Crushing feed grain involves hammer crushers, which are characterized by high specific energy consumption and its uneven fractional composition. It is possible to obtain high-quality shredded grain with less energy when using a centrifugal-impact crusher of the new design with a hole in the loading neck to supply the chopping chamber with additional air at a rate of up to 4.8 m/s. An additional hole provides a 1.8...13-time increase in the airspeed through the unloading neck when the rotor's rotation frequency changes from 3,750 to 2,250 min^{-1}, thereby enabling the timely evacuation of the shredded material from the crusher.

The regression equations have been derived to determine the structural and regime parameters of the shredder, which ensure the maximal performance and minimal unit energy costs. The greatest impact on crusher productivity is exerted by the diameter of the sieve holes and the area of the bunker's unloading window. The greatest effect on the specific energy intensity of the grinding process is exerted by the diameter of the sieve holes. The maximal performance of the crusher, 1,440 kg/h, and the minimal energy capacity, taking into consideration the achieved grinding degree, of 2.1 W·s/(kg·grinding degree unit), are observed when using a sieve with the holes' diameter of 7 mm, the rotor's rotation frequency of 3,500 min^{-1}, and the maximally open unloading window of the bunker, at F=1.458 m^2·10^{-3}. The specific energy consumption for chopping barley is less by 1.22...1.89 times than that of the hammer crushers RVO 35, DB-5, KD-2A. The dust-like fraction is less than 5.74 %, which is half the amount of the hammer crusher DM-6. The rational crusher operation modes have been determined in order to prepare feed grain for feeding farm animals of different species and ages

Keywords: feed grain, centrifugal-impact crusher, coarsely ground grain, grain grinding degree, grain crusher

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STUDYING THE OPERATIONAL EFFICIENCY OF THE CENTRIFUGAL-IMPACT FEED GRAIN CRUSHER OF THE NEW DESIGN

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1. Introduction

Modern livestock puts forward, as a consumer, increasingly stringent requirements for the quality of feed. Feed costs reach 65...75 % of the total production costs in pig and poultry production. Feed grain is one of the most important and most expensive feed for farm animals. Its effective use is one of the factors influencing the productivity of animals and the level of cost of their maintenance.

Preparing feed grain for feeding involves grinding it [1, 2] to produce coarsely ground grain of the required granulometric composition. The particle size of the coarsely ground grain, fed to farm animals, affects nutrient absorption, animal productivity, and health [3].

Most enterprises use hammer crushers to grind feed grains, which, despite many advantages, have two significant drawbacks. The first is a high unit energy consumption of 6...15 kWh per 1 ton of grinding. The second drawback is the uneven fractional composition of the shredded product, the content of a dust-like fraction is up to 40 % at fine grinding, and up to 20 % of the incompletely ground fraction at coarse grinding [4].

It is possible to obtain shredded material with an aligned granulometric composition that meets zoo-technical requirements when grinding grain at centrifugal-impact crushers [5, 6]; this ensures the specific energy consumption within 3.3...4.5 kWh/t [6–8].

The main drawback of these crushers is a significant reduction in the quality of the chopping, clogging the working chamber with an increase in the supply of the material, over 1,000 kg/h. This is due to the imperfection of the rotor and deck design, the weak airflow inside the chopping chamber, which does not sufficiently promote the material's particles flow from the inlet to the outlet, and the cleaning of the working bodies. In most known centrifugal crushers, the removal of shredded products is largely due to centrifugal force, without the involvement of gravity.

It is a relevant task to design a centrifugal-impact shredder of feed grain with a capacity exceeding 1,000 kg/h, capable of producing coarsely ground grain that meets the zoo-technical requirements for all major species and sexually-age groups of farm animals while reducing specific energy costs.

2. Literature review and problem statement

Grains are not only one of the main human foodstuffs but also the most important and irreplaceable food for most farm animals and poultry. According to FAO (Food and Agriculture Organization of the United Nations), global cereal production in 2019 amounted to 2,708.5 million tons, including 1,446.2 million tons of feed grain, or 53.39 %. According to the forecast for 2020, 2,790 million tons, including feed grain – 1,519 million tons (feed grain, 52.07 %) [9].

There are many ways to prepare feed grain for feeding – crushing, roasting, boiling, and steaming, malting, fermentation, yeasting, extrusion, micronization, exposure to the magnetic field of ultra-high frequency. These grain preparation techniques for feeding are used in order to increase the grain feed value and its decontamination; they, however, do not meet the zootechnical requirements for the size of particles. When applying these techniques, grains must be crushed before or after processing.

