JUSTIFICATION OF PARAMETERS AFFECTING INCREASE
OF HAMMER CRUSHER PRODUCTIVITY

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Abstract. The analysis of the efficiency of the particle sizes of the feed components used in feed rations resulted in proof of the significance of the feed particle size not only while feeding animals with loose dry or wet mixtures but also with feed granules. The study showed that to increase the efficiency of hammer crushers it is relevant to substantiate the parameters of the hammer rotor and the method the raw materials are supplied into the crusher's working chamber. The experiment involved a stand, which enabled determining the strength of stems while being broken. A sieve classifier was applied to measure the average particle size of the ground products. The rotor speed was monitored electronically and duplicated by a manual tachometer. The average diameter of clover samples was 1.64 mm and correspondingly 3.3 mm of lupine; the length of the samples was 50 and 100 mm. The breaking force on a clover stalk with 13.2% of moisture was 97 N max and 4.4 N min, and correspondingly in the case of a lupine stalk – 22.7 N max and 1.5 N min with 12.3% of moisture. In our case, grinding clover and lupine hay with the minimal energy density Q_s, 60 m·s^{-1} was considered to be the efficient speed of the hammers $v_м$, and the grinding modulus M was within 1.0-1.3 mm. With the different values of the hammer speed and the crusher grinding chamber width of 180 mm, the results of the experimental studies showed that regardless of a supply method and a type of processed raw materials, the output of the ground products was distributed quite unevenly across the width of the working chamber. However, it was found that the peripheral feeding method was significantly more effective than a central one, since the quicker the work was done, the more efficient it became. While at speed $v_м = 30$ m·s^{-1}, the unevenness of the product output under the central supply method was greater than that of the peripheral one only in 8-14%, at speed $v_м = 75$-80 m·s^{-1} this difference reached 20-32%.

Keywords: grinding, hammer rotor, rotation frequency, size of feed particles, energy consumption.

Introduction

The list of raw materials used in modern animal husbandry for feeding livestock and poultry is very wide, the basis of fodder rations is the fodder of plant origin [1; 2]. The main operation in the process of preparing fodder for feeding is grinding, which effectively enables carrying out other processing methods, and preparing combined and balanced fodder. The effect of particle size on the efficiency of feed use is explained by some factors: their contact area with gastric juice and physical condition. In particular, it is stated [1; 2] that small particles stay longer in the gastrointestinal tract, and their nutrients are better digested and more fully absorbed.

Processing roughage into flour increases the live weight gain of cattle by 15-18% [3]. When growing broilers, it has turned out to be more effective to use the feed in the form of grits from granules made from ingredients of medium (1.0-1.8 mm) grinding [1; 4]. At the same time, some research data show [5; 6] that excessive grinding of feed with a large output of dust (particle size less than 0.2 mm) leads to a decrease in the live weight gain of pigs by 15% compared to the use of feed, the average particle size of which is 1.8 mm. Accordingly, it has been proven that the productivity of shredders is inversely dependent on the degree of fodder grinding. Therefore, the costs of feed processing increase, and it becomes necessary to reduce the size of the particles of grinding products [7-9]. The energy intensity of the feed processing is determined directly by the specified particle size of the grinding products [10; 11].

It is possible to achieve effective processing of feed raw materials and ensure high-quality preparation of animal feed by implementing a set of measures related to the improvement of the machines for grinding, as well as preparing compound feed. Also, it seems efficient to enhance the requirements towards the management of the relevant processes and the control of the output.

Materials and methods

The analysis of the main methods of loading and deformation nature showed that in the case of mechanical grinding, normal and tangential forces that act on the processed material result in simple strains in its structure: compression, stretching, and shear. However, only the last two directly destroy

the material by tearing it into particles or displacing some particles with others [12; 13]. In grinding, material destruction does not always occur while overcoming the molecular forces of adhesion. It is known, for example [6; 14], that the experimental values of the strength limit for the vast majority of materials are several times smaller than the values that correspond to the molecular bonds of substances. In the paper [9; 15] it is stated that a few times less energy is spent on grinding pre-deformed materials than those that do not have remnants of previous damage and deformations. The study of the quality and energy indicators of grinding processes [9; 16; 17] concludes the relevance of the devices' specialization under the material processing that differ significantly in physical, mechanical, and technological properties.

The research aimed at identifying the optimal parameters of hammer grinders for the processing of agricultural raw materials is carried out in different countries [21-23]. Hammer speed is generally recognized as the most particular parameter of shredders, which constantly attracts the attention of researchers and designers. The significant complexity of the mechanics of processing materials in a hammer crusher and a wide variety of physical, mechanical, and technological properties of raw materials affecting the grinding process are the two factors that have made inefficient the attempts [4; 18-20; 22; 23] to obtain a general and sufficiently reliable formula to determine the working speed of hammers. Due to this, the aforementioned scientific endeavours have not resulted in any practical application yet.

