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DETERMINATION OF THE AVERAGE SIZE OF PRELIMINARY GRINDED WET FEED PARTICLES IN HAMMER GRINDERS

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In the conditions of farms, it becomes necessary to grind feed that has a different degree of moisture. Therefore, the choice of universal working bodies is the object of research, and the theoretical determination of the average size of pre-crushed feed particles is of great scientific and practical importance and is a problem that needs to be solved. Proceeding from this, a constructive-technological scheme of a grinder with a universal grinding working body is proposed. The grinding apparatus is equipped with a hammer working body which has cutting edges. In this case, hammers with cutting edges crush the wet mass, and also create an air flow and work as flow accelerators at high speed. As a result of theoretical studies, the steps for arranging these working bodies were determined. Analytical expressions are obtained for determining the average length of pre-crushed feed particles depending on the distance between the faces of replaceable knife working bodies, i.e. from the step of arranging them in rows. At the same time, the calculation results showed that with a distance between the faces of replaceable hammers of 20 mm, the value of the average length of the grinded particles was 38.38 mm. The average size of pre-crushed particles from feed raw materials intended for farm animals was 37.64 mm, i. e. the difference between theoretical and actual value is only 2.0 %. This proves the reliability of the obtained analytical expression, which provides the determination of the main parameter of the grinding working body, i. e. spacing of radial knives in rows. The proposed method of determining the average length of crushed particles allows theoretically finding and planning the required particle size

Keywords: length of grinded particles, hammer working body, hammers, hammer spacing

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1. Introduction

The process of grinding feed is the main operation in preparing it for feeding to farm animals. The vast majority of feed raw materials require grinding. At the same time, in some cases, depending on the size and hardness of the crushed raw materials, it is required to carry out preliminary and final fine grinding. In such cases, hammer and knife cutting bodies are used to grind feed.

As it is known, hammer grinders provide high-quality grinding of dry feed. It should be noted that in the case of obtaining fodder flour, final fine grinding is used. Therefore, however, in many cases there is a need for preliminary grinding of feed with high moisture content. This article draws attention to the preliminary grinding of feed particles. Therefore, devices equipped with knife working bodies are used to grind wet feed particles. The development of small-sized grinding devices that provide grinding of the wet mass that meets the requirements, including with the regulation of the average size of the crushed particles, is a solution to the urgent problem of feed preparation processes.

Along with the above, it should be noted the growth of individual entrepreneurship and the emergence of small farms that need small grinding devices. In farms, it is important to obtain feed of different fractions, required by recipes for a variety of farm animals and birds, depending on the requirements. It is also required to eliminate the overload of the grinding equipment, thereby carrying out the preliminary grinding of raw materials, especially wet raw materials, first.

Important here is the conduct of scientific and experimental design work based on advanced mathematical methods for the development of new theoretical expressions. Important and necessary is the confirmation of scientific hypotheses by experimental work and approbation in tests. At the same time, the main indicator of the grinding process is the degree of grinding and the achievement of crushed particles to the required size in the most profitable way, especially with the use of scientifically based and calculated methods. Also, in many production cases, it is often required to predict the size of the crushed particles, but this is not always possible to solve. Therefore, research devoted to finding calculation methods for determining and varying the size of crushed particles depending on the parameters of the grinder will bring significant practical benefits in the feed preparation process and are highly relevant.

2. Literature review and problem statement

Many feed preparation lines provide for preliminary and final grinding [1]. Some technological lines use equipment that combines grinding and drying processes [2]. Grinding is often associated with limiting overloading of the grinding equipment [3]. It is also possible to pay attention to the organization of production and the optimal choice of the type of technological equipment [4]. At the same time, the efficiency of forage grinding has been proven in previous studies [5].

