Determination of the main efficiency indicators of forage grain grinder

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Abstract. Grinding of forage grain is a required operation for preparing it for feeding. Crushers, which are widely used for fodder grain crushing, do not provide making a crushed product with a leveled fractional composition, and the grinding process requires high energy intensity. Therefore, the development of alternative grinders that will ensure high-quality grinding of forage grain with less energy is relevant. The article describes the design of the developed test model of a fodder grain grinder of impact centrifugal effect, presents a method for studying its operation when grinding winter rye grain. Grain grinding was carried out with different productive capacity and speed of rotor rotation, and using sieves with holes of different diameters. Based on the study of granulometric composition of the crushed grain, dependence diagrams were plotted that show main quality indicators of grinding process. When using sieves with holes of different diameters, it is possible to obtain a crushed product that meets the requirements of standards for various kinds of farm animals. When comparing energy consumption of a test model of impact centrifugal grinder with hammer-type crushers, the efficiency of using the proposed design of a grinder is confirmed.

1. Introduction
Grinding is an important process in most industries in our country. The importance of producing small-sized materials is explained by the fact that due to increased reactive capacity, their use is technologically and economically more effective than that of large-sized materials. Practical use of most solids is impossible without their preliminary grinding. An increase in volumes while reducing the size of materials being crushed, leads to a sharp increase in energy consumption. The grinding process consumes more than 10 % of the world's energy, only 0.05 % of which is spent on grinding the materials. In this regard, the use of more efficient methods of grinding in new designs of grinding machines is an urgent task.

Forage grain is one of the main diet components for all farm animals and poultry. Preparation of forage grain for feeding includes its crushing (with rare exceptions) to break down the hard shell, and the repeated increase in external surface area of feed particles, thus it is easier for farm animals to chew and digest the feed resulting in good metabolizing of nutrients [1, 2]. Besides, grain grinding causes an increase in the homogeneity of mixing and quality of granules when preparing forage.

When grinding forage grain, it is necessary not only to provide the required grinding module, but also to obtain a crushed product with balanced fractional composition. For this purpose, heavy-duty grinders with high loading speed are widely used. These grinders, in particular, include impact and impact-reflective grinders [2].

Most enterprises use hammer-type crushers for crushing forage grain, which, despite their many advantages, have two significant disadvantages:
• high specific energy consumption (from 6 to 15 kW·h per 1 ton of grinding);
• uneven fractional composition of the crushed product (the content of dusty fraction up to 40 % in fine grinding and up to 20 % of the under-ground fraction in coarse grinding) [3, 4].

Research carried out by a number of scientists on improving hammer-type crushers design do not lead to a significant increase in the efficiency of their work [5–8].

It determines the urgency of developing new and more advanced designs of grinders that would allow us to obtain a homogeneous fractional composition of a crushed product with less energy consumption, in comparison with hammer-type crushers. One of the most promising technical means for grinding forage grain is impact-centrifugal grinders [9–12].

**The purpose of the research** is to carry out experiments on forage grain grinding, using a test model of an impact centrifugal grinder to determine and preliminary evaluate main indicators that characterize the efficiency of its operation.

2. **Materials, methods and objects of the research**

The test model of an impact-centrifugal grinder (Fig. 1) contains the body of the grinding chamber 1, the back wall 2 of which is welded to the frame 3, and the front wall 4 is attached to the back one, using stud pins 5. The hopper 6 has an adjustment damper plate 7, and its neck 8 is welded to the front wall 4. The bearing housing 9 is attached to the back wall 2. The drive of the grinder rotor includes an electric motor 10 and a V-belt transmission 11.

An overall view of the test model of an impact centrifugal forage grain grinder is shown in Fig. 2. The photo (Fig. 2) does not show the bearing housing and V-belt transmission.

The grinding chamber (Fig. 3) contains a housing 1 with a discharging neck 2, inside which there are brackets 3 for attaching passive working bodies, which include sieves 4 and deck plates 5 with impingement plates 6. Active working body- rotor is formed by a solid 7 and an annular 8 disks, between which there are accelerating blades 9, connecting to the disks 7 and 8 with stud pins 10. The rotor is mounted on the drive shaft with a hub 11, which is rigidly connected to the disk 7, and is fixed from radial and axial movements using a key (not shown in the scheme) and a bolt with a washer 12.