The task is further complicated by the fact that it is necessary to obtain not only the speed sufficient for the material destruction but also the optimal speed of the hammers, which would ensure the high quality of grinding products.

Results and discussion

As a result of the conducted research, we found that moisture content and the scale factor (sample size) have a considerable influence on the level of deformation and strength of grass stems. A rise in humidity reduces the limits of strength variation, and a decrease in the sample size enhances the level of the latter. Thus, static breaking enabled determining variations of strength indicators (Tables 1, 2). Moreover, we found that the destruction of the grass stems first of all begins in the weakest areas: at the bends, in the zones of some other damages received during the harvest; near nodes that break the homogeneity of the structure, and near clamps, which actions injure the samples. During static crushing, it was also determined that the strength of the samples along the fibres is several times higher than across the fibres.

Table 1

Strength indicators of broken grass stems

Sample material	Humidity, %	Breaking force per grass stem, N			Average strength limit, $\cdot 10^5$ N·m^{-2}
		maximal	minimal	average	
Clover	13.2	97	4.4	16.9	80
	15.2	58.3	5.9	19.4	92
	20.2	40	12.4	22.5	106
Lupine	12.3	22.7	1.5	10.1	26
	18.4	28	11.7	18.2	46

Table 2

Study results on the strength of clover hay stalks under static compression

Compression direction	Sample length, mm	Deformation amount		Destructive effort, N	Average strength limit, $\cdot 10^5$ N·m^{-2}
		absolute, μm	relative, %		
Along the fibres	3	119	4.0	137 ± 7.5	428
	10	121	1.2	106 ± 6.0	335
Across the fibres	3	30	1.0	31 ± 4.6	85
	10	38	0.4	58 ± 3.6	47

The experimental studies on the substantiation of the rational design and functional scheme of the hammer crusher were carried out on a specially developed machine (Fig. 1), which made it possible:

- to carry out peripheral or central supply of raw materials to the working chamber;
- to change the rotation frequency of the hammer rotor 4 (Fig. 1);
- to grind feed materials with closed and open circuit designs of the working chamber;
- and to measure the output of the ground products from different zones of the working chamber along its width.

A sieve classifier enabled defining the average particle size of the ground products. The rotor speed was monitored electronically and duplicated by a mechanical tachometer. The average diameter of clover samples was 1.64 mm and that of lupine – 3.3 mm; the length of the samples was 50 and 100 mm correspondingly.
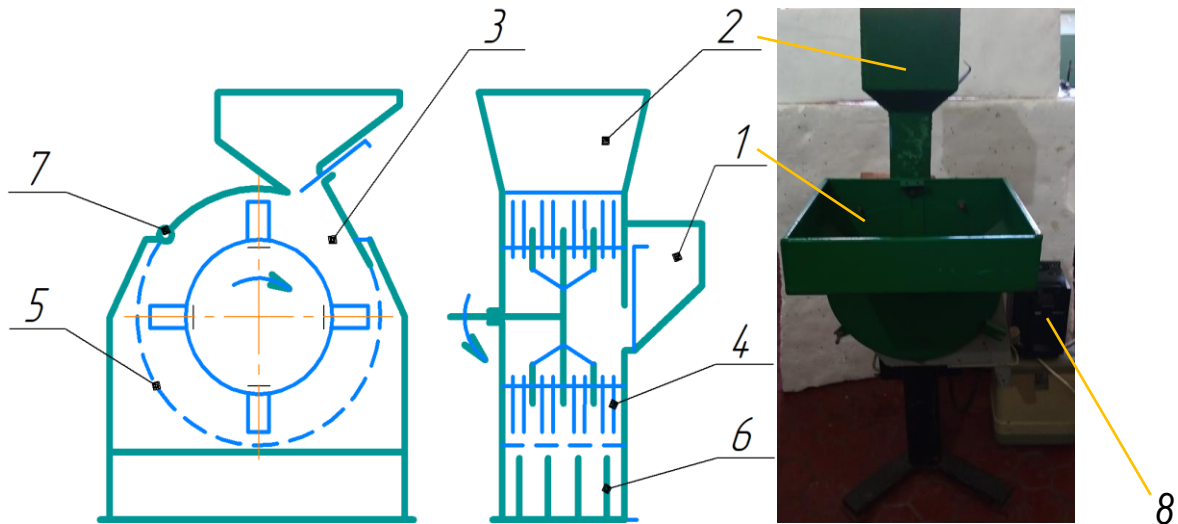