As is known, in the real process of preliminary grinding, the deformation of the pieces and the formation of new surfaces occur simultaneously. Among the crushers of various ways of impact of the working bodies on the crushed material, the most advantageous are crushers with a shock effect on the crushed material. At the same time, a precursor of separation, destruction [6] of pieces into particles by means of impact, is the formation of cracks in the crushed material, which in turn will quickly lead to the separation of the crushed piece into particles. Consideration of the dynamics of a solid body under large deformations and thermoelasticity in a modern computing system is reflected in the paper [7]. A great scientific contribution was made by the theory of Griffiths, who considered brittle bodies, in which almost all deformation up to destruction is elastic [8]. In [9], an attempt was made to modernize Griffith's theory of brittle fracture. The stable crack length according to Frenkel and according to the modernized Griffith equation corresponds to a local minimum of potential energy, which actually eliminates the singularity at zero crack length. In [10], the behavior of a Griffith crack in a piezoelectric material under an antiplanar shear load is studied using a nonlocal theory for the conditions of an impermeable crack surface. Using the Fourier transform, the problem can be solved with two pairs of dual integral equations. These equations are solved by the Schmidt method. In contrast to previous results, it is found that there is no stress singularity and no electrical displacement at the crack tip. The paper [11] investigated the actual states of the movement of hammers with a stable movement of a hammer mill, which is an important basis for analyzing the dynamic characteristics of the hammer mill rotor and the wear mechanism between the hammers and the hammer hinges. The results showed that for each hammer there is a random static deviation and for all hammers there are phenomena of chaos with relative rest in the range of a certain angle. It was pointed out in [12] that the specific conditions at the crack tip and material inhomogeneities are a challenge when analyzing crack growth using traditional methods. The crack path was successfully predicted and the branching of the crack was recorded. The results confirm the ability to simulate crack growth in impact problems. In [13], equations were derived from the Hamilton principle using the theory of first-order shear deformation. In the framework of the theory of viscoelasticity, in [14], the problem of a dynamic transitional crack was considered. It is about a finite-length crack moving in a strip-like viscoelastic body under shock loading. In this case, the Laplace and Fourier transforms were used, and the dual integral equations were reduced to the Fredholm integral equation of the second kind.

Impact crushers, in comparison with other alternatives, whether roller, cone or jaw, have a fairly high degree of crushing, low metal consumption, low power consumption, obtaining particle sizes of various granulometric composition. However, in impact crushers, when obtaining crushed particles, the possibility of calculating the size of crushed particles is not taken into account in order to effectively influence the productivity and quality of crushed particles, which is an urgent scientific problem that requires additional scientific research.

In [11], the actual states of hammer movement with a stable movement of a hammer mill were studied, which is an important basis for analyzing the dynamic characteristics of the hammer mill rotor and the wear mechanism between the hammers and the hammer hinges. The results showed that for each hammer there is a random static deviation and for all hammers there are phenomena of chaos with relative rest in the range of a certain angle. However, when considering hammers, due attention is not paid to the issues of reasonable location of hammers relative to each other.

In [15], it is recommended to design hammers so that their collisions with crushed particles occur in the center of the hammer impact. In this case, the hole of the swivel joint of the hammer wears out less, the imbalance and vibration of the hammer crusher rotor are eliminated. However, in this design of the hammer, attention is paid only to the impact action of the working body, which could be combined with another grinding method, such as cutting, which would enhance the grinding effect. At the same time, it should be noted that the combination of grinding by cutting and crushing with the supply of the crushed material to the cutting pairs due to inertia forces, and not due to pneumatic transport, can significantly reduce specific energy consumption compared to the most common crushers – hammer crushers [16].

The work [17] reports on the optimization of the hammer crusher parameters. The result showed that the initial grinding is fast, while further grinding is gradually reduced. The study of the granulometric composition of the ground particles showed that the ground material is mainly concentrated in the range of sieve sizes. It is clearly seen here, as in many other crushers that the sieve is a certain regulator of the size of the crushed particles. However, it should be noted that it is difficult to theoretically determine the average size of the crushed particles due to the lack of derived mathematical expressions.

The paper [18] presents a method for calculating the maximum collision forces in kinematic chains based on their momenta. The main advantage of this method is its simplicity based on algebraic equations. Collisions between feed, hammer and rotor in a hammer mill are used as an example to demonstrate the implementation of the proposed method. The results obtained are compared with the reference model in the time domain. The proposed method can be used by mechanical engineers in the early stages of design to assess the loads acting on parts during collisions, as well as to find more optimal geometric parameters. However, this method does not allow to regulate and plan the required degree of grinding.

Based on Hooke's law of elasticity, Bond's grinding hypothesis, and Hertz's static theory of impact, a mathematical model of the material crushing process by applying a free impact was developed in [19]. The analytical dependence of one of the main indicators of the dispersion process, i. e. the degree of crushing depends on the mass of the row of hammers, the radius of the center of mass of the hammer, the length of the working surface of the hammer, the radius of the axes of the rotor suspension. With this in mind, the area and average particle diameter of the crushed raw materials, the angular velocity of the rotor, the modulus of elasticity of the crushed material, and the operating coefficient were determined. However, it should be noted that in this work the influence of the spacing of the hammers has not been studied, which can significantly affect the degree of crushing.

In [20], the result of particle size analysis showed that the particle size decreased with increasing grinding speed. However, this method of increasing the degree of grinding can be supplemented by changing the design of the working bodies, their location and quantity, which will lead to more perfect grinding.