The grinding of feed grain is a mandatory operation and should make it possible to obtain a homogeneous granulometric composition of grinding, with a minimum content of whole grains and dust-like fraction [10]. The average size of chopped feed particles should not be minimally possible but optimal for a given species and age of animals. Feed with a high dust-like fraction is dangerous not only by reducing nutrient absorption but can also lead to various diseases and even animal deaths [3].

Thus, for example, when feeding pigs on fattening with feed with an average particle size of 1.159 mm, 67 % of them, after slaughter, had a normal stomach without any diseases. At feeding with an average feed particle size of 0.711 mm, 50 % of animals experienced stomach erosion. When feeding with an average feed particle size of 0.456 mm, the animals showed not only erosion but also stomach ulcers. When the grain crushed into flour is fed (the average particle size is less than 0.25 mm), the death of animals begins [3].

In the world, at least 95 % of all feed grains are crushed by various hammer crushers, which differ in their technological, kinematic, and structural parameters [11–13]. Hammer crushers have a significant drawback – the high specific energy consumption. For example, the DB-5 crusher (Russia) and its analogs, AKR-1 (Russia), DKM-5 (Russia), whose electric motor power is 30 kW, have a capacity of up to 5 t/h, with a specific energy consumption of at least 6 kWh/t; the KDU-2 (Russia) crusher, and its analogs KD-2A (Russia), KDM-2 (Russia), have a capacity of up to 3 t/h with a 22 kW electric motor power – the specific energy consumption of at least 7.33 kWh/t [14, 15]. One of the best crushers in its segment is the NEUERO RVO 35 (Germany): it has a capacity of up to 1.585 t/h with a 7.5 kW electric motor power – the specific energy consumption is at least 4.73 kWh/t [16]. The crushers A1-DMR-12 (Russia) and Van Aarsen HM-700-2D (The Netherlands) have a capacity of up to 12 t/h with 110-kW engine power, the specific energy consumption is least 9.17 kWh/t [17].

Pneumatic hammer crushers enable pneumatic grain flow through the ejector and a suction pneumatic mass line to the working chamber, as well as the pneumatic transportation of the crushed product through the pumping pneumatic mass line. They do not require peripheral conveyors but have a higher specific energy consumption. Thus, the KU-203 crusher (Russia) has a maximum performance of 2.5 t/h with a rated engine power of 22 kW [18] – the specific energy consumption is at least 8.8 kWh/t; the PDM-18.5 (Russia) crusher has a maximum capacity of 2.1 t/h at a rated engine power of 18.5 kW [19], the specific energy consumption is at least 8.8 kWh/t; the DOZAmeh H-119/3 crusher (Poland) has a maximum performance of 2 t/h at a rated engine power of 18.5 kW, the specific energy consumption is at least 9.25 kWh/t [20].

In addition, hammer crushers are characterized by heterogeneity of the granulometric composition of the ground product, high metal consumption, significant repair costs due to the small resource of their working bodies.

It is possible to obtain the high-quality shredded grains at minimal energy costs when using the centrifugal-impact shredders whose rotor has fixed shoulder blades, while, inside the working chamber, around the rotor, there is a sieve and a deck with reflectors. Both hammer and centrifugal-impact shredders destruct grains by a free impact. The fundamental difference is that in hammer crushers the impact is applied to the grain by a hammer, connected via a hinge to the rotor, which moves in the circle. In the centrifugal-impact shredder, the rotor's blade is used to accelerate a grain to a speed of 80...100 m/s to be destroyed by a blow against a stationary reflector on the deck. In this case, grain destruction is much more effective than when grinding with free hammer blows [5, 6]. This produces a shredded material with a more uniform granulometric composition that meets zootechnical requirements while the specific energy consumption is 3.3...4.5 kWh/t [6–8].

There is a centrifugal shredder of feed grain [21], which has a body with an unloading neck, a lid with a loading bunker and a movable gate, and an electric motor. Within the body, directly on the shaft of the electric motor, a rotor with flat blades is fixed with the ability to install them at an angle from 0° to 45° to the diameter of the rotor in the direction of rotor rotation. Inside the body, six flat brackets are used to host, around the rotor, slabs with reflectors and sieves with holes of the required diameter. The drawbacks of this crusher are:

– the presence of two slabs with reflectors and six flat brackets significantly reduces the area of the usable cross-section of the sieve holes, which worsens the evacuation of the shredded product from the working chamber and reduces the capacity of the grinder;

– for compact shredders with a small rotor diameter, which is mounted directly on the shaft of the drive electric motor, it is difficult to reach the speed of grain movement on the blades of the rotor that would be sufficient to grind them when hitting the reflectors;

– the use of reflectors with a square cross-section and the crusher's rotor with the blades radially mounted on it leads to a decrease in the intensity of the grinding process because the particles hit against the reflectors out of the perpendicular;

– the space between the reflectors with a square cross-section is clogged with the material's particles, which leads to a decrease in capacity and an increase in cleaning costs.

