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DEVELOPMENT OF A GRINDER-MILLER WITH ROLLING WORKING BODIES FOR SMALL FARMS

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The object of the research is the technological process of grain feed crushing in a roller-type crusher with small working dimensions and the interaction of individual grains with the roller surfaces within the inter-roller gap. The study focuses on ensuring stable productivity of up to 200 kg/h for small farms. A structural and technological scheme of a compact grinder-miller was developed, and an experimental prototype was produced. The length and diameter of the rollers were selected according to the operational requirements of small agricultural enterprises.

A hypothesis was formulated, assuming that grain particles behave as discrete bodies stochastically distributed in the inter-roller gap and partially aligned along the roller length before deformation. This allows a realistic description of their interaction with the working surfaces and the resulting energy consumption. Analytical expressions were obtained for determining productivity and required power based on a mathematical model linking roller geometry, kinematic parameters, and the probabilistic nature of grain flow.

Experimental studies verified the model by varying roller rotation speed from 56 to 178 min^{-1}. At 178 min^{-1}, the productivity reached 180 kg/h, and the consumed power was 1020 W. The discrepancy between theoretical and experimental productivity was 7.5%, and between power values 2.02%. The results confirm the validity of the developed discrete–probabilistic model and its applicability for optimizing the design and operating parameters of compact roller-type crushers for decentralized feed production

Keywords: grinder-miller, interroller gap, productivity, required power, roll rotation frequency

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1. Introduction

Roller mills are widely used for crushing grain feed by crushing, and are widely used to crush grain into flour and to produce grain meal in feed mills.

In roller mills, the rotating rollers have varying circumferential speeds, while for grain crushers, the ratio of the roller circumferential speeds should be equal to one [1].

Currently, hammer mills are widely used for crushing grain feed. However, many livestock farms actively use grain crushers.

This is due to the fact that crushing grain feed completely destroys the grain husk, i.e., completely destroys the kernel. For example, when crushing grain feed in hammer mills [2, 3] and impact-grinding organs as part of combined devices [4], the crushed feed will contain uncrushed whole kernels, albeit in small quantities. Therefore, when preparing compound feed, preference is given to the process of crushing grain feed.

It is known that the productivity of a crusher depends on the peripheral speed and length of the rollers.

Currently, crushing machines with a productivity of 0.5 to 9.0 tons/hour are manufactured [5].

There is a need for such machines for farms and households with livestock of up to 30–50 head of cattle. The productivity of crushers for such small farms should be in the range of 150 to 200 kg/hour. The focus on small farms reflects the current structure of agricultural production in developing regions, where more than 70% of livestock feed is prepared locally and not supplied from centralized plants.

Existing small-sized crushers have a productivity of 400 to 500 kg/hour and an electric motor power of 2.2 kW [5]. However, it would be advisable to use a crusher with a productivity of 200 kg/hour and an electric motor power of 1.1 kW.

The growing demand for locally produced livestock feed highlights the need for compact and efficient crushing equipment that can operate in decentralized agricultural systems.

In many developing regions, small and medium-sized farms dominate livestock production, but they often lack access to industrial feed processing infrastructure. As a result, the quality and uniformity of feed depend directly on the technological level of on-farm grain processing. Developing reliable and energy-efficient crushers for small farms is therefore an important factor in improving overall productivity and feed quality.

In recent years, attention has shifted toward optimizing the structure and operation of roller-type crushers, which combine high crushing quality with relatively low energy consumption. Studies have shown that feed particle size and uniformity significantly affect the digestibility of nutrients and the efficiency of livestock feeding systems. Maintaining the integrity of the grain husk while achieving the required degree of flattening contributes to better feed absorption and reduces losses during storage and transportation.

At the same time, despite the long history of research on roller-type crushing machines, there are still unresolved issues concerning the interaction between individual grain kernels and the roller surface. Most existing models describe the process as continuous, ignoring the discrete and probabilistic nature of grain motion within the roller gap. This limits the accuracy of theoretical calculations when designing equipment for small capacities, where the number of simultaneously deformed grains is relatively small and boundary effects are more pronounced.

The development of mathematical models that take into account the discrete behavior of grains, their random distribution in the inter-roller gap, and the mechanical properties of the material remains a relevant scientific task. Such models can improve the prediction of energy consumption, optimize roller geometry, and enhance process stability. In addition, they support the design of compact crushers that provide sufficient productivity while using single-phase electric drives suitable for rural conditions.

Therefore, studies that are devoted to the improvement of roller-type grain crushers, the modeling of grain deformation processes in the roller gap, and the optimization of operational parameters for small-capacity systems are of high scientific relevance in modern agricultural engineering.