The grinder runs as follows. After starting the electric motor 10 (Fig. 1), the adjustment valve 7 is opened and grain from the hopper 6 enters the body of the grinding chamber 1. Then the grains fall on the accelerating blades 9 (Fig. 3), where they move from the center of the rotor to the periphery under centrifugal force. The grinding of grain mass occurs when grains hit the impingement plates 6, when flying out from the accelerating blades 9.

The resulting crushed product under the influence of air flow created by rotation of the rotor passes through the holes of the sieve 4 and is removed through the discharging neck 2.

Many researchers have established the fact that grinding process occurs at impact loading speeds from 60 to 90 m·s⁻¹. In this case, this speed will be the one of grains departure from the accelerating blades.

In this speed range, the lowest energy consumption of the grinding process is achieved, and the content of non-crushed and dust-like particles in the grinding does not exceed the permissible values. Based on the above and within the available technical capabilities, the following values of grinder rotor speed were selected: the minimum value is 2700 min⁻¹, which corresponds to the particle departure speed of 61.5 m·s⁻¹; the maximum value is 4050 min⁻¹, which corresponds to the particle departure speed of 91.9 m·s⁻¹. These speed values were determined for a rotor with a diameter of 380 mm. To change the speed of rotation, replaceable pulleys of different diameters were installed on the rotor shaft.

One of the main characteristics of any grinder is its throughput capacity. Based on the results of a preliminary experiment, empirical values of the grinder capacity were established, which are convenient to use when planning experiments. The maximum capacity at which the grinder can operate without overloading was 1500 kg·h⁻¹. The minimum one was 500 kg·h⁻¹. Below this value energy consumption of the grinding process increases significantly. The average capacity value is defined as arithmetic mean and is 1000 kg·h⁻¹.

To account for electricity costs, a wattmeter built into the electric network of the electric motor was used.
**Figure 1.** General scheme of the test model of the grinder: 1 – grinding chamber body; 2 – back wall; 3 – frame; 4 – front wall; 5 – stud pin; 6 – hopper; 7 – damper plate; 8 – neck; 9 – bearing housing; 10 – electric motor; 11 – V-belt transmission.

**Figure 2.** Overall view of the test model of the grinder: 1 – grinding chamber housing; 2 – back wall; 3 – frame; 4 – front wall; 5 – stud pin; 6 – hopper; 7 – damper plate; 8 – neck; 9 – bearing housing; 10 – electric motor; 11 – V-belt transmission.
Grain material used for experiments is winter rye of the “Falenskaya 4” variety.
To evaluate quality of forage grain grinding, average size of the crushed particles was determined by selecting an average sample from a portion of the crushed product, followed by determining its granulometric composition using a set of sieves and sieving.

3. Research results
The design feature of the impact-centrifugal grinder under consideration is a sieve with holes and decks with impingement plates which are made in the form of sectors that are attached to brackets inside the grinding chamber. There are six sectors in total, with a coverage angle of 60°, respectively. On the layout scheme of working bodies (Fig. 3) each sector is assigned an ordinal number (from 1 to 6) in the counterclockwise direction. Experiments were carried out to assess the influence of the number of deck plates with impingement plates on the efficiency of grain grinding and on the throughput capacity of the grinder. The lowest capacity equal to 500 kg·h⁻¹ was chosen, as well as sieves with a gage of 6 mm and 7 mm. With an increase in the number of deck plates with impingement plates, coverage angle of the ring space around the rotor increases, while coverage angle of the sieves decreases. It led to a significant deterioration in the evacuation of grinding product from the grinding chamber housing through the discharging neck. A further increase in productivity to 1000 kg·h⁻¹ with the simultaneous installation of three deck plates with impingement plates led to a sharp increase in the load on the motor, followed by an emergency stop. It happened due to a threefold decrease in the area of the live section of sieves, which had a negative influence on the evacuation of crushed material. The multiplicity of circulation of the crushed material in the grinding chamber housing increased, which, in turn, led to an increase in the content of the dust fraction in the grinding product and to increase in energy costs for grinding process.
Installing a deck plate with impingement plates into sector 6 will worsen the conditions for evacuation of crushed material, since most of the discharging neck will be blocked. The experiments were carried out at a rotor speed of 2700 min\(^{-1}\). This is the actual lowest speed of impact loading of crushed particles in the grinder under consideration, which is 61.5 m·s\(^{-1}\). At a higher speed of rotor rotation, the process of grain grinding and its subsequent unloading will be more effective.