Hammer grinders are used for grinding dry roughage. Here, the adjustment of the average size of the grinded particles is carried out by the number of counter-hammers installed in the grinding chamber [21]. In grinders of this design, the transportation of chopped feed is carried out by the air flow created by the hammer rotor. However, when chopping wet hay, rows of counterhammers retain the wet mass, which does not contribute to obtaining a sufficient speed of the transport mass in the chopping chamber.

Based on the results of the work, it was found that the most promising technology for grinding feed raw materials together with drying [22]. Mechanization and automation of shredders is accompanied by the use of electric drives [23]. The layout of technological lines is made with the optimal use of sequential grinding in the composition of the technological line [24]. The destruction and mixing with contact of drying particles in a variable gas flow is used [25]. However, in these works, due attention is not paid to theoretical calculations to determine the size of the crushed particles inside the grinding chamber, which is very important for predicting and planning the grinding process.

It is pointed out in [26] that impact hammers are important components of impact crushers and are often short lived due to the high impact nature of their use. Wear-resistant alloys are welded to the surface of impact hammers to increase their service life. A simulation model of the rotor and impact hammers of an impact crusher was developed using the discrete element method. The wear-resistant alloy on each impact hammer has been divided into twenty-two areas of action. The distribution of the load on each block of alloy depends on the design and manufacturing parameters of the impact crusher. The results showed that the actual wear distribution measurements on the impact hammer were similar to the simulated load distribution measurements on the same surface. The study of the load distribution of impact hammers has laid the theoretical foundation for the optimal design of impact crushers. However, the rows of hammers were not taken into account, which would also affect the distribution of the load on the areas of each hammer and contribute to the optimization of grinding.

The paper [27] provides information that in a hammer crusher, when the rotor rotates, the hammers simultaneously swing around their axes. This wobble affects the movement of the rotor, causing vibration. By simulating the rotation process of a hammer mill, the angular velocity of the rotor and the motor power are obtained, and using the digital filtering method, a method is developed to estimate its magnitude in rms by extracting the vibration component contained in this simulation result. With this evaluation method, the simulation result of the movement process of various structures is evaluated to find a new structure model with very small value of vibration components in angular velocity and engine power. However, this does not take into account the interaction and arrangement of adjacent hammers arranged in rows on the hammer crusher rotor. It would also be necessary to carry out computational actions and theoretical research, which would allow designing a more advanced technical solution.

The paper [28] considers and presents such factors and parameters that affect crushing in hammer crushers, such as imbalance and equilibrium of the rotor. The design and technological factors of impact crushing equipment are analyzed. These factors affect not only the energy performance of grinding, but can also lead to increased wear of parts and assemblies of the hammer crusher. Improvement methods are proposed by means of prompt and timely balancing of the rotor in a hammer mill and on a balancing stand. The destruction of crushed materials and working conditions with and without vibration due to an unbalanced rotor and a balanced rotor are considered in order to understand how this affects the performance of a hammer mill and energy loss. Balancing managed to balance the rotor. However, this does not provide information about the arrangement of hammers on the rotor, and also does not provide information about the possibilities of influencing the size of the crushed product.

In [29], the influence of technological (physical and mechanical properties, size class, granulometric composition, etc.), mechanical (speed in the annular space of the hammer, dynamic characteristics of the rotor, air consumption in the crushing unit, etc.) and design (dimensions of the crushing unit, shape of the hammer, size of the gap between the walls of the unit and the edges of the hammer, the way the crushing unit is fed, the way the product is unloaded, the screen area, the impact plate, etc.) factors and their impact on energy costs. However, at the same time, theoretically and practically, methods for improving the working bodies that affect the grinding of a wide range of products (dry, wet, etc.) have not been proposed.

The work [30] indicates the low reliability of feed crushers, among which the majority are hammer crushers. Most of these crushers have a service life of 10 to 13 years and are low reliability objects. Basically, emergency stops occur due to the destruction of the rotor bearings. In the event of a sudden failure, unscheduled repairs and a decrease in production efficiency occur. However, among the possible reasons for the decrease in the reliability of hammer crushers, one should additionally take into account the design features of the working bodies, their location in the working chamber, which also affects the operation of feed crushers.

