [9, 10] was created on the basis of educational workshops of faculty of mechanization of agriculture of FSBEI of HE “Stavropol State Agrarian University” and is presented in figure 1.
The horizontal impact crusher is mounted on a frame 15 and consists of a hopper 1 for the initial product with a volume of 1.5 l, a stator housing 4 with an outer diameter of 173 mm, an inner diameter of 142 mm, and a rotor 6 with a length (l) of 30 mm, 60 mm and 90 mm (assembly diameter D = 100 mm). The deck of the stator 5, with 1 or more counter-cut (riffle), is installed with a gasket 9 to adjust the working gap δ.

Based on the established diameter, the grooves (riffles) of the rotor were performed in the following geometry step t = 11.5 mm, height h = 1.6 mm in accordance with the known average geometric characteristics of grain crops (wheat, oats, corn, etc.). The number of grooves on the detachable surface of the rotor 7 made 28 pieces. In the interaction with the original product, riffles of the rotor and the stator have the form “edge to edge” for the predominance in the fracture zone shear and the shear stress on grains. The angle of the tip of 60° and angle of inclination of the wall of the corrugation (groove) of 15° are made.

The principle of operation can be described as the uploading of material (grains) in the hopper 1, transport of the product in the area of the destruction of the crushing chamber 14 and withdrawal of the crushed original product from the cavity between the stator and the rotor through the discharge window 11.

At the same time, the experimental horizontal impact crusher of the laboratory installation provides:
- ability to adjust the feed of the original product by means of a rotating damper 2 and moving the hopper 1 in three positions 3 on the stator housing 4;
- various acquisition of the deck 5 with one, two or three counter-cuts, with its installation in different positions 10 on the stator 4;
- reconfiguring or repairing the surface of the rotor 6 by replacing its surface 7 with flutes attached to the base 8;
- ability to change the installation location of the discharge window 11, which has two additional options for the location of 12 on the body 4;
- the possibility of limiting the space in the stator cavity with “lip” 13 to block the zones of the crushing chamber 14 not used in the grinding process.

It is possible to vary the working characteristics:
- feed rate - 0...100 %;
- the clearance between rotor and stator - 0...3 mm;
- the speed of rotation of the rotor with the help of frequency converter made by OVEN company.

The drive of the crusher was carried out by belt transmission from a three-phase asynchronous motor AIR80A6 GOST 2479, powered by a 220 V network (power 0.8 kW, rotation speed 1000 rpm), and the crusher is installed on a sheet of plywood 20 mm thick, tightly fixed to a specially made frame.

To carry out a multifactorial experiment on grinding grain materials in the crusher described above, a three-level plan of the 2nd order of the Box-Behnken was developed and three factors affecting the efficiency of the grinding process in the horizontal impact crusher were determined: the circumferential (linear) speed of the rotor $v_r$, the working gap $\delta$ and the rotor length $l$. As an optimization parameter (response function), the quality of grinding was chosen (uniformity of granulometric composition, the absence of whole and dust particles of grain), which was estimated by the degree of grinding $\lambda$, the grinding module $M$, and the indicator of the actual efficiency of the grinding process of $A_{ep}$ [11].

In the course of preliminary experiments, the ranges of values of the factors included in table 2 were determined.

| Indicator          | Code value | $v_r$, the circumferential speed of the rotor, m/s | $\delta$, specific gap, mm | $l$, rotor length, mm |
|--------------------|------------|-----------------------------------------------|-----------------------------|-----------------------|
| Upper level        | +1         | 8                                             | 1.5                         | 90                    |
| Basic level        | 0          | 5                                             | 1                           | 60                    |
| Lower level        | -1         | 2                                             | 0.5                         | 30                    |
| Variation interval | $\Delta X$ | 3                                             | 0.5                         | 30                    |

A mixture of cereals (35% barley, 17% oats, 24% wheat and 24% corn) was taken as the test material. At the same time, not regulated (constant) factors are taken: one counter-cut on the deck of the stator (more suitable for medium and coarse grinding), the moisture content of the material is not more than 14.5%, the angle of impact of the rotor is minimal based on their possible locations of the loading and unloading window, and the maximum feed rate of grain material.

3. Results

During realization of multifactorial experiment (coarse grinding of a mixture of grain crops: 35% barley, 17% oats, 24% wheat and 24% corn) on a three-level plan of Box-Behnken of the 2nd order, a program was developed in Microsoft Excel, the algorithm of which corresponded to the known method of processing experimental data.

As a result, mathematical models of optimization criteria $M$, $\lambda$, $A_{ep}$ are constructed. The resulting equations were subjected to statistical testing developed by the program according to the criteria of Student and Fisher. The decoded equations are presented below:

\[ Y_{A_{ep}} = 39.3 - 1.5v_r - 5.5\delta - 0.1v_r^2, \]  
\[ Y_M = 2.19 - 0.017v_r + 0.12\delta, \]  
\[ Y_{\lambda} = 1.43 + 0.01v_r - 0.12\delta, \]

We analyze the response surfaces of the equations reflecting the qualitative component of the grinding process.