2. Literature review and problem statement

The paper [6] presents the results of research on determining the productivity of grain feed crushers depending on the roller length, circumferential speed, inter-roller gap, and material density before crushing. It was shown that a correction coefficient $K = 0.1–0.2$ must be introduced into the analytical formula, which reduces the obtained productivity values by 5–10 times. However, there were unresolved issues related to the physical interpretation of this coefficient and to the simplified assumption that a uniform layer of feed material passes through the inter-roller gap as a belt of thickness equal to the gap. The reason for these inaccuracies may be objective difficulties associated with the complex geometry of grain flow and the random orientation of kernels in the roller zone, which were not considered in the model. A way to overcome these difficulties can be the use of a probabilistic approach that takes into account the statistical distribution of grain positions relative to the gap line.

The study [7] presents the results of theoretical and experimental investigations of a grain crusher equipped with a feeding device. It was shown that using such a feeder increases productivity by up to two times compared with conventional designs. But there were unresolved issues related to the influence of grain alignment and the simultaneous entry of kernels into the inter-roller gap, which directly affect throughput and energy consumption. The reason for this limitation may be that the authors focused mainly on feeder geometry and installation height, without analyzing the grain's kinematic behavior inside the gap. A way to overcome these difficulties can be to model the real distribution of individual grains and to link it mathematically with roller speed and geometry. This approach was partially used in [8], however, the obtained dependences were empirical and cannot be directly generalized for compact machines of low capacity. All this suggests that it is advisable to conduct a study aimed at developing a theoretical model that relates crusher productivity to the number of kernels simultaneously passing through the roller gap.

In [9, 10], the results of research on a two-stage grain crusher were presented. It was shown that such machines provide a more uniform structure of crushed material and reduce specific energy consumption. However, there were unresolved issues related to the high structural complexity and cost of two-stage systems, which make them impractical for small farms. The reason for this may be the large number of working elements and high power demand, while the required productivity for small producers does not exceed 150–200 kg/h. A way to overcome these difficulties can be the development of a compact single-stage roller crusher with optimized roller dimensions and a simplified drive. This approach was used in several experimental prototypes, however, their design parameters were not theoretically justified. Therefore, it is necessary to carry out further studies aimed at theoretically substantiating the parameters of small-sized crushers that provide low energy consumption and sufficient productivity.

The paper [11] presents the results of experimental research on a grass-crushing machine. It was shown that the optimal values of roller speed 670 min^{-1}, feed rate 2.0 m/s, and gap 0.02 m ensure stable performance. But unresolved issues remain related to the influence of grain size, shape, and moisture on productivity. The reason for these gaps is the use of plant stems instead of cereal grains, which differ significantly in mechanical properties. A way to overcome these difficulties can be to conduct similar experiments with actual grain material and to refine the obtained dependences for smaller machines.

In [12–15], studies were carried out on various technical means for crushing and flattening plant materials. It was shown that the main parameters affecting the process are roller diameter, peripheral speed, and surface configuration. However, unresolved issues remain concerning the choice of these parameters for small-capacity devices. The reason may be the absence of models that simultaneously consider geometric dimensions, physical-mechanical properties of the material, and operational constraints typical for small farms. The study [12] provides a valuable analysis of hay harvesting system losses and drying rates, but it focuses primarily on large-scale systems and does not account for energy efficiency in low-power crushers, which limits its applicability to small farms. Research [13] offers detailed measurements of grain flattening energy and material properties for various crops; however, the experimental setup is oriented toward biomass energy production rather than feed grain crushing, making its conclusions only partially relevant to the present study. The review [14] gives an extensive overview of high-pressure grain flattening roll modeling and introduces advanced simulation methods, yet it overlooks the adaptation of such models for low-speed, small-diameter rollers typical in compact feed crushers. Similarly, [15] proposes new correlations for energy consumption in lignocellulosic biomass reduction, but the generalized equations it provides do not fully reflect the discrete nature of grain movement in small-capacity crushing machines. A way to overcome these difficulties can be the introduction of a combined analytical and experimental approach where the process is described not by a continuous material layer but by discrete grains. This approach was used in [16, 17] for hammer and rotary crushers; however, it has not yet been applied to roller-type machines of low productivity. All this confirms the need to perform theoretical studies that determine the relationship between roller speed, grain size, and energy consumption for compact grain crushers.