There is a centrifugal crusher of feed grain [22], similar in design to the previous one, which has a mechanism that makes it possible to push the blades of the rotor as they wear, and regulate the intensity of grinding. However, this technical solution leads to a complicated rotor design, increased labor costs for the maintenance of the crusher, and a high probability of the rotor imbalance.

The common major drawbacks of known centrifugal-impact shredders include a significant reduction in the quality of grinding, clogging of the working chamber at an increase in the feed of material. This is due to the weak airflow inside the shredding chamber, which does not sufficiently promote the motion of material particles from the inlet to the outlet and the cleaning of the working bodies. In addition, the unloading branch pipe axis deviates from the vertical position; the removal of shredding products is largely due to the action of centrifugal force, without the participation of gravity.

The imperfection of the structure, the lack of detailed studies into the operational process of centrifugal-impact shredders inhibits their widespread practical application in the national economy.

3. The aim and objectives of the study

The aim of this study is to define the patterns of the influence of the structural and technological parameters of a grinder of the new design on the performance of the grain grinding process.

To accomplish the aim, the following tasks have been set:

– to establish the effect of the rotor's rotation frequency and the presence of a hole for the selection of air and feed into the chopping chamber in the loading branch pipe on the speed of air in the unloading neck of the crusher;

– to build regression equations that describe the effect of the rotor's rotation frequency, the diameter of the sieve holes, the area of the bunker's unloading window on the performance, and specific energy intensity of the barley grinding process;

– to assess the quality of grinding feed grain with a centrifugal-impact crusher and determine the rational modes of its operation when grinding feed grains for animals of different species and ages.

4. Materials and methods to study the centrifugal crusher of feed grain

The study involved a centrifugal-impact crusher of feed grain [23] with bed 1 (Fig. 1) onto which working chamber 2 is attached. The working chamber hosts sieve 3, rotor 4 with flat blades, rotated in the direction of rotation to the diameter of the rotor at 10°, and deck 5 with reflectors of the trapezoidal cross-section. The sieve and deck are attached to brackets 6. Removable filter bag 8 is attached to unloading neck 7. located at the bottom of the working chamber. Bunker 9 with adjustable flap 10 via loading neck 12 is attached to the front wall of the working chamber. The loading neck has an air selection hole for feeding into the chopping chamber with gate 11. The rotor's drive shaft is located in the case of bearings 13. The drive is enabled by electric motor 15, controlled by a frequency controller, through V-belt transmission 14.

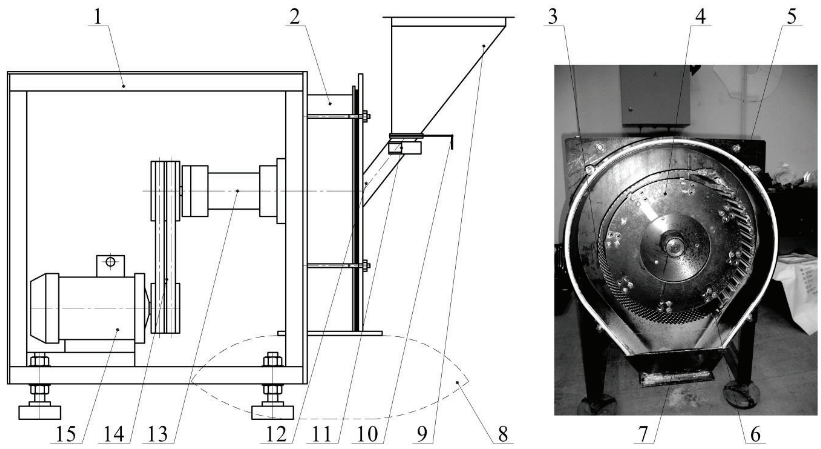

Fig. 1. Feed grain crusher: 1 — bed; 2 — work chamber; 3 — sieve; 4 — rotor; 5 — deck; 6 — bracket; 7 — unloading neck; 8 — filter bag; 9 — bunker; 10 — adjustable flap; 11 — hole with a gate; 12 — loading neck; 13 — bearing case; 14 — V-belt transmission; 15 — electric motor

The technical problem of grinding feed grain in order to obtain the high-quality ground grains that meet zootechnical requirements at minimal energy costs of the process with a maximum capacity has been solved by the following:

– the installation of flat blades on the rotor with an inclination angle to the rotor diameter in the direction of its rotation of 10°;

– the rational placement and fixing of the deck with reflectors and a sieve using two brackets only;

– the use of reflectors with the trapezoidal cross-section;

– the cutting of a hole in the loading neck to select air and feed into the chopping chamber;

– the vertical orienteering of the unloading neck of the chopping chamber.