In the grinding chamber, deck plates with impingement plates were installed on sectors 1, 2 and 3 (Fig. 3). This sequence is selected taking into account the kinematics of crushed particles movement in the grinding chamber. The thing is, crushed material particles that fall from the center of the rotor to the moving accelerating blade, located in the lowest position, begin to interact with the impingement plates of the deck plate, located in sector 1. In this regard, the question arises of determining the optimal number of deck plates with impingement plates necessary for the effective grinding process.

The results of experiments in using sieves with holes of 6 mm in diameter were obtained. When using a single deck plate with impingement plates (experiment no.1), installed on the 1st sector in the working grinding chamber (Fig. 3), the average size of the crushed particles was 1.19 mm, power consumption was 4138 W. The content of dusty fraction in the grinding product was 3.6 %. When using two deck plates with impingement plates (experiment no.2) installed on sectors 1 and 2, the average size of crushed particles decreased by 14 % compared to the previous experiment no.1, power consumption increased by 4 %; the content of dust fraction increased by 24 % compared to experiment no. 1. To carry out experiment no.3, three deck plates with impingement plates were installed on sectors 1, 2 and 3. Average size of crushed particles compared to experiment no.2 remained unchanged and was 1.02 mm. Power consumption increased by 6 % compared to experiment no.1 and was 4396 W. The content of dusty fraction in the grinding product was 5.4 % – this exceeds the value obtained in experiment no.1 by 43 %.

The results of experiments in using sieves with holes of 7 mm in diameter are as follows. In experiment no.4, where a single deck plate with impingement plates was installed in sector 1, an average size of crushed particles was 1.17 mm. Power consumption was 3983 W; dust content in the grinding product was 2.6 %. When installing two deck plates with impingement plates on sectors 1 and 2 (experiment no.5), an average size of crushed particles decreased by 4 % compared to experiment no.4. Power consumption increased by 4 %, and the content of the dust fraction increased by 4 %. In experiment no.6, when installing three deck plates with impingement plates on sectors 1, 2 and 3, an average size of crushed particles was 1.09 mm. This indicator is lower than in experiment no.4 by 7 %. Power consumption was 4285 W, which is 7 % more than in the experiment no.4. The content of the dust fraction increased by 37 % compared to experiment no.4 was 4.1 %.

Comparing the results obtained, we can note the following. With a decrease in diameter of sieves holes, while increasing the number of installed deck plates with impingement plates, in all cases, there is an increase in power consumption for the grinding process. In experiments no.3 and no.6, the content of the dust fraction in the crushed material increases significantly, which indicates that the material is delayed in the working grinding chamber before unloading. In experiments no.1 and no.2, no.4 and no.5, the difference in values of an average size of crushed particles and the content of dusty fraction is insignificant. But the power consumption is less in experiments with one deck plate with impingement plates compared to the experiments with two deck plates with impingement plates. All mentioned above indicates the efficiency of grinding process when using sieves with holes of 6 mm and 7 mm and one deck plate with impingement plates installed on the 1st sector of the working grinding chamber.

Here are the results of experiments obtained using sieves with holes of 4 mm, 5 mm, 6 mm, 7 mm and one deck plate with impingement plates installed on the 1st sector of the working grinding chamber (Fig. 3).

The results of experiments on grinding of rye forage grain using the studied sieves at the grinder capacity of 1000 kg·h\(^{-1}\) are presented in the form of graphs in Figure 4.
Figure 4. Dependence graph of average size of the crushed grain particles on the diameter of sieve holes at the rotor rotation frequencies studied.