The works [18–20] present the results of research on improving the efficiency of crushing plants by introducing vibration or changing the roller geometry. Research by [18] presents a modeling approach to simulate vibration-assisted crushing processes, showing that induced oscillations can enhance material evacuation and reduce energy losses. However, the proposed model is mainly applicable to large industrial plants and lacks consideration of the mechanical limitations and cost constraints inherent to small-scale crushers. The study also does not provide experimental validation for low-frequency oscillation systems that could be implemented in compact devices. The analysis of the M900 roller crusher [19] demonstrates practical industrial solutions for grain flattening and crushing, including adjustable roller spacing and reliable throughput characteristics. Yet, this design relies on high-capacity drives and heavy-duty construction, which makes it unsuitable for farms requiring portable or energy-efficient equipment. The absence of published efficiency data also limits the possibility of quantitative comparison with low-power models. In turn, [20] provides valuable experimental data on the influence of hammer mill screen size on grain processing parameters and starch enrichment. The results confirm that proper geometric configuration can significantly affect grain flattening efficiency. Nonetheless, the study focuses exclusively on hammer-type mills and does not account for the behavior of material in roller gaps, reducing its direct applicability to two-roll crushers for small-scale use. Overall, the presented studies demonstrate that vibration excitation and geometric optimization improve crushing efficiency, but unresolved issues remain regarding the adaptation of these solutions to small-sized machines with single-phase electric motors. The complexity and high cost of vibration systems make them impractical for household or small-farm use. A way to overcome these difficulties can be to simplify the design while maintaining acceptable performance through rational selection of roller diameter and length. This approach was partially implemented in industrial crushers [19, 20]; however, they remain oversized for small-scale production. Therefore, further research is needed to adapt design principles to compact, energy-efficient crushers with a capacity of about 200 kg/h.

The paper [21] presents the justification of optimal parameters of wet-grain crushers and shows that the minimum energy consumption is achieved at a peripheral speed of 4.0 m/s. Nevertheless, unresolved questions remain about whether these dependencies hold for dry-grain crushing and for small machines with reduced roller length. The reason may be that the authors considered industrial-scale machines and did not take into account scaling effects. A way to overcome this limitation can be to experimentally verify theoretical dependences for low-power devices and to correct the formulas accordingly.

Summarizing the above-mentioned studies, it can be concluded that significant progress has been achieved in improving roller-type grain crushers, including the optimization of roller size, peripheral speed, and feeding systems. However, unresolved issues remain related to the theoretical determination of productivity and required power for small-sized machines designed for farms with limited livestock. The reason for this is the lack of models that take into account the discrete nature of grain flow and the probabilistic arrangement of kernels in the roller gap. A way to overcome these difficulties can be to formulate a new hypothesis according to which grain kernels align themselves along the roller gap line before entering it. All this suggests that it is advisable to conduct a study on the development of a compact roller-type grain crusher for small farms, including theoretical and experimental justification of its productivity and required power.

3. The aim and objectives of the study

The aim of the study is to develop the design and operating principles of a compact roller-type grain crusher for small farms, supported by mathematical models that describe the discrete nature of the grain flow and the probabilistic distribution of grains in the inter-roller gap. This will allow optimizing the design parameters and operating modes of roller-type crushers to ensure the required productivity of up to 200 kg/h while maintaining low energy consumption and high feed quality.

To achieve this aim, the following research objectives were set:

– to justify the design and technological scheme of a small-sized roller-type grain crusher that ensures the required productivity for small farms while maintaining compact dimensions and low energy consumption;

– to derive an analytical expression for determining the performance of the grain feed crushing process based on the probabilistic distribution of grain kernels in the inter-roller gap and their geometric and kinematic parameters;

– to derive an analytical expression for determining the power required for the grain feed crushing process based on the torque balance, roller geometry, rotational speed, and the physical and mechanical properties of the grain kernels;

– to experimentally verify the proposed model using a prototype of a compact roller-type crusher and to evaluate the accuracy of theoretical predictions.

4. Materials and methods

The object of the research is the technological process of grain feed crushing in a roller-type crusher with small working dimensions and the interaction of individual grains with the roller surfaces within the inter-roller gap.

The main hypothesis assumes that grain particles behave as discrete bodies that are stochastically distributed within the roller gap. Their alignment along the roller length before deformation allows for a more uniform load distribution and reduced specific energy consumption during the crushing process.

Assumptions adopted in the work: It is assumed that grains are homogeneous in physical-mechanical properties, have a spherical or ellipsoidal shape, and that the roller surface is ideally smooth and rigid. The temperature and humidity of the grains during experiments were considered constant.

Simplifications adopted in the work: The air resistance, vibration effects, and friction losses in the bearing assemblies were neglected, as their influence on the total power consumption of the crusher was found to be minimal in preliminary measurements. Additionally, the deformation of rollers was not taken into account, assuming their absolute rigidity within the operational speed range.

The development of a small-sized grinder-miller focused on the technological processes of crushing grain feed using the method of aligning the grain along the inter-roller gap.

When developing the design and technological scheme of the small-sized grinder-miller, it was assumed that its main design and technological parameters would meet the needs of small farms and households.

To determine the relationship between the installed power of the geared motor and the required crusher performance, as well as to validate the analytical expressions obtained, experimental studies were conducted on a compact grain feed grinder-miller.

To determine the grinder-miller performance, the feed material was weighed using an F1976 electronic scale.