The crusher operates in the following way. The grain is fed from the bunker by gravity through the loading neck when the adjustable flap and gate are opened. In this case, a hole in the loading neck wall provides the supply of air to the work chamber. The grain accelerates to a speed of 80...100 m/s when moving on the blade of a rotating rotor and, when coming off the blade, is directed to the deck, where it is crushed when hitting the reflectors.

The particles formed during the destruction of grains by the airflow are carried through the holes of the sieve into the unloading neck and leave the work chamber.

If the size of the crushed particles is too large to pass through the sieve holes, they rotate in the air-product layer and are subjected to repeated blows against the reflectors of the deck until crushed to the required size.

We studied the operational effectiveness of the centrifugal-impact crusher using barley of the «Gonar» variety; in accordance with the Box-Benkin plan, we performed a three-factor three-level experiment.

The optimization parameter (Fig. 2) used was the specific energy intensity, E, W·s/(kg·grinding degree unit), which was determined from the following dependence:

$$E = \frac{N}{Q \cdot \lambda}, \qquad (1)$$

where N is the power consumed, W; Q is the performance of the crusher, kg/s; λ is the degree of grinding.

The basic variable factors adopted are:

– n is the frequency of rotation of the rotor, min^{-1};

– d is the diameter of the sieve holes, m;

– F is the area of the bunker's unloading window, m^2.

The controlled factors are: grain moisture, ω, %; δ is the initial size of the grain, m; γ is the volumetric mass of the grain, kg/m^3.

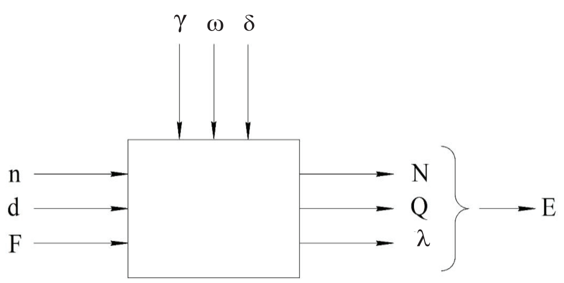

Fig. 2. Simulation of the grain grinding process

The factor variance levels and their coded designations are given in Table 1. The choice of the n and F factors' variance levels was determined by the technical capabilities of the crusher structure; for the d factor – by the technological and zoo-technical requirements for the shredded product.

Table 1

Factor variance levels

Variance level	Rotor's rotation frequency, n, min^{-1}·10^3	Sieve hole diameter, d, m	Bunker's unloading window area, F, m^2·10^{-3}
Lower	2.5	0.004	0.702
Zero	3.0	0.006	1.08
Upper	3.5	0.008	1.458

During our experiments involving grain grinding, the coarsely ground grain was fed to filter bag 8 (Fig. 1).

The repeatability of the experiments varied from 3 to 7 so that the relative warranted error of experience did not exceed 10 %.

The laboratory studies were carried out to determine the rational technological parameters of the centrifugal-impact crusher of the new structure. For our research, the plant was equipped with all the necessary instruments and systems in accordance with standards procedures.

The coarsely ground grain was taken out of the filter bag; the sample with a weight of 100 grams was taken; it was scattered on a sieve analyzer (Fig. 2, *a*). Sieves with a diameter of the sieve holes of 3; 2, 1; 0,5; 0.25 mm were used, and a bottom. The batch from each sieve was weighed on the scales (Fig. 2, *b*).

The average diameter of grains and particles of crushed material was determined on the basis of the analysis of data on the granulometric composition from the following formula:

$$d_{ave} = \frac{\sum_{i=1}^{n} d_i \cdot p_i}{100} = \frac{d_1 \cdot p_1 + d_2 \cdot p_2 + \ldots + d_n \cdot p_n}{100}, \qquad (2)$$

where d_i is the average size of the holes of two adjacent sieves, mm; p_i is the weight yield (mass) of the class, %.

The degree of material grinding was determined as the ratio of the average diameter of the particles of the source material (grain) to the average diameter of the particles of the crushed material:

$$\lambda = \frac{D_E}{d_{ave}}, \qquad (3)$$

where λ is the degree of material shredding; D_E is the average grain diameter, mm; d_{ave} is the average diameter of the particles of the shredded material, mm.

The power consumed by the electric motor was measured by a wattmeter. The performance of the centrifugal-impact crusher was determined by the cut-off method while the stopwatch measured the time of grinding a certain grain mass; next, we calculated their ratio.