If the rotor speed is 2700 min\(^{-1}\) and when using sieves with holes of 4 and 5 mm in diameter, average size of the crushed grain particles is in the range of 0.928 to 0.996 mm, which corresponds to fine grinding with an average particle size of 0.2 to 1.0 mm. At the same rotor speed and when using sieves with holes of 6 mm and 7 mm in diameter, the average size of the crushed grain particles was in the range of 1.03 and 1.19 mm, which corresponds to middle grinding with an average particle size of 1.0 to 1.8 mm.

At a rotor speed of 4050 min\(^{-1}\), fine grinding was obtained using all sieves: average size of the crushed grain particles was 0.742...0.857 mm.

Describing the dependencies (Fig. 4), we can note the following thing. If the rotor speed is 2700 min\(^{-1}\), we can adjust the average size of crushed grain particles, changing sieves with holes of different diameters. And if the rotor speed is 4050 min\(^{-1}\), when using sieves with holes of 5 mm, 6 mm and 7 mm in diameter, we get a product with almost the same average size of particles. With middle capacity of the grinder under study and rotor rotation speed of 4050 min\(^{-1}\), it is impossible to adjust the size of the grinding product.

Thus, it is obvious that the speed of grains departure from accelerating blades at rotor rotation speed of 2700 min\(^{-1}\), equal to 61.5 m·s\(^{-1}\), is sufficient for their grinding and obtaining crushed particles of various sizes when using sieves with holes of different diameters. Thus, rotor rotation frequency, equal to 4050 min\(^{-1}\), is redundant. Increasing rotor rotation speed to the values of 2900...2950 min\(^{-1}\) is justified only for compact grinders, which rotor is mounted directly onto electric motor shaft.

Forage grain is the basis for the production of concentrates, so to evaluate forage grain grinding quality one must follow normative documents regulating quality indicators for feed concentrates:

- GOST (State Standard) 9268-2015 Feed concentrates for cattle. Specifications;
- GOST (State Standard) 10199-2017 Feed concentrates for sheep and goats. General specifications;
- GOST (State Standard) R 51550-2000 Feed concentrates for pigs. General specifications.

The main indicators of quality include the following ones: residue on a sieve (per cent) with 5 mm size of cell side; sieve residue (in percent) with 3 mm cell width, passing through a sieve (in percent) of 1 mm size of the cell; content of particles (per cent) less than 0.25 mm in size.

In Table 1 there are quality indicators of grain grinding, based on the study of granulometric composition of the crushed product.
Table 1. Quality indicators of grain grinding at a productivity of 1000 kg·h⁻¹ s for the studied rotor rotation speeds

| Rotor rotation speed, min⁻¹ | 2700 | 4050 |
|-----------------------------|------|------|
| Diameter of the sieves holes, mm | 4 5 6 7 | 4 5 6 7 |
| Residue on a sieve with 5 mm size of cell side, % | 4.0 0.3 1.8 2.1 0.3 0.5 0.5 0.5 |
| Residue on a sieve with 3 mm size of cell side, % | 36.4 25.6 27.0 10.6 48.9 44.0 45.1 44.1 |
| Passing through a sieve with 1 mm size of cell side, % | 36.4 25.6 27.0 10.6 48.9 44.0 45.1 44.1 |
| Content of particles less than 0.25 mm in size | 6.9 6.7 3.8 3.1 18.8 14.7 12.6 10.3 |

Table 1 data analysis shows that the quality of the crushed product obtained at the rotor speed of 2700 min⁻¹ meets the requirements. There are no grains left in sieving. At the same time, in experiments with a rotor rotation speed of 2700 min⁻¹, there are twice less particles less than 0.25 mm in size, than in experiments with a rotor rotation speed of 4050 min⁻¹, and significantly less than in grinding grain material with hammer-type crushers.

Experiments have been carried out in grinding of forage grain in an impact centrifugal grinder at a rotor rotation speed of 2700 min⁻¹ for capacity range under consideration. The results obtained are presented as graphs in figures 5 and 6, and the data about certain granulometric composition are shown in table 2.

During the experiments, it was found that an electric motor with a power of 5.5 kW cannot provide a capacity of 1500 kg·h⁻¹ when using sieves with holes of 4 mm and 5 mm in diameter. When grain material is being fed, the electric motor overloaded, followed by an emergency stop. The diagrams (Fig. 5 and Fig. 6) do not contain data on the average size of grain grinding and power consumption for grinder capacity of 1500 kg·h⁻¹.