Based on the foregoing, it is important to improve the working bodies aimed at grinding a variety of feed raw materials, including wet raw materials. The most common and effective technological equipment for pre-grinding is technological equipment using impact action on the crushed products. However, in the operation of such equipment, there are such disadvantages as not always satisfying and planned performance in terms of the quality of the crushed particles, in some cases there is no justification for the location of the working bodies in crushers and grinders, the lack of calculation formulas for determining the size of the crushed particles, which makes it difficult to plan and vary the sizes crushed particles, as a result of which the grinding process is carried out repeatedly in technological equipment, the steps for the location of crusher hammers and grinders, which are the main working bodies that affect grinding, are not justified, hammer designs are not perfect enough, there is little scientific research on the study and justification of the design parameters of grinders. At the same time, it is necessary for improvement to expand the function of working bodies, for example, a hammer aimed at striking and cutting in the form of a knife with a possible increase in the speed of the ejected fodder mass. In this case, the study and application of the main provisions of existing grinding theories and the development of new, scientifically based theoretical expressions and formulas are of great scientific importance. A lot of scientific research is devoted to the study of cracks in the crushed material. Predictions were successfully carried out for modeling crack growth in impact problems, including those based on the Griffith theory and the Hamilton principle. From a scientific point of view, the theory of shear deformation of the first order, the theory of viscoelasticity, and the non-local theory are of interest. However, further research is required. As a result of the analysis and review of scientific and technical information, it is especially important to note the lack of justification for the step of arranging the working bodies of the hammer type, aimed at obtaining crushed particles with the required average size, which is the solution to the actual problem of feed preparation processes.

3. The aim and objectives of the study

The aim of the study is to substantiate the step of arrangement of hammer-type knife working bodies, which ensured the production of grinded particles with the required average size.

To achieve this aim, the following objectives are accomplished:

– theoretically determine the average size of the grinded feed particles depending on the step of the arrangement of the working bodies;

– experimentally determine the average size of grinded particles.

4. Materials and methods of research

In feed preparation processes, their main quality is estimated by the mass fraction of crushed particles with the required size, i.e. the average size of crushed feed raw materials. To eliminate the overload of technological equipment, preliminary grinding is often used. Therefore, the object of research is the technological process of preliminary grinding of wet feed raw materials by a hammer working body with cutting edges. At the same time, a hypothesis is proposed, which consists in the fact that the average size of the crushed particles should be mainly influenced by the spacing of the radially located working bodies.

Using the methods of probability theory, as well as taking into account the location of particles in the horizontal and vertical planes, let's obtain an analytical expression for the theoretical determination of the average size of crushed particles. From here it is clear that the resulting expression determines the step of arrangement of the working bodies, i.e. the main parameter of preliminary grinding of wet feed raw materials. In its composition, feed raw materials have particles of different sizes, which, during the preliminary grinding, simply circulate in the grinding chamber. When theoretically determining the maximum value of the angle of location of the particles of feed raw materials in the horizontal plane, the maximum particle size of the feed raw materials was chosen to be 70 mm. Here, the assumption was made that when grinding feed raw materials, they have different components in size, i.e. there are smaller and larger components. In theoretical consideration, these components are not taken into account. Here, smaller constituents reduce and larger constituents increase the average size of the crushed particles. At the same time, it was assumed that these components are mutually compensated, and in the theoretical determination of the average size of crushed particles, this assumption should not have a significant impact on the actual value of the average size of crushed particles. This is done to simplify the theoretical analysis of the process of preliminary grinding of feed raw materials.

To determine the actual value of the average size of pre-crushed feed, the method of a single-factor experimental study was used. Here, the experiment was carried out only at one level, with a distance between the faces of adjacent hammers equal to 20 mm or with a spacing of hammer working bodies with cutting edges equal to 30 mm.

When determining the average size of pre-crushed particles, well-known statistical methods for processing empirical data were used [31].

The theoretical determination of the average size of the crushed particles provides the design of new feed grinders. Therefore, the obtained analytical expression is of major value in the choice of working bodies and their parameters for preliminary grinding of high-moisture feed. When solving a theoretical problem, well-known methods of probability theory and mathematical analysis were used, which are used to determine the average value of functions. At the same time, the method of one-factor experiment, which is the most reliable method, was used to solve the problem.

In the experimental part of the work, an experiment was carried out on a wet fodder mass, while the number of parallel experiments was equal to at least three. When conducting parallel experiments, the feed mass was taken into account in terms of composition, moisture content and productivity.

To obtain a crushed mass during the operation of an experimental sample of the developed universal grinder together with hammers, testing methods for agricultural machines were applied.

5. The results of the justification of the parameters of the grinder with hammers

5. 1. Determination of the average size of crushed particles when arranging the working bodies of the grinder

For grinding various types of feed, a feed grinder has been developed, consisting of a belt conveyor, a pre-pressing drum, a hammer rotor, rows of counter-hammers and a deflector (Fig. 1).