5. Results of studying the operational effectiveness of the designed centrifugal-impact grain crusher

Our experimental studies to determine the effect of the rotor's rotation frequency and the presence of a hole for air selection and feed to the chopping chamber in the loading branch-pipe on the speed of air in the unloading neck of the crusher (Table 2) have determined the following. When the crusher operates with a closed hole in the loading neck, the air enters the chopping chamber together with the grain from the bunker and through the filtering via the grain layer in the bunker. In this case, the maximum speed of air in the unloading neck at a rotor's rotation frequency of 3,750 min^{-1} is 2.7 m/s. The hole in the loading branch-pipe makes it possible to increase the speed of air in the unloading neck to 4.8 m/s.

Table 2

Airspeed in the unloading neck, m/s

No.	Indicator. Experiment condition	Rotor's rotation frequency, min^{-1}·10^3						
		2.25	2.50	2.75	3.00	3.25	3.50	3.75
1	Airspeed, υ_1, m/s. The hole in the loading branch-pipe is closed	0.2	0.3	0.8	1.7	2	2.4	2.7
2	Airspeed, υ2, m/s. The hole in the loading branch-pipe is open	2.6	2.7	3.1	3.3	3.8	4.5	4.8
3	Speed increase, υ_2/υ_1	13.0	9.0	3.9	1.9	1.9	1.9	1.8

The statistical treatment of data from the experimental study of the operational effectiveness of the centrifugal-impact grain shredder employed the universal software package STATGRAPHICS® Centurion XV.

$$Q = -4{,}711.75 - 75.14 \cdot d - 2{,}473.10 \cdot F^2 + 434.85 \cdot n + 1{,}055.87 \cdot d + 1{,}037.93 \cdot F + 105.14 \cdot d \cdot F - 23.98 \cdot d \cdot n. \qquad (4)$$

It follows from the variance analysis of the regression equation that the model is informationally adequate because the determination coefficient of the parameter n is quite large and is 98.60 %; the resulting model explains a 98.60 % change in n. The model is significant, there is a statistically significant ratio between the variables at the level of 95 %.

Based on the resulting regression equation, Fig. 3 shows a graphic illustration of the dependence of the crusher performance on the variable factors n, d, and F.

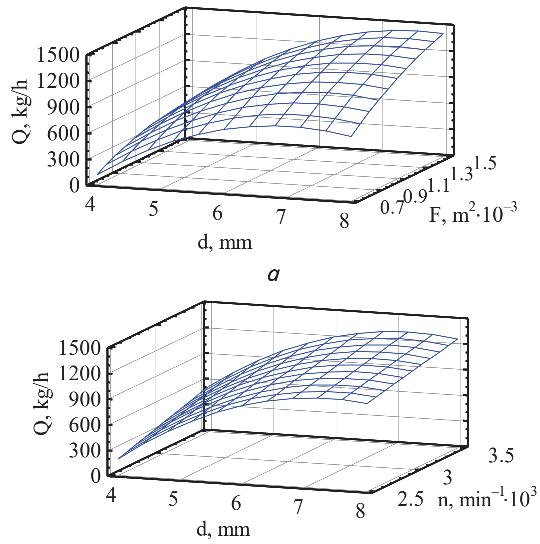

Fig. 3. The crusher performance dependence: *a* – on the diameter of the sieve holes and the rotor's rotation frequency; *b* – on the diameter of the sieve holes and the area of the bunker's unloading window

Our multi-factorial regression analysis to determine the effect of the rotor's rotation frequency n, the diameter of the sieve holes d, the area of the unloading window of the bunker F on the specific energy intensity E has made it possible to derive the following mathematical model:

$$E = 23.67 + 0.19 \cdot d^2 + 0.49 \cdot F^2 - 4.01 \cdot n - 3.58 \cdot d - 0.07 \cdot F - 0.28 \cdot d \cdot F + 0.41 \cdot d \cdot n. \quad (5)$$

It follows from the variance analysis of the regression equation that the model is informationally adequate because the determination coefficient of the parameter n is quite large and is 95.92 %; the resulting model explains a 95.92 % change in n. The model is significant; there is a statistically significant ratio between the variables at the level of 95 %. Fig. 4 shows the lines of equal responses for the specific energy intensity of grain grinding in the factor space n-d and F-d.