![Figure 5](image-url)  
**Figure 5.** Diagram of an average size of the crushed product particles dependence on the diameter of the sieve holes for the studied grinder capacity.
For normal operation of the grinder at high capacity when using sieves with a gage of 4 mm and 5 mm, we need to install a more powerful electric motor. At the same time, it is possible to increase the grinder capacity up to 2000 kg·h\(^{-1}\) when using sieves with a gage of more than 6 mm.

When analyzing the data in figure 5, we should note the following items. For sieves with a gage of 7 mm, the difference between the minimum and maximum values of an average size of crushed particles was 6 %. For sieves with a gage of 6 mm, this difference was 15 %, while the maximum particle size was obtained at a capacity of 500 kg·h\(^{-1}\). For sieves with a gage of 5 mm and 4 mm, difference in the average particle size was 6 % and 1.1 %, respectively. In general, we can say that with increasing capacity, the average size of the crushed product particles changes slightly (within the range of 0.1...0.2 mm).

The diagram data in Figure 6 is quite natural: when increasing the capacity of the grinder while reducing the diameter of the sieve holes, there is an increase in power consumption for the grinding process. Since the diagram does not show all the power data for the 1500 kg·h\(^{-1}\) capacity, we will compare the power consumption for the grinding process for the 500 and 1000 kg·h\(^{-1}\) capacity of the grinder. For a sieve with 7 mm holes, the difference was 10 %; for a sieve with 6 mm holes, 16 %; for a sieve with 5 mm holes, 20 %; for a sieve with 4 mm holes – 16 %. When the sieves’ diameter decreases from 7 mm to 5 mm, the power consumption difference increases. When the diameter of the sieve holes decreases further, the difference in power consumption decreases. This is due to a decrease in the throughput capacity of the grinder and an increase in the multiplicity of material circulation inside the working chamber of the grinder.

| Table 2. Grain grinding quality indicators for the studied capacity range at a rotor speed of 2700 min\(^{-1}\) |
|---------------------------------------------------------------|
| Grinder capacity, kg·h\(^{-1}\) | 500  | 1000  | 1500  |
| Sieve holes’ diameter, mm | 4  | 5  | 6  | 7  | 4  | 5  | 6  | 7  | 4  | 5  | 6  | 7  |
| Residue on a sieve with 5 mm size, % | – | – | – | – | – | – | – | – | – | – | – | – |
| Residue on a sieve with 3 mm size, % | 0.5 | 0.3 | 3.8 | 1.7 | 0.4 | 0.3 | 1.8 | 2.1 | – | – | 0.1 | 2.9 |
| Passing through a sieve with 1 mm, % | 36.8 | 31.4 | 13 | 15.7 | 36.4 | 25.6 | 27 | 10.6 | – | – | 20.4 | 10.3 |
| Content of particles less than 0.25 mm in size | 8.4 | 7.9 | 3.6 | 2.6 | 6.9 | 6.7 | 3.8 | 3.1 | – | – | 5.5 | 2 |
Table 2 Data analysis showed that the quality indicators of the crushed product meet the current requirements for the studied capacity range.

![Energy consumption diagram](image)

Figure 7. Dependence diagram of energy consumption of the grinding process on the diameter of the sieve holes for the studied capacity of the grinder.

Dependence diagram of energy consumption of the grinding process on the diameter of the sieve holes, shown in Figure 7 is of practical interest. In comparison with the diagram shown in figure 6, the things are different. With the increased capacity, the energy consumption of the grinding process is reduced. Since energy consumption value is proportional to the amount of power consumed, when it is compared for the capacities of 500 and 1000 kg·h\(^{-1}\), a similar change in the percentage difference will be observed, but in the direction of decreasing.