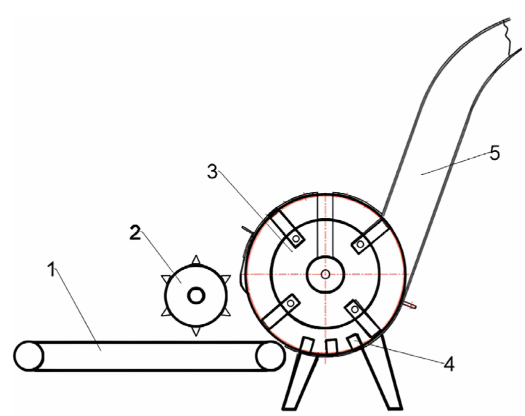

Fig. 1. Structural and technological scheme of the hammer open chopper: 1 – feeding conveyor; 2 – pressing drum; 3 – hammer rotor; 4 – rows of counter-hammers; 5 – deflector

Here, the hammers are made of a sheet 10 mm thick and have two cutting edges (Fig. 2). The hammers are set in rows with a certain pitch, and they have a certain speed of 65–68 m/s. At the entrance, the wet raw material is crushed by the cutting edges of the hammers and, subsequently, the flow of the ejected mass is accelerated, i. e. on a smooth section of the deck, they work like paddles and provide an acceleration of the flow.

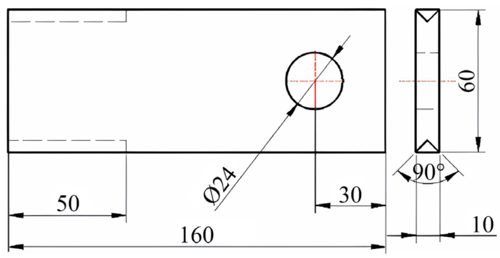

Fig. 2. Scheme of the cutting edges of the hammer working body

In addition, when grinding dry feed raw materials, the cutting edges of the hammers work as a hammer working body and create a strong air flow.

In theoretical studies, the value of the average length of the crushed wet feed particles will be determined depending on the distance between the faces of adjacent hammers. This is due to the fact that when feed raw materials fall under the blows of a number of hammers, the smallest length of the particles of feed raw materials will be equal to the distance between the faces of adjacent hammers.

To accurately determine the value of the average length of the grinded particles, let's consider the impact of particles of feed raw materials under the blows of two adjacent hammers. Since the hammers have cutting edges, therefore, let's consider the minimum size of the crushed particles to be equal to the distance between the faces of the replaceable hammers (Fig. 3).

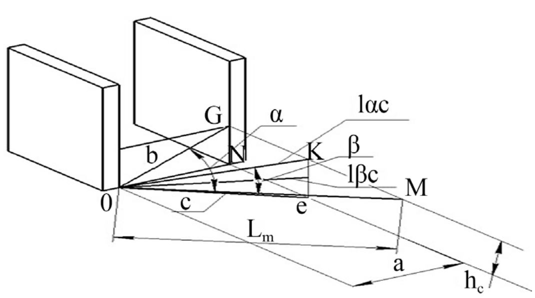

Fig. 3. Scheme of the location of a feed raw material particle with a length l_m between the faces of replaceable hammers in a layer with a height h_c

At the same time, the horizontal arrangement of the particles of feed raw materials can be limited with the maximum value of the angle a_m. When hit by hammers, feed particles will be aligned on the plane of the front face of the hammers. Therefore, the maximum length of the particles of feed raw materials when hit by hammers depends on the spacing of the hammers, i. e. from the value between the faces of interchangeable hammers.

In previous studies, it was found that in order to obtain crushed particles with a maximum mass fraction and an average size of up to 30–50 mm, the spacing of hammers should also be within 30–40 mm. In this case, the maximum length of crushed particles with a length of up to 70 mm is about 90 %.

The composition of the crushed feed raw materials contains particles with a length of more than 70 mm and small particles with a size of up to 10 mm. At the same time, small particles are not crushed by hammers. The theoretical definition of the average size of crushed feed particles does not take into account small particles and large particles with a size of more than 70 mm. Therefore, when determining the actual average size of the crushed particles, they are mutually compensated, and the value of the average size of the crushed particles must remain within the limits of the crushed particles with the maximum value of the mass fraction of the fraction. Based on this, the maximum value of the angle α, i. e. the angle of location of the particles of feed raw materials in the horizontal plane is determined from the OGM triangle by the formula:

$$\alpha=\arccos b/l_m. \quad (1)$$

Here the leg of the triangle b is determined by the formula:

$$b=\sqrt{a^2+h_c^2}, \quad (2)$$

where a is the distance between the faces of interchangeable hammers, m; h_c is the height of the circulating layer, m.

In this case, the value of the grinded particles will be located within the angle α, i. e. 0 arccos b/l_m with uniform probability.