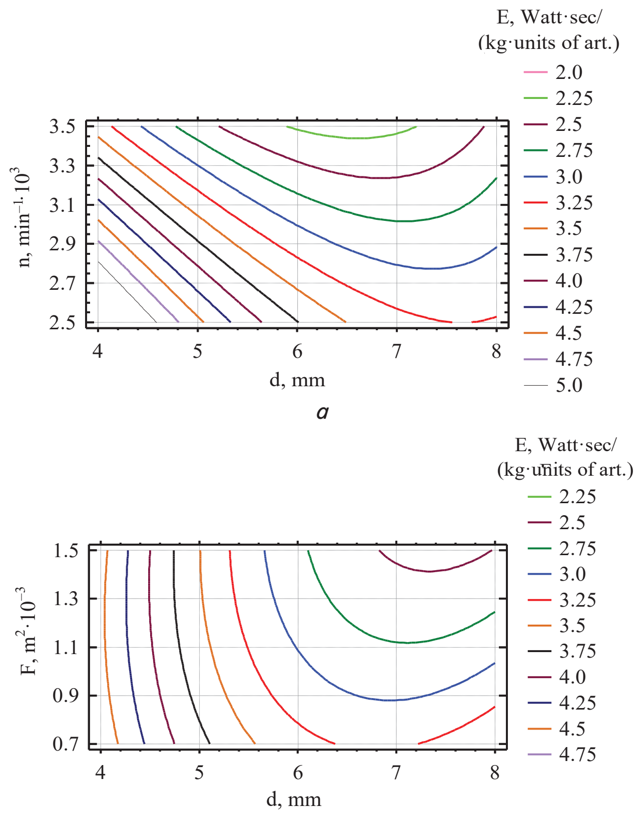

Fig. 4. The grain grinding specific energy intensity dependence: *a* – on the diameter of the sieve holes and the rotor's rotation frequency; *b* – on the diameter of the sieve holes and the area of the bunker's unloading window

The quality indicators of feed grain, fed to farm animals of different species and ages as part of the crumbly feed, are regulated by interstate standards. Consolidated requirements for the particle size of the coarsely ground grain for different species and sex-age groups of animals are given in Table 3. However, the information provided does not regulate the average particle size of the coarsely ground grain. Studies by the U.S. scientists [3, 24] determined that the optimal size of feed particles for young pigs on fattening ranges within 0.5...0.9 mm. Recommendations by Russian scientists are about the same [25, 26] – for suckling piglets, 0.5...0.8 mm; for weaned piglets, 0.9...1.1 mm; and for other groups of pigs – 1...1.4 mm.

Table 3

Requirements for the particle size of coarsely ground grain

No. of entry	Name of sex-age groups of animals	Mass share of residue on sieve, %, not exceeding	
		hole diameter, 5 mm	hole diameter, 3 mm
1	Calves and young cattle to 18 months	2	10
2	Dairy cows, heifers, breeding bulls, and fattening cattle	5	25
3	Lambs up to 4 months and goats up to 3 months	0	2
4	Adult animals and young sheep over 4 months and goats over 3 months	5	12
5	Suckling pigs up to 2 months and weaning pigs from 2 to 4 months	0	5
6	Sows, breeding boars, and fattening pigs	1	5

The results of the sieve analysis of the coarsely ground grain obtained during the experiments are given in Table 4.

Table 4

Coarsely ground grain granulometric composition

Experiment No.	Sieve hole diameter, mm	Rotor's rotation frequency, $min^{-1} \cdot 10^3$	Bunker's window area, $m^2 \cdot 10^{-3}$	Residue on laboratory sieves, %							Average particle size, d_{ave}, mm
				Laboratory sieves' hole diameter, mm							
				5	3	2	1	0.5	0.25	0	
1	4	2.5	1.08	0	1.13	23.41	46.82	14.18	10.42	4.04	1.48
2	4	3.0	0.702	0	0.26	9.47	53.95	15.96	14.63	5.74	1.24
3	4	3.0	1.458	0	0.63	14.89	50.18	20.31	10.73	3.26	1.35
4	4	3.5	1.08	0	0.26	7.8	51.68	32.85	6.36	1.04	1.25
5	6	2.5	0.702	0.39	21.39	35.41	28.32	9.78	3.89	0.82	2.28
6	6	2.5	1.458	0.28	31.72	32.59	23.99	8.04	2.79	0.58	2.53
7	6	3.0	1.08	0.25	16.82	38.84	29.54	6.72	6.13	1.7	2.18
8	6	3.0	1.08	0.31	16.34	40.89	30.3	5.92	4.81	1.43	2.22
9	6	3.0	1.08	0.32	16.54	38.18	30.34	8.4	5.21	1.01	2.17
10	6	3.5	0.702	0	8.54	30.5	37.34	12.71	8.64	2.27	1.79
11	6	3.5	1.458	0.11	11.98	32.56	37.03	10.29	6.17	1.87	1.96
12	8	2.5	1.08	0.47	40.61	32.14	18.99	4.69	2.48	0.63	2.79
13	8	3.0	0.702	0.49	23.6	38.85	26.87	5.43	3.87	0.88	2.4
14	8	3.0	1.458	0.47	27.35	35.04	27.76	5.48	3.2	0.79	2.45
15	8	3.5	1.08	0.36	22.08	41.23	29.48	3.83	2.26	0.76	2.42