From the point of view of production operation of the studied impact-centrifugal grinder in comparison with similar hammer-type crushers, we should note the following items. At maximum capacity of the grinder, there is minimum energy that, when using sieves with holes of 6 and 7 mm in diameter, is about 3.5 W·h·kg\(^{-1}\), which significantly reduces the energy intensity of hammer-type crushers. For comparison, we can give the test results of two hammer (not pneumatic) crushers:

- the energy consumption of the DM-4-1 crusher produced by JSC "Slobodskoy machine-building plant" with an average size of crushed product particles of 1.3 is 6.59 W·h·kg\(^{-1}\) [13];
- the energy consumption of the ACR-1 crusher produced by JSC «Remmash» with an average particle size of 1.4 mm is 6. W·h·kg\(^{-1}\) [14].

4. Conclusions

1. We proposed the design of a test model of an impact centrifugal grinder, which provides forage grain grinding in accordance with zootechnical requirements for various kinds of farm animals.
2. We determined that rotor rotation speed of an impact centrifugal grinder with a diameter of 380 mm, sufficient for an effective process of grinding forage grain, was 2700 min\(^{-1}\).
3. We established experimentally that it is necessary to install one deck plate with impingement plates in sector 1 of the working grinding chamber for effective grinding of grain material when using sieves with a gage of 6 mm and 7 mm. The use of a single deck plate with
impingement plates installed in sector 1 of the working grinding chamber, and sieves with holes of 4 mm and 5 mm in diameter, will avoid over-grinding of grain material and over-consumption of energy for the grinding process.

4. We established that an electric motor with a power of 5.5 kW, when using sieves with holes of 6 mm and 7 mm in diameter can provide grinder capacity equal to 1500 kg·h\(^{-1}\), with the lowest energy consumption of the grinding process. When using sieves with holes of 4 mm and 5 mm in diameter, the grinder will provide capacity of up to 1000 kg·h\(^{-1}\).

5. We confirmed experimentally that the minimum energy consumption of the grinding process is provided with the maximum grinder capacity. For sieves with holes of 6 mm and 7 mm in diameter, the energy consumption is 3.5 W·h·kg\(^{-1}\), which, in turn, is 1.9 times less than that of DM-4-1 hammer-type crusher and 1.8 times less than that of ACR-1 hammer-type crusher under the same operating conditions.

6. To get a high-quality product for pigs using an impact centrifugal grinder, forage grain must be crushed using sieves with a gage of 4 mm, 5 mm and 6 mm (depending on the age of the animals). For cattle, sheep and goats, forage grain must be crushed using sieves with holes of 6 mm, 7 mm and 8 mm.

The positive aspects of the scientific research presented include the fact that a new design of an impact centrifugal grinder has been developed, and it differs from existing analogues in its compactness, easy maintenance, and low metal content. The design of the grinder is quite simple, that will allow every specialist to make it in the conditions of repair and mechanical workshops of agricultural enterprises. Due to the low metal content of the unit, the cost of purchased materials required for grinder’s original parts making won’t be high. It will reduce the payback period of an agricultural enterprise’s investments required for manufacturing or purchasing of the impact centrifugal grinder designed.

The design of the working grinding chamber provides for the installation of sieves with holes of the required diameter and deck plates with impingement plates in six sectors. To carry out an effective grinding process, it is enough to install one deck plate with impingement plates onto 1 sector of the working grinding chamber. To get a high-quality product of forage grain grinding for different kinds and ages of animals, it is enough to use sieves with a gage of 4 mm, 5 mm, 6 mm, 7 mm, installed on five sectors of the working grinding chamber. If necessary, one can easily replace one sieve with another.

The disadvantages of the impact centrifugal grinder developed include the fact that when installing sieves with holes of 4 mm and 5 mm in diameter, it does not provide the maximum possible capacity. At the same time, there is a significant increase in the energy intensity of the grinding process.

The most common equipment for grinding of grain materials are hammer-type crushers. When using them, the grinding of grain material occurs due to impact of moving hammers. That’s why their intensive wear occurs, resulting in frequent replacement, accompanied by partial or complete assembling – disassembling of the grinding chamber.

The impact-centrifugal grinder is almost devoid of this problem, since the grinding process is organized in a slightly different way: two working bodies participate in the grinding process – the accelerating blades rotating together with the rotor and the impingement plates fixed on an immovable deck plate.

The research results discussed above are a continuation of the authors’ work in the development of new energy-efficient equipment for bulk materials grinding. It is possible to use the results of the research to create complex forage units.

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