The crusher's operating time was recorded using an electronic stopwatch.

To determine the required power for the grain feed crushing process at different roller speeds, a KIP-505 measuring instrument set was used. This instrument measures power by phase. For each repeat of the experiments conducted at a specific roller speed, the required power was determined for a separate phase.

At the beginning of the experiments, the grinder-miller was started, and before the grain was fed, the idle power of the crusher was recorded at each roller speed.

5. Research results on the development of a small-sized grinder-miller for grain feed

5. 1. Justification of the design and technological scheme of a small-sized grinder-miller of grain feed for small farms

The process of crushing grain feed is considered an effective method for ensuring the easy digestibility of crushed grain feed by animals.

This is due to the fact that crushing grain destroys the grain husk, meaning the grain feed is completely broken down. Compared to crushing grain feed, hammer mills do not completely destroy the husk of all grain feed. Therefore, it can be considered that the most effective method of preparing feed for feeding is the use of grain crushing.

Currently, small-sized crushers for crushing grain feed are widely used.

A review of small-sized crusher designs showed that their roller diameters range from 200 to 400 mm, and roller lengths range from 100 to 1200 mm. However, the given crusher parameters for a small machine with a capacity of up to 200 kg/h are overestimated. For example, the PVZ-3 wet grain crusher has a single pair of rollers with a capacity of 700 kg/h [18]. This capacity, with a grain moisture content of approximately 30%, is achieved with a roller length of 700 mm. This indicates that 1 mm of roller length provides 10 kg/h of productivity.

[5] shows that with a roller length of 100 mm and crushing dry grain, the machine's productivity was 500 kg/h, i.e., 1 mm of roller length provides 5 kg/h of productivity.

In this case, for a crusher with a capacity of 200 kg/h, the roller length should be 40 mm. With this roller length, when crushing wet grain, its productivity increases by a factor of 2.0. Therefore, it can be considered that a rational roller length for a compact crusher is 40 mm.

After selecting the main dimensions of the compact crusher's working elements, the design and process flow diagram were developed (Fig. 1). According to the developed design and technological scheme, the drawing documentation was prepared, and an experimental prototype of the small-sized crusher was manufactured (Fig. 2).

The grinder-miller consists of the following main units: frame 1, electric motor 2, pressing mechanism 3, movable roller 4, movable roller supports 5, racks 6, hopper 7, damper 8, fixed roller 9, fixed roller supports 10, scraper springs 11, roller drive chain 12, roller cleaning mechanism 13, drive chain tensioner 14, chute 15, gearbox 16, coupling clutch 17.

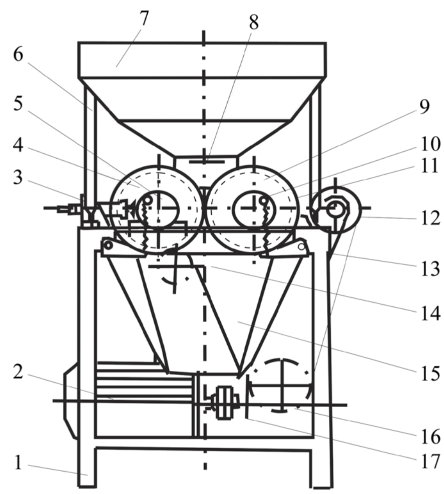

Fig. 1. Schematic diagram of a grain feed grinder-miller (side view): 1 – frame; 2 – electric motor; 3 – pressure mechanism; 4 – movable roller; 5 – movable roller support; 6 – stand; 7 – hopper; 8 – damper; 9 – fixed roller; 10 – fixed roller support; 11 – scraper spring; 12 – roller drive chain; 13 – roller cleaning mechanism; 14 – drive chain tensioner; 15 – chute; 16 – gearbox; 17 – coupling

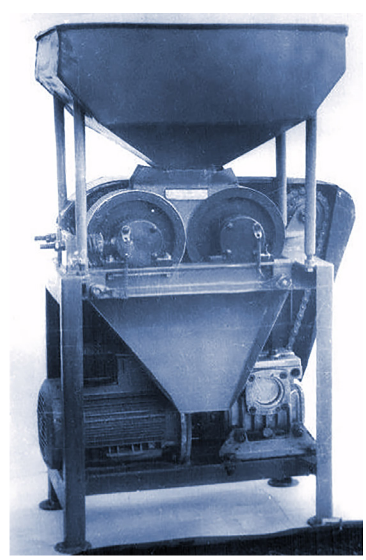

Fig. 2. General view of the grain feed grinder-miller

The grinder-miller consists of two counter-rotating rollers 4 and 9. The rollers rotate in supports 5 and 10 mounted on a common frame 1. The rollers are driven by a coupling 12 via sprockets mounted on their shafts. The sprockets are driven by a gearbox 16 from an electric motor 2 through a clutch 17. Normal drive tension is ensured by a spring-loaded tensioner 14.