The current value of the length of the grinded particles is determined by the formula:

$$l_a=\frac{b}{\cos\alpha}. \quad (3)$$

Let's use the methods of probability theory and mathematical analysis, which are used to determine the average value of the function (3):

$$l_{\alpha c}=\frac{b}{\arccos\frac{b}{l_m}}\cdot\int_0^{\arccos\frac{b}{l_m}}\frac{1}{\cos\alpha}d\alpha=$$

$$=\frac{b}{\arccos\frac{b}{l_m}}\cdot\int_0^{\arccos\frac{b}{l_m}}\frac{d\alpha}{\sin\left(\frac{\pi}{2}+\alpha\right)}. \quad (4)$$

To solve the problem, the well-known expression is used: $x=(\alpha+\pi/2)$:

$$\sin x=\frac{2\operatorname{tg}\frac{x}{2}}{1+\operatorname{tg}^2\frac{x}{2}},\ u=\operatorname{tg}\frac{x}{2},$$

from here:

$$\sin x=\frac{2u}{1+u^2},\ x=2\operatorname{arctg}u,$$

$$\frac{dx}{du}=(2\operatorname{arctg}u)'=\frac{2}{1+u^2},\ dx=\frac{2du}{1+u^2}.$$

Substituting the above substitutions into formula (4), let's obtain:

$$l_{\alpha A}=\frac{b}{\arccos\frac{b}{l_m}}\cdot\int\limits_0^{\arccos\frac{b}{l_m}}\frac{2\mathrm{d}u}{1+u^2}\cdot\frac{1+u^2}{2u}=$$

$$=\frac{b}{\arccos\frac{b}{l_m}}\cdot\int\limits_0^{\arccos\frac{b}{l_m}}\frac{\mathrm{d}u}{u}=$$

$$=\frac{b}{\arccos\frac{b}{l_m}}\ln\left|\mathrm{tg}\frac{x}{2}\right|_0^{\arccos\frac{b}{l_m}}=$$

$$=\frac{b}{\arccos\frac{b}{l_m}}\ln\left|\mathrm{tg}\left(\frac{\alpha}{2}+\frac{\pi}{4}\right)\right|_0^{\arccos\frac{b}{l_m}}=$$

$$=\frac{b}{\arccos\frac{b}{l_m}}\left[\ln\left|\mathrm{tg}\left(\frac{\arccos\frac{b}{l_m}}{2}+\frac{\pi}{4}\right)\right|-\ln\left|\mathrm{tg}\left(\frac{\pi}{4}\right)\right|\right]. \quad (5)$$

It is known that $\ln\left|\mathrm{tg}(\pi/4)\right|=0$, therefore, the average value of crushed particles in the horizontal plane is determined by the formula:

$$l_{\alpha c}=\frac{b}{\arccos\frac{b}{l_m}}\ln\left|\mathrm{tg}\left(\frac{\arccos\frac{b}{l_m}}{2}+\frac{\pi}{4}\right)\right|. \quad (6)$$

To determine the average length of the crushed wet feed particles in the vertical plane, the maximum size of the crushed particles was taken equal to l_{ac}, and the minimum size of the grinded particles was determined by the formula:

$$c=\sqrt{l_{ac}^2-h_c^2}. \quad (7)$$

The value of the angle β is determined by the formula:

$$\beta=\arccos\frac{c}{l_{ac}}. \quad (8)$$

The average size of the grinded wet feed particles in the vertical plane, i. e. the final average length of the crushed feed particles is determined by the formula:

$$l_{\beta c}=\frac{c}{\arccos\frac{c}{l_{ac}}}\cdot\int\limits_0^{\arccos\frac{c}{l_{ac}}}\frac{\mathrm{d}\beta}{\sin\left(\frac{\pi}{2}+\beta\right)}=$$

$$=\frac{c}{\arccos\frac{c}{l_{ac}}}\cdot\ln\left|\mathrm{tg}\left(\frac{\arccos\frac{c}{l_{ac}}}{2}+\frac{\pi}{4}\right)\right|. \quad (9)$$

The analysis of the obtained analytical expressions shows that the value of the average length of the crushed feed depends on the size of the maximum length of the particles of feed raw materials l_m and the distance between the faces of the replaceable hammers a. In previous production tests, it was found that the main wear of the hammer working body was carried out with a wear length of hammers of 30–40 mm. Therefore, the maximum value of h_c will be taken as h_c=40 mm.

With a distance between the edges of the replaceable knife working bodies of 20–30 mm, the value of the maximum length of the grinded wet feed in the vertical plane will be about 50 mm.

In the feed chopper developed by us, the distance between the faces of the replaceable hammers was 20 mm. As noted above, the main size of grinded particles with a mass fraction of about 90 % accounted for grinded particles with a size of up to 70 mm, so for the calculation let's take l_m=70 mm.

The values of the initial data and the results of the calculation are shown in Table 1.