Fig. 1. **Experimental machine:** 1 and 2 – devices, respectively, for the central and peripheral supply of raw materials; 3 – grinding chamber; 4 – hammer drum; 5 – working surface of the grinding chamber (sieve); 6 – devices for separate collection (by the width of the working chamber) of ground products; 7 – unloading valve; 8 – frequency converter

The next step was to analyze the obtained data on the efficiency of grinding feed raw materials with a hammer crusher (Fig. 2).
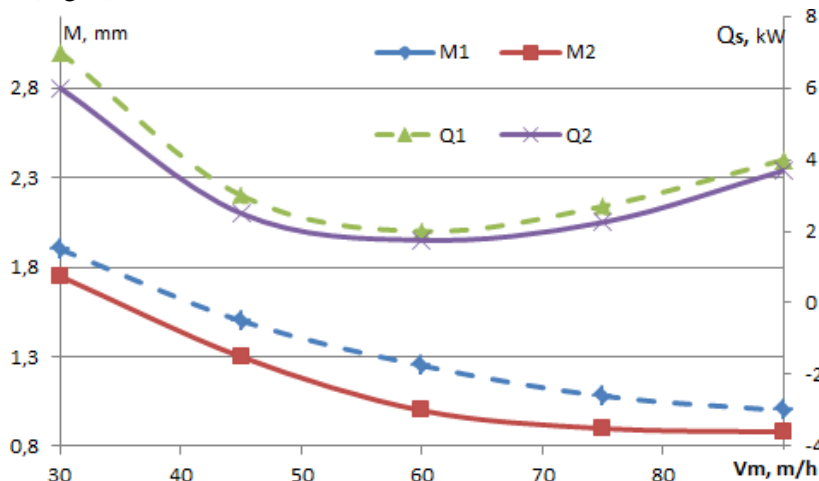

Fig. 2. **Dependencies of energy intensity Q_s (Q1, Q2) and grinding module M (M1, M2) on the hammer speed v_m when grinding clover (——) and lupine hay (- - - -)**

Figure 2 illustrates that the increase in the destructive factor value (e.g. the impact force and impact impulse, the frequency of the hammers' collisions with the processed material) and the reduction of the time the material remains in the working chamber result in the initial intense reduction in the particle

size (grinding modulus M) of the ground products and the energy intensity (Q_s) of the process as the hammer speed (v_m) rises. The fact of a gradual decrease in the reduction intensity of the product particle size with a further increase in the hammer speed (in our case, $v_{m \geq} 55\text{-}60 \, \text{m·s}^{-1}$) can be explained not only by the value of the maximum impact impulse, determined by the limiting mass of the processed material particles, but also by "hardening" of the processed material. The latter occurs as the particle number shrinks and they become closer to a complete and homogeneous structure. Therefore, the further reduction of the particle size meets additional obstacles and requires a more intensive increase in the hammer speed and a sharp rise in the energy consumption for grinding.

Concerning hammer crushers, the negative phenomena of the technological plan are the influence of the high speed of movement of the processed layer along the grating surface on the intensity of sieving of the ground products, as well as the increase in the output of the dusty fraction. As the speed of the hammers rises, the unevenness of the processed material distribution across the width of the working chamber also increases. As a result, this chamber is not used to its full potential.

The central and peripheral options for supplying raw materials to the working chamber have both strengths and weaknesses. Meanwhile, the results of experimental studies show that in the case of central supply, the energy intensity of the process is on average 7-12% higher compared to peripheral supply.

In crushers with an open circuit design of the working chamber, multiple circulations of the processed layer are eliminated, and as a result, the time the material stays in the working chamber is reduced. At the same time, it might seem that such conditions contribute to increasing productivity and reducing the energy consumption of the process. This is what most literature reviews tend to claim, i.e. the productivity of non-sieve crushers is higher, and the energy intensity of the process is lower than that of closed-circuit crushers. But the problem is that such studies hardly consider the quality indicators of the products of grinding. Meanwhile, the comparison of technical and economic indicators of well-known non-sieve crushers with the best examples of closed-circuit crushers, when the quality indicators of ground products are the same, results in finding no significant advantages of non-sieve mechanisms either in terms of their productivity or energy and metal intensity of the process. At the same time, regarding the grinding quality (uniformity of the fractional composition of the product), open circuit crushers are inferior to sieve ones.