Above the rollers, a hopper 7 for the processed grain is mounted on four support posts 6. The hopper is equipped with a valve 8 that regulates the grain feed to the rollers.

Roller supports 9 are fixedly mounted on the frame's guide channels. Relative to roller 9, roller 4 can move, increasing or decreasing the overall gap between the rollers, due to its supports sliding along guides. The required gap between rollers 4 and 9, as well as the force exerted on roller 4, is regulated by clamping mechanism 3.

Cleaning mechanisms 13, driven by springs 11, press the scrapers against the rollers and remove any adhering feed.

Grain passing between the rollers falls onto chute 15, slides down it, and is collected in a container (bucket, box, bag, etc.).

5. 2. Determining the performance of a grain feed crusher

In previous studies, the crushing process of grain feed was considered as a layer passing through a roller gap. The layer thickness was assumed to be equal to the roller gap. In this case, it is clear that the crusher's performance is directly proportional to the roller gap. However, this relationship is not observed when crushing grain feed.

During machine operation, the hypothesis that prior to crushing, the grains are aligned in a single row along the roller gap line (Fig. 3, 4) proved reliable.

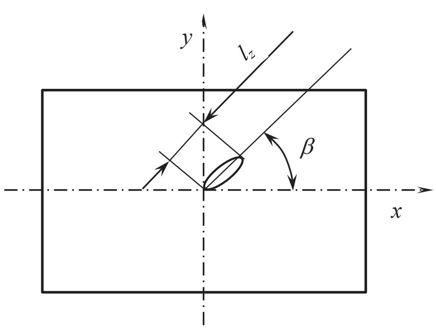

Fig. 3. Diagram of the arrangement of a row of grains on the inter-roller gap line

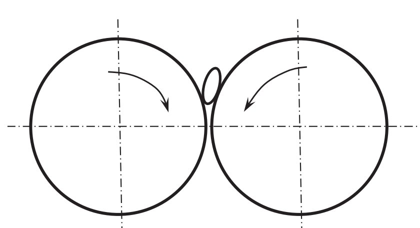

Fig. 4. Grain arrangement diagram along the length of the inter-roller gap

Let's assume that when crushed feed passes through the inter-roller gap, the average grain length is equal to the average value of its projection onto the inter-roller gap line. The amount of grain located on the gap line along the length of the roller (K_{zl}) depends on the angle of inclination of the grain (β) to the inter-roller gap line.

The projection length of the grain (l_{zx}) onto the inter-roller gap is determined by the formula

$$l_{zx} = l_z \cos\beta, \tag{1}$$

where is a random variable, which value, according to probability theory, is distributed with uniform density between angles of 0...2π. In this case, the average value of the projection length of the grain is determined by the formula

$$l_{zxc} = \frac{\int_0^{\pi/2} l_z \cos\beta \cdot d\beta}{\pi/2} = \frac{2l_z}{\pi}\int_0^{\pi/2}\cos\beta \cdot d\beta = \\ = \frac{2l_z}{\pi}\left(\sin\beta\right)\Big|_0^{\pi/2} = \frac{2l_z}{\pi}\left(\sin\frac{\pi}{2} - \sin 0\right) = \frac{2l_z}{\pi}. \tag{2}$$

Here the number of grains aligned on the inter-roller gap line is determined as follows

$$K_{zl} = \frac{L_b}{l_{zxc}} = \frac{\pi L_b}{2l_z}, \tag{3}$$

where L_b – roller length, m.

From Fig. 4 it can be seen that the projection of an individual grain onto the axis y equal

$$l_{zy} = l_z \sin\beta. \tag{4}$$

The average length of an individual grain located along the circumference of the roller is also determined by the formula

$$l_{zyc} = \frac{\int_0^{\pi/2} l_z \sin\beta \cdot d\beta}{\pi/2} = \frac{2l_z}{\pi}\int_0^{\pi/2}\sin\beta \cdot d\beta = \frac{2l_z}{\pi}. \tag{5}$$

In this case, the number of grains located along the length of the roller circumference in one row is determined by the formula

$$K_{3D} = \frac{\pi D_b}{l_{zyc}} = \frac{\pi^2 D_b}{2l_z}, \tag{6}$$

where D_b – roller diameter.

The number of grains located on the side surface of the roller is determined by the formula

$$K_{zo} = K_{zl} \cdot K_{3D} = \frac{\pi^3 D L_b}{4l_z^2}. \tag{7}$$

When determining the number of grains located on the X and Y axes, the grain length l_z is considered as a line with no thickness. However, each grain has a thickness, so the actual values K_{zl} should be smaller than their calculated values. For example, the calculated value for the length of the roller (40 mm) is $K_{zl} = 6$ grains, but in reality, there are 4.7 grains. Therefore, the actual number of grains along the X and Y axes is determined by multiplying by the grain reduction factor ($K_X = 0.78$).