The response surface of the equation (1) shows that the $A_{ep}$ is higher at a gap $\delta$ up to 0.5 mm and the circumferential speed of the rotor $v_r = 3.6...5.5$ m/s. At an operating gap $\delta$ of more than 1 mm, the actual performance index is lower due to the appearance of underground grains and due to the formation of dust-like fractions at increased circumferential speeds of the rotor (figure 2).
Figure 2. The dependence of the actual efficiency of grinding $A_{ep}$ on the circumferential speed of the rotor $v_r$, m/s and the working gap $\delta$, mm.

In figure 3 a and b, it can be seen that the grinding module has an inverse degree of grinding dependence on the linear velocity and the working gap, which is explained by the different physical meaning of these two quantities. That is, the higher the degree of grinding of the original product, the lower the grinding module (average particle size) achieved and vice versa.

Figure 3. The dependence of the grinding module $M$, mm (a) and the degree of grinding $\lambda$ (b) on the circumferential speed of the rotor $v_r$, m/s and the working gap $\delta$, mm.
The greatest efficiency of the process of grinding a mixture of grain materials in this design of horizontal impact crusher was observed at a maximum rotor length \( l = 90 \text{ mm} \) and its circumferential speed \( v_r = 4.5...6 \text{ m/s} \), when the specific energy costs \( (N_{sp}) \) was up to 2 WH/kg, and the productivity \( Q = 230...260 \text{ kg/h} \).

With separate grinding (medium grinding) of grain material (wheat, barley, oats, corn) in a horizontal impact crusher, the fraction with particles of the required size was 91...98%, which corresponds to the actual efficiency of the process \( \eta_{ep} = 9.2...61.5 \), with a capacity of \( Q = 97...267 \text{ kg/h} \), the specific energy costs \( (N_{sp}) = 1.3...2 \text{ WH/kg} \).

4. Discussing of the results

The experiments allowed us to find out the design parameters at which the maximum efficiency, grinding quality and performance of the experimental horizontal impact crusher are achieved:
- minimum travel of the material during grinding;
- the one influencing counter-cut on the deck of the stator;
- form of working bodies – “tip to tip”;
- the size and shape of the rotor and stator flutes must correspond to the geometric parameters of the crushed grain;
- the smallest possible gap between the tooth and the rotor (close to 0);
- circumferential rotor speed \( 4.5...6.5 \text{ m/s} \).

Analyzing the results of the experiments and the representation of the response surface of the decoded regression equations, it is possible to establish the final rational modes of operation of the horizontal impact crusher when grinding a mixture of crops with one counter-cut on the deck of the stator:
- coarse-grinding \( (M = 2...3 \text{ mm}) \): \( \delta = 0.4...0.8 \text{ mm} \), \( v_r = 4.5 \text{ m/s} \);
- medium-grinding \( (M = 1...2 \text{ mm}) \): \( \delta = 0.3...0.5 \text{ mm} \), \( v_r = 5.2 \text{ m/s} \);
- thin-grinding \( (M = 0.5...1 \text{ mm}) \): \( \delta = 0...0.2 \text{ mm} \), \( v_r = 6.5 \text{ m/s} \).

Summing up, we can say that the decrease and increase in the circumferential (linear) rotor speed from its critical (optimal) value of 4.5...6.5 m/s leads to a deterioration in the actual efficiency of the grinding process. The value of the gap between the working bodies of the rotor and the stator must be kept to a minimum of 0.5 mm. When varying the length of the rotor, you can adjust the performance based on the power of the motor used, without changing the overall design and technological scheme of the horizontal impact crusher.

The developed horizontal impact crusher can be used instead of the widely used small-sized hammer grain crushers, since in comparison with them, its specific energy consumption is reduced to 50%, and 98% of the finished product balanced by the particle size is obtained, which meets the zootechnical requirements for various types of grinding.

5. Conclusions

- Cereals are diverse in varieties and species, hardness (soft and hard), size and weight characteristics and humidity, depending on the method of storage, the region of production and other environmental conditions. The study of physical and mechanical properties of the grain material is needed for further improvement of the design of horizontal impact crushers and manufacture the most progressive of the working bodies of the grinding machines.
- The indicator of \( \eta_{ep} \) in assessing the quality of the grinding process of grain materials is more sensitive to changes in the particle size distribution in comparison with the degree of grinding and the grinding module, as quantitatively takes into account the actual ratio of particle sizes, and not their average value.
- Processing of all crops simultaneously in the presented design of the horizontal impact crusher is less effective than each separately, but even in this case the number of dust fractions (less than 0.25 mm) did not exceed 5%.
- The creation of a combined horizontal impact crusher-mixer consisting of separated working zones along the length of the rotor for simultaneous grinding of various types of feed grain and their
subsequent mixing to obtain homogeneous feed mixtures based on one machine is a promising task that will reduce energy costs, labor of workers and improve the efficiency of the technological process of grinding grain materials.

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