6. Discussion of results of studying the designed centrifugal crusher of feed grain

The issue relating to reducing the throughput capacity of the crusher and clogging the work chamber with the material is resolved by the presence of an air screen in the loading bunker and the vertical orientation of the unloading neck axis. When the loading neck is closed, the air is fed into the work chamber by filtering it through a layer of grain in the bunker. This did not provide for the air intake of the work chamber in a sufficient amount. Accordingly, the speed of air in the work chamber was low; in the unloading neck, it was 0.2...2.7 m/s (Table 2). When the loading neck is open, the airspeed in the unloading neck increases by 1.8...13 times depending on the rotor's rotation frequency and reaches 4.8 m/s. The hovering speed of crushing products of most agricultural materials with dimensions of 0.25...1.5 mm is in the range of 1.0...3.5 m/s. Therefore, the flow of air into the chopping chamber through a hole in the loading neck and the vertical orientation of the unloading neck axis guarantee an improvement in the evacuation of the shredded material. The particles of the crushed material are steadily moving to the outlet and the crusher's working bodies are cleaned by the constant airflow at a sufficient speed. This contributes to increased productivity, obtaining the ground grains of the predefined granulometric composition, and improved operational reliability of the crusher.

The resulting regression equations (4) and (5) make it possible to define the structural and mode parameters that provide maximum performance and a minimum of specific energy costs.

The greatest impact on the performance of the crusher is exerted by the diameter of the sieve holes and the area of the bunker's unloading window. Productivity increases rapidly, from 100 to 1,422 kg/h, when the diameter of the sieve holes increases from 4 to 6 mm (Fig. 3). Maximum performance values are observed at the unloading window area of the bunker F=1.458 $m^2 \cdot 10^{-3}$, which ensures the maximum possible supply of grain from the bunker to the work chamber. The effect of the rotor's rotation frequency on performance decreases with the increase in the diameter of the sieve holes.

Taking into consideration the values of the coefficients in the derived mathematical model, analyzing the character of the lines of equal responses (Fig. 4), we notice that the greatest impact on the specific energy intensity of the grinding process is exerted by the diameter of the sieve holes. The minimum energy intensity, taking into consideration the achieved degree of grinding, 2.1 W·s/(kg·grinding degree unit), is observed when using a sieve with a diameter of 7 mm, the rotor's rotation frequency of 3,500 min^{-1}, and the maximally open unloading window of the bunker.

An analysis of the coarse grounded grain granulometric composition (Table 4) reveals that the average particle size of the coarsely ground grain decreases with the reduction in the diameter of the sieve holes and the area of the bunker's unloading window while increasing the rotation frequency of the rotor.

The average particle size of the coarsely ground grain, obtained from experiments No. 1...4, when shredded using a sieve with a hole diameter of 4 mm, is 1.24–1.48 mm. This corresponds to the requirements for all sex-age groups of pigs, as well as for lambs, goats, and calves. The lowest unit costs and the maximum performance of 543 kg/h could be achieved at n=3,500 min^{-1}, F=1.458 $m^2 \cdot 10^{-3}$.

The average size of the coarsely ground grain, obtained from experiments Nos. 10 and 11, when shredded using a sieve with a hole diameter of 6 mm, is 1.79–1.96 mm. This corresponds to the requirements for dairy cows, heifers, breeding bulls, and fattening cattle, as well as for adult sheep and goats. The lowest unit costs and the maximum performance of 1,422 kg/h, could be achieved at n=3,500 min^{-1}, F=1.458 $m^2 \cdot 10^{-3}$.

The average size of the coarsely ground grain, obtained from experiments Nos. 13 and 15, when shredded using a sieve with a hole diameter of 8 mm, is 2.4–2.42 mm. This corresponds to the requirements for dairy cows, heifers, breeding bulls, and fattening cattle. The lowest unit costs and the maximum performance of 1,385 kg/h, could be achieved at n=3,500 min^{-1}, F=1.458 $m^2 \cdot 10^{-3}$.

The rational modes of operation, defined as a result of our scientific research, ensure that the coarsely ground grain of the required granulometric composition for all major species and sex-age groups of animals is obtained.

The comparison of the operational effectiveness of the centrifugal-impact grinder and existing hammer shredders should be carried out taking into consideration the earlier specified main shortcomings of hammer crushers – the low energy efficiency and uneven granulometric composition of the coarsely ground grain obtained.

With an electric motor power of 5.5 kW, the impact-centrifugal shredder has a capacity of up to 1,422 t/h, the specific energy consumption of 3.87 kWh/t, which is 1.22...1.89 times less than that for the hammer crushers RVO 35, DB-5, KD-2A [14–16], 2.37 times less than that for the crushers A1-DMR-12 and Van Aarsen HM-700-2D [17].