The total mass of grains located on the side surface of the roller is determined by the formula

$$M_z = K_X^2 \cdot K_{zo} \cdot G_z = \frac{K_X^2 \cdot \pi^3 D_b \cdot L_b \cdot G_z}{4l_z^2}, \tag{8}$$

where G_z – weight of one grain, kg.

In this case, the hourly productivity of the crusher (kg/h) is determined by the formula

$$Q_n = 3{,}600\frac{K_X^2\pi^3 D_b L_b G_z n_b}{4l_z^2 60} = \frac{464.4 K_X^2 D_b L_d G_z n_b}{l_z^2}, \tag{9}$$

where n_b – roller rotation frequency, min^{-1}.

Thus, an analytical expression for determining the productivity of the grain feed crushing process was obtained.

5. 3. Determining the required power of a grain feed crusher

In a stationary operating mode, in accordance with the diagram of forces acting on the grain in the inter-roller gap (Fig. 5), the following condition must be met

$$M_{DB} = M_{OC}, \tag{10}$$

where M_{DB} – torque generated by the engine, Nm; M_{OC} – moment of resistance on both rollers, Nm.

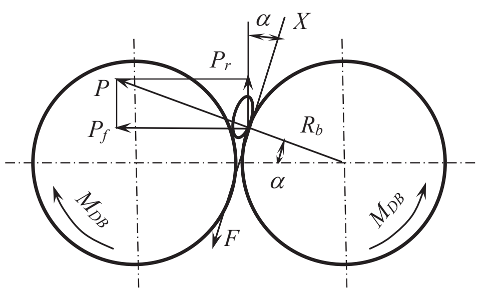

Fig. 5. Diagram of the forces acting on the grain in the inter-roller gap

The moment of resistance during crushing of one grain is determined by the formula

$$M_{C1} = P_r\cos\alpha\cdot R_b = P\sin\alpha\cdot\cos\alpha\cdot R_b, \tag{11}$$

where P – the pressure force required to obtain flakes of a thickness corresponding to zootechnical requirements, N; R_b – roller radius, m.

In this case, the total moment of resistance is determined by the formula

$$M_{OC} = 2K_{zl}P\sin\alpha\cdot\cos\alpha\cdot R_b. \tag{12}$$

Here, the number of grains located in the inter-roller gap along the roller length K_{zl}, is determined by formula (3).

Substituting the K_{zl} value into formula (12) and taking into account the roller rotation speed, a formula was obtained for determining the power consumption required for crushing grain feed

$$N_{\Pi} = \frac{\pi\cdot L_b}{l_z}P\sin\alpha\cdot\cos\alpha\cdot R_b\frac{\pi\cdot n_b}{30} = \frac{\pi^2 L_b P\sin\alpha\cdot\cos\alpha\cdot R_b n_b}{30 l_z} = \frac{0.329 L_b P\sin\alpha\cdot\cos\alpha\cdot R_b n_b}{l_z}. \tag{13}$$

Thus, using the new hypothesis, an analytical expression was obtained for determining the power required for the grain feed crushing process. Analysis of the resulting expression shows that the formula includes the diameter, length, and rotational speed of the roller, the crushing force, and the length of a single grain. This means that the formula incorporates the machine's key design and kinematic parameters, as well as the key physical and mechanical properties of the grain feed.

5. 4. Conducting experimental studies to determine the reliability of the obtained analytical expressions

To determine the relationship between productivity and the crusher roller speed, special experimental studies were conducted at various crusher roller speeds.

To determine certain parameters of barley kernels at 10% moisture content, special experiments were conducted.

The weight of a single kernel was obtained by measuring the total weight of 1,000 kernels. The weight of a single barley kernel was found to be $G = 0.00006$ kg, or 60 mg. The length of a barley kernel was determined by measuring the length of 100 kernels and was found to be 10.5 mm, or 0.0105 m.

Here, the theoretical crusher productivity values were determined as a function of the roller speed using the derived formula (9).

The results of the experimental and theoretical studies to determine crusher productivity are shown in Fig. 6.

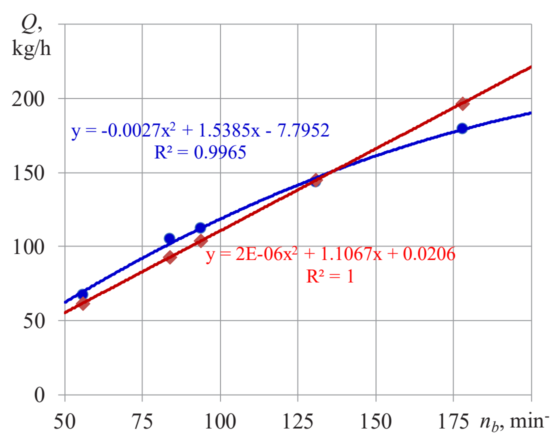

Fig. 6. Dependence of grinder-miller performance on the rotation frequency of the rollers

A comparison of theoretical and experimental values of crusher productivity shows that when the crusher productivity is more than 100 kg/h, the average deviation between these values is on average 7.5%, that is, this deviation is insignificant for practical calculations.