Table 1

Initial parameters and calculation results according to the obtained analytical expressions

Initial parameters		Calculation results, mm			
		According to formula (6), mm		According to formula (9), mm	
a	20	b	44.72	c	33.04
h_0	40	α	50.28°	β	50.45°
l_m	70	l_{ac}	51.88	$l_{\beta c}$	38.38

Table 1 shows that when the angle changes from 0 to 50.28°, the average length of the crushed particles in the horizontal plane was equal to l_{ac}=51.88 mm. Calculations carried out according to formula (9) showed that the average length of the grinded particles within the angle B change from 0 to 50.45 °C was equal to l_{BC}=38.38 mm.

Thus, according to the obtained analytical expressions, at a distance between the faces of interchangeable hammers of 20 mm, i. e. with a spacing of radial knives of 30 mm, the average size of the grinded particles was 38.38 mm. This indicates the average size of the grinded particles, i. e. the quality of feed grinding is mainly influenced by the step of arrangement of working bodies in the rows.

5. 2. Experimental determination of the average size of grinded particles in a grinder equipped with hammer-type radial knives

To determine the reliability of theoretical studies, a grinder was used (Fig. 4), developed according to the design and technological scheme shown in Fig. 1.

In this grinder, the hammers are mounted on the rotor with a pitch of 30 mm, i. e. the distance between the faces of adjacent hammers was 20 mm and they have cutting edges (Fig. 5).

To determine the influence of the spacing of the hammers on the quality of the crushed feed, all rows of counter-hammers were removed from the cutting chamber. The experiments were carried out on raw materials with a moisture content of 64.6 %. To test theoretical studies, this process was chosen due to the fact that during the grinding process, the bulk of the wet raw material is crushed when it gets under the blows of knives. When grinding the dry mass, a significant part of the fine particles can be crushed by grinding.

In this case, the supply of feed raw materials was carried out by a belt conveyor. A certain feed capacity is achieved by spreading feed raw materials on one meter of the conveyor. In the experiments, 1.5 kg of mass was decomposed per 1 meter of the conveyor, which corresponded to a productivity of 5.4 t/h. The average size of the crushed particles was determined by sampling. Table 2 shows the results of analysis of one sample.

Fig. 4. General view of the experimental feed grinder

Fig. 5. General view of the location of the hammers on the rotor

Table 2

Results of sampling to determine the average size of grinded particles

Class cutting length, mm (l)	Sample weight, g	Mass fraction, % (f)	Average length of fractions, mm (lxf/100)
0–10	3.9	13.93	0.70
10–20	3.6	12.86	1.93
20–30	5.6	20.0	5
30–40	3.7	13.2	4.62
40–50	3.4	12.14	5.46
50–60	4.2	15.0	8.25
60–70	0.8	2.86	1.86
70–80	0.7	2.5	1.88
80–100	1.6	5.71	5.14
100–120	0.5	1.79	1.97
0–120	Σ28	100	Σ36.81

The results of the disassembled sample show that the average size of the crushed particles was 36.81 mm, and the average length of the grinded particles for the three disassembled samples was 37.64 mm. It is known that the average size of the grinded particles according to the obtained analytical expressions was 38.38 mm. This shows that the difference between the theoretical and actual values of the average sizes of grinded particles is only 2.0 %. This proves the reliability of the obtained analytical expression. It can be used to determine the parameters of grinders designed to process feed with high moisture content.

6. Discussion of the results of the study on the justification of the parameters of grinders for wet feed

As a result of the theoretical studies carried out, analytical expressions were obtained for determining the average size of pre-crushed particles in the horizontal (6) and vertical (9) planes. In this case, according to formula (9), the final average size of pre-crushed particles is determined by a hammer working body with cutting edges. Here it is clear that the obtained analytical expressions provide the definition of the main quality indicator of pre-crushed feed raw materials. In contrast to the analytical expression we derived for determining the average size of pre-crushed particles, in the earlier work [21], an analytical expression was obtained for determining the mass fraction of the required fractions in fractions of a unit (or in percent). Considering the arrangement of crushed feed particles in the horizontal and vertical planes, a mathematical model of the process of dosed delivery of crushed feed was obtained [32]. Here, the probability of the location of particles with a certain size in the feed layer is determined, however, in the studies presented, analytical expressions for determining the average size of pre-crushed feed raw materials were not obtained. As a result of experimental studies, the reliability of the obtained analytical expression was proved.