The centrifugal-impact crusher provides a coarsely ground grain with a dust-like fraction content in significantly smaller quantities compared to hammer crushers. When chopping barley using a sieve with a hole diameter of 4 mm at the hammer crusher DZM-6 [26], the coarse grounded grain with the content of 11.52 % of the fraction less than 0.2 mm was obtained. When using the new grinder, during the experiments Nos. 1...4, the content of the fraction of up to 0.25 mm in the coarsely ground grain was less than 5.74 %.

Special features of the new design of the centrifugal-impact shredder open the possibility of its use at enterprises with different livestock to operate with various peripheral devices or at existing industrial lines of feed production. The low specific energy intensity of grinding and the high quality of the coarsely ground grain provide a reduction in the cost of preparing feed grain to feed farm animals and, consequently, the high competitiveness of the crusher.

A disadvantage that can be attributed to the new centrifugal-impact shredder design, in comparison with pneumatic crushers [18–20], relates to that the loading of the grain and unloading the coarsely ground grain from the crusher require additional transporters and the coordination of their performance.

The merits of our study, in comparison with the results reported in known studies [7, 8, 29] include a comprehensive analysis of the effectiveness of the crusher operation. In the study, performance is considered in conjunction with energy efficiency and the quality of grain grinding. It is the cumulative consideration of all aspects of the crusher's operational efficiency that allows us to define the rational working regimes and to argue about the benefits of its use in agricultural production.

The results of this study are a continuation and the next stage of our work, aimed at the development of new equipment for the mechanization of livestock [28]. In the future, it is possible to use the results of the current study to substantiate and build a shredder with systems of automated grain supply for grinding and unloading the coarsely ground grain.

A limitation of the reported study is the identification of the patterns of the effect of the structural-technological parameters of the newly-designed shredder on the performance of the grinding process of barley only. For a crusher used in the agriculture and feed industry, versatility is very important, that is, the ability to grind all kinds of grains and various additives – oilseed meal, cattle cake, etc. In addition, in the study, a sieve with a hole diameter of 3 mm was not used to obtain coarse grounded grain with an average particle size of less than 1 mm; the possibility of using mesh sieves in the grinder was not investigated. Therefore, the study should be advanced in the direction of identifying the effectiveness of grinding different types of concentrated feed using different sieves.

7. Conclusions

1. The additional air supply to the chopping chamber through a hole in the loading neck increases the airspeed in the unloading neck by 1.8...13 times when the rotor's rotation frequency changes from 3,750 to 2,250 min^{-1}. The speed of air in the unloading neck at the rational rotation frequency of the rotor of 3,750 min^{-1} reaches 4.8 m/s, exceeds the rate of hovering of the products of grinding most agricultural materials, ensures timely removal of the shredded material's particles from the crusher.

2. The derived regression equations (4) and (5) allowed us to determine the structural and mode parameters that provide maximum performance and a minimum of unit energy costs.

The maximal performance of the crusher of 1,440 kg/h and the minimal energy intensity, taking into consideration the achieved degree of grinding of 2.1 W·s/(kg·grinding degree unit), are observed when using a sieve with a diameter of 7 mm, the rotor's rotation frequency of 3,500 min^{-1}, and the maximally open unloading window of the bunker, at F=1.458 m^2·10^{-3}.

The specific energy consumption for chopping barley is 1.22...1.89 times less than that for the RVO 35, DB-5, KD-2A hammer crushers.

3. The average diameter of the coarsely ground grain particles has a uniform composition and ranges from 1.23 mm to 2.74 mm. The content of dust-like fraction in the coarsely ground grain, when using a sieve with a hole diameter of 4 mm, was less than 5.74 %, which is 2 times lower than that for the hammer crusher DZM-6.

When preparing the grain for feeding, it is necessary to adjust the centrifugal-impact crusher considering the species and age of the animals.

For all sex-age groups of pigs, as well as for lambs, goats, and calves, one should install a sieve with a hole diameter of 4 mm, set the rotor's rotation frequency to n=3,500 min^{-1}, open the adjustable flap of the bunker to the size of the unloading window area of F=1.458 m^2·10^{-3}.

For dairy cows, heifers, breeding bulls, and fattening cattle, as well as for adult sheep and goats, one should install a sieve with a hole diameter of 6 mm, set the rotor's rotation frequency to n=3,500 min^{-1}, open the adjustable flap of the bunker to the size of the unloading window area of F=1.458 m^2·10^{-3}.

For dairy cows, heifers, breeding bulls, and fattening cattle, one should install a sieve with a hole diameter of 8 mm, set the rotor's rotation frequency to n=3,500 min^{-1}, open the adjustable flap of the bunker to the size of the unloading window area of F=1.458 m^2·10^{-3}.

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