All this indicates the validity of the proposed hypothesis and the resulting analytical expression for determining the productivity of the grain feed crushing process.

During experimental studies that determined crusher productivity depending on the crusher roller speed, the power required for the grain feed crushing process was also determined.

To verify the validity of the resulting analytical expression, the results of experimental studies conducted on a grain feed grinder-miller were used.

Parameters of this feed grain grinder-miller. In this case, $L_B = 0.04$ m, $R_B = 0.09$ m. According to the results of laboratory studies for barley grains, $l_P = 10.5$ mm, for barley ($W = 10\%$) $P = 254.51N$ [22]. The maximum value of the force P should be obtained when the distance between the roller circumferences is equal to the size of the flakes that meet zootechnical requirements, i.e. for barley it is equal to 1.1...1.8 mm. With a gap between the rollers of 1.5 mm, as well as with a distance between the rollers of 1.5 mm, the value of the angle $\alpha = 6°$. Using these parameter values, the theoretical values expended on barley crushing were calculated, depending on the rotational speed of the rollers.

During experimental studies, the required idle power of the crusher and the power expended on the process of crushing barley grain with a moisture content of 10% were determined.

The results of experimental studies and calculations to determine the theoretical required power, obtained using formula (13), are presented in Table 1.

To more accurately demonstrate the consistency of the experimental and theoretical values of the required power for the process of crushing grain feed, a graph of the dependence of the required power for the process of crushing grain feed on the rotation frequency of the rollers was constructed based on these results (Fig. 7).

Fig. 7 also shows the experimental values of power expended in barley crimping. As is seen, the experimental and theoretical power values agree with reasonable certainty. Across the entire graph, the discrepancy between the theoretical and actual power values is within 1.06% to 2.02%.

Fig. 7 also shows the experimental values of the power required for barley crimping. The experimental and theoretical power values demonstrate a satisfactory level of agreement. Throughout the entire range of data, the discrepancy between the theoretical and experimental values of power N_P remains within 1.06–2.02%.

Table 1

Results of theoretical and experimental studies to determine the productivity and required power of the grain feed crushing process depending on the rotation frequency of the grinder-miller rollers

Peripheral speed of the roller, υ, m/s	0.504	0.756	0.846	1.206	1.602
Roller rotation frequency, n, min^{-1}	56	84	94	131	178
Performance, $Q_{exploit.}$, kg/h	68	105.8	112.5	144	180
Performance $Q_{theoret.}$, kg/h	62	93	104.06	145.02	197.04
Total power requirement, N_o, Watt	610	700	720	880	1020
Idle power, N_{XX}, Watt	440	448	452	464	480
Required power, $NP_{exploit}$, Watt	170	252	266	416	540
Required power, $N_{theoret}$, Watt	166.56	249.83	279.57	389.62	529.41

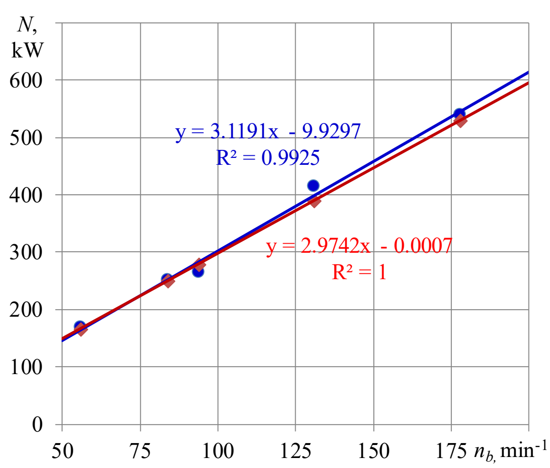

Fig. 7. Dependence of required power for the grain feed crushing process on the roller rotation speed

All of this demonstrates the validity of the hypothesis and the resulting analytical expression for determining the power required for grain feed crimping.

6. Discussion of research results on the development and performance of a roller grain crusher

The main distinguishing feature of the conducted research is the selection of key parameters for a compact grinder-miller (Fig. 1, 2), ensuring efficient operation in small farm and household settings, as well as the implementation of theoretical research based on a new hypothesis for determining the productivity and power requirements of the grain feed crushing process.