In theoretical studies, there are limitations in determining the maximum values of the angles α and β. When determining the maximum value of the angle α, the initial length of the crushed particles with a size of 70 mm was chosen. This limitation of the initial length of the crushed particles is due to the fact that at the selected distance between the faces of adjacent hammers, the main size of the crushed particles was up to 70 mm. In addition, when the hammers strike, the feed particles are oriented in a horizontal plane, and therefore this limitation did not affect the reliable value of the average length of the crushed particles. This analytical expression is used to determine the average size of crushed particles with a radial arrangement of the working bodies. The reliability of the obtained analytical expression is proved by experimental studies. Therefore, this expression can be successfully used to determine the spacing of the working bodies from the condition of the required size of the crushed particles of feed materials. It should be noted that the average size of the crushed particles depends on the spacing of the working bodies. Therefore, it can be emphasized that this analytical expression gives reliable results within the limits of zootechnical requirements for feed materials, and also provides the choice of the main parameter of ground feed, i.e. step of arrangement of working bodies in rows. At the same time, it was noted earlier that this expression is used for the radial arrangement of the working bodies of feed choppers. Therefore, the result of this theoretical study can be aimed at solving a similar problem when grinding feed with drum-type knife working bodies. From this it is clear that we have determined the main direction of the new theoretical research. When solving such a problem, there are difficulties in reliably determining the speed of the layer circulating in the grinding chamber,

i. e. when determining the reliable value of the number of impacts by the working bodies on the crushed mass.

At the same time, the results of the experiments the have shown to explain the reliability of the obtained analytical expression used to justify the main parameter of the grinding rotor, i. e. step of arrangement of working bodies in rows. The proposed method for determining the average length of crushed particles based on the obtained analytical expression makes it possible to theoretically find and plan the required particle size obtained as a result of grinding, taking into account the required spacing of hammers in the rows of the grinder working body. A feature of the proposed method is that it is aimed at determining the parameters of grinders designed for grinding wet feed particles. Using this method, it was found that the average size of crushed particles, i. e. the quality of grinding of feed particles is dominated by the step of arrangement of the working bodies in the rows. The developed method for determining the average length of crushed particles based on the obtained analytical expression, compared with existing sampling methods, makes it possible to determine in advance the size of particles subjected to grinding at a particular arrangement of hammers in rows, thereby adjusting the need to obtain crushed particles in accordance with the need. It should also be noted here that the theoretical determination of the average size of the crushed feed raw material provides for the development of new feed grinders equipped with similar working bodies. The experiments carried out showed only the reliability of the obtained analytical expression. In other studies, we did not find such an expression. Therefore, the obtained results of theoretical and experimental studies are of high value for science. In addition, the high accuracy (error of only 2.0 %) of the obtained expression ensures wide application in the development of new feed grinders.

From the previous sections of this article, it is known that in order to determine the average size of pre-crushed feed, new theoretical studies have been carried out that consider the process of the spatial arrangement of crushed particles and, in connection with this, a solution to a complex problem has been obtained – the problem of theoretically determining the average size of pre-crushed particles. Although the resulting expressions are used only to determine one parameter. But this parameter is the main quality indicator of pre-ground feed.

When developing feed grinders, the question always arises of designing the working body and its spacing in rows depending on the type of feed, i. e. solving the issue is the main challenge in the development of feed grinders. Therefore, the research results are of practical value. Here, the conditions for applying the obtained analytical expression depend on the type of feed being ground. In this case, the resulting expression can be used in the development of wet feed raw material grinders and the selection of feed grinders. As noted above, high-quality feed grinding ensures an increase in livestock production. At the same time, using the results of the research, grinders are being developed that provide high-quality grinding of feed. This increases the production of livestock products, i.e. the results obtained have economic efficiency.

The results of the studies carried out are mainly used to determine the average size of crushed feed raw materials in machines with radially arranged working bodies. This is a limitation in the practical use of the research results. Further development of this direction can be carried out in the direction of conducting theoretical studies aimed at obtaining analytical expressions for determining the average size of crushed feed by drum grinders of feed raw materials. Based on the foregoing, it should be noted the importance of developing this method for determining the average length of crushed particles based on a reasonably obtained analytical expression with experimental confirmation, which is of great scientific and practical importance.

7. Conclusions

1. Analytical expressions have been obtained for determining the average length of grinded particles depending on the distance between the faces of replaceable knife working bodies, i. e. from the step of arranging them in rows. At the same time, the calculation results showed that with a distance between the faces of adjacent hammers of 20 mm, the value of the average length of the crushed particles was 38.38 mm.

2. To verify the reliability of theoretical studies, experiments were carried out on an experimental feed grinder.

The results of the analysis of samples obtained from feed raw materials intended for farm animals showed that the average size of the grinded particles was 37.64 mm, i. e. the difference between theoretical and actual value is only 2.0 %. This proves the reliability of the obtained analytical expression, which provides the determination of the main parameter of the grinding working body, i. e. spacing of radial knives in rows.

Conflict of interest

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

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Data availability

Data will be made available on reasonable request.

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