In previous studies [6], when determining the productivity of grain feed crimping, the process was considered as if a belt of a thickness equal to the roller gap passed through the roller gap. It was also assumed that the density of the passing layer was equal to the density of the original material. This hypothesis is flawed because, when crimping grain feed, changing the roller gap within 0.5–1.8 mm does not affect the productivity of the crimping process.

Therefore, a new hypothesis was proposed, which posits that grain kernels align themselves along the gap line before passing through the roller gap. Based on this hypothesis, the probability theory method was applied to determine the mean value of the function and the number of grain kernels located along the roller gap line. Taking into account the average weight of each grain, the productivity of the grain feed crimping process was determined (Table 1). When determining the required capacity for the grain feed crimping process, the number of grain kernels simultaneously crushed as they pass through the roller gap was also taken into account.

The validity of the proposed hypothesis is supported by the results of experimental studies. The theoretical and experimental dependences for grain feed crimping productivity are consistent, within a range of roller rotation speeds from 56 to 178 min^{-1}.

Here, the average deviation between the two dependences is 7.5%, meaning this deviation is insignificant for practical calculations.

A comparison of theoretical and experimental relationships for determining grain feed crimping productivity reveals positive results, i.e., the two relationships are very close. This demonstrates the validity of the resulting analytical expression for determining grain feed crimping productivity (9).

A comparison of theoretical and experimental relationships for determining the power requirements for the grain feed crushing process yields favorable results-both relationships are very close to each other. This demonstrates the validity of the proposed hypothesis and the resulting analytical expression (13).

It also shows that the chosen roller length and diameter at a rotation speed of 178 min^{-1} provide sufficient productivity for small farms. Moreover, the power consumption is 1020 watts, meaning the installed motor-gearbox capacity is also reasonable for small farms and households.

The main limitations of this study are related to the simplifications adopted in the mathematical model and the experimental setup. The theoretical model assumes uniform grain size, constant friction coefficients, and ideal roller geometry, which may differ from real operating conditions where grain heterogeneity and roller wear occur. Experimental verification was carried out using barley grain only; therefore, the obtained dependencies require additional validation for other crops with different mechanical properties. The study also considered steady-state operating conditions and did not account for dynamic fluctuations in feed rate or roller slippage. Furthermore, scaling the results for industrial-size crushers may introduce deviations due to changes in kinematic parameters and load distribution. These limitations should be considered when applying the proposed analytical expressions in practical engineering calculations and in further theoretical developments.

In the future, it would be advisable to expand the discrete-probability model and conduct additional experiments taking into account new factors (e.g., variations in grain size, shape, and moisture content, as well as roll surface texture). Numerical methods can also be used to optimize roll design (geometry and profiling) and operating modes to improve energy efficiency. Testing with different grain types, gap conditions, and multi-stage crushing will improve productivity and confirm the applicability of the developed model and design across a wider range of conditions.

7. Conclusions

1. A design and process flow diagram for a compact grinder-miller with roller working elements was developed. The roller length and diameter were selected to ensure a grain feed crushing capacity of up to 200 kg/h, which is sufficient for small and medium-scale agricultural enterprises. Drawings were developed, and an experimental grinder-miller prototype was manufactured.

2. To determine the grain feed crushing capacity, a new hypothesis was proposed, which assumes that grain kernels align themselves with the gap line before passing through the roller gap. Using probability theory, the average length of a grain kernel's projection onto the roller gap line was determined. This determines the number of grain kernels passing through the roller gap in a given period of time. The inter-roller gap is provided by the movement of one of the roller working elements due to its supports sliding along guides. The inter-roller gap, along with the crushing force of the working element (roller), is adjusted by a clamping mechanism.

3. Taking into account the number of grain kernels simultaneously passing through the inter-roller gap and the average crushing force of each kernel, analytical dependencies were obtained for determining the power required for the grain feed crushing process and the productivity of the process. These expressions relate the required power to the roller geometry, the number and mass of grains, and their deformation characteristics, while the productivity equation links the roller rotation speed, the length of the roller working surface, and the average projection of the grain along the inter-roller gap. The derived dependencies make it possible to evaluate the influence of geometric and kinematic parameters on energy consumption and overall process efficiency.

4. Experimental studies were conducted on the developed compact grain feed crusher and chopper to determine the productivity and power requirement for the grain feed crushing process. The productivity and power requirement were determined with the roller speed varying from 56 to 178 min^{-1}. At a roller speed of 178 min^{-1}, the crusher's throughput was 180 kg/h, and the power consumption was 1020 watts. This demonstrates that this roller speed provides a reasonable throughput and power requirement for the grain crushing process. Using the resulting analytical expressions, theoretical values for the throughput and power requirement for grain feed crushing were determined. The discrepancy between the theoretical and experimental throughput values was 7.5%, and the discrepancy between these power requirements was 2.02%. This confirms the validity of the resulting analytical expressions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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