The assessment results of the relative unevenness value by the coefficient of variation v_m of the yield of ground products across the width of the working chamber and the analysis of this indicator are shown in Figure 3:
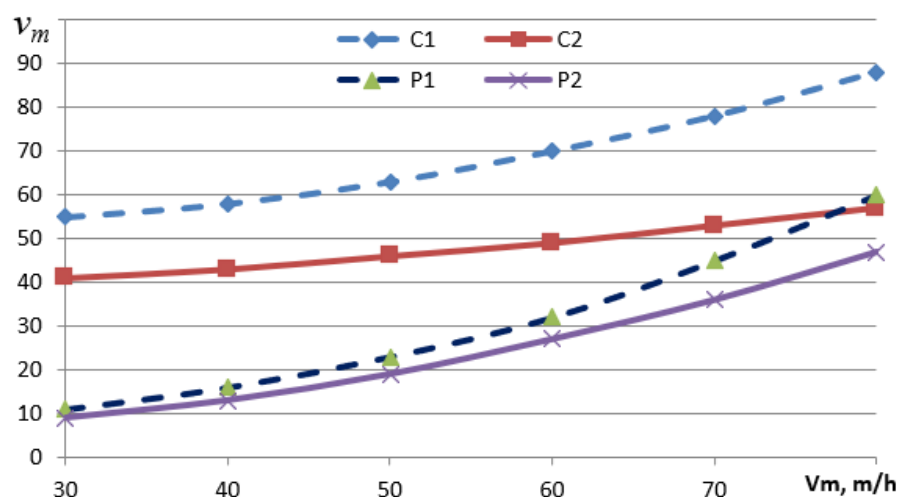

Fig. 3. **Coefficient of variation v_m of yield of ground products across the width of the working chamber (diameter of the chamber is 0.66 m) with peripheral (——) and central (- - - -) feeds depending on the speed of hammers v_m:** 1 – when processing clover hay; 2 – when grinding barley grain

The results are as follows.

- A significant advantage of peripheral feeding compared to central one. The faster the speed of the working parts, the more beneficial peripheral feeding operates. If, for example, at a speed

of $v_{m} = 30$ m·s$_{-1}$, the unevenness of the product output at the central feed was higher by only 8-14% than at the peripheral one, then at $v_{m} = 75$-80 m·s^{-1} this difference reached 20-32%;

- The processing of stem materials showed greater yield unevenness than during grinding fodder grain. However, the faster the hammers' speed is, the less influential the type of processed material becomes. Thus, at $v_{m} = 40$ m·s$_{-1}$, the indicator of the uneven yield of the product vt during the processing of clover hay was 6-7 times higher than the corresponding indicator of the yield of barley grain grinding products; at $v_{m} = 75$-80 m·s^{-1}, this difference was only 10-40%;
- An increase in the diameter of the working chamber, when the hammer speeds are equal, boosts the unevenness of the output of ground products along its width.

The carried out research has outlined that generally crushers with a peripheral supply of raw materials and with a tangential one in particular, are featured by more uniform speed and pressure of the airflow on the working surface of the grinding chamber. Above all, in the case of peripheral feeding, the raw material enters the grinding chamber relatively evenly across its width, compared to the central feeding type.

However, when the air regime is relatively uniform, even with peripheral supply, in the middle of the sieve surface of the working chamber width, the air speed and pressure will be somewhat higher than near the chamber side panels. The latter tend to create an additional braking effect on the airflow from the hammer drum during its rotation.

Higher pressure in the middle of the working chamber width results in an axial shift of the processed material to the zones with lower pressure. In other words, the material seems to be blown by the airflow from the middle of the grid surface to the chamber side panels. The latter have a braking effect on the recycled layer, which moves inside the working chamber directly near these panels and interacts with them. The movement speed of the processed material near the side panels decreases, which results in its greater concentration within these zones. Apparently, materials with a higher density will better resist the effect of the airflow. To confirm this, we see that the ground product output across the working chamber width while grinding fodder grain is less uneven compared to the processing of coarse fodder (shown in Fig. 3).

The distribution of the ground product output under the central feeding is featured by the greatest intensity at the beginning of the working chamber (from the side of the raw material loading) and a sharp decrease in the middle zone of the sieve surface (asymmetric parabola). This proves the issue that the initial regularity of the raw material distribution while loading affects the way the final distribution of processed material across the chamber width is organized. Additionally, central feeding makes the air regime across the width of the grinding chamber even more uneven, since the air enters the chamber from the side, and redistributes the processed material more intensively in the axial direction. According to the nature of the distribution curves of the ground product output, the displacement of the material occurs mainly in the direction opposite to the place of loading of raw materials. This is quite natural, since in the working chamber area, which is the furthest from the loading place of raw materials and air suction, there will be a minimum environment density or a reduced pressure in comparison with the other places of the chamber.

Therefore, the uneven air regime across the width of the working chamber and the braking action of its side panels are the main causes of the uneven distribution of processed material (the loading) in the middle of the chamber and the ground product output. While the asymmetry of the distribution during central feeding is the result of the lateral loading of raw materials into the grinding chamber.

Conclusions

1. It has been stated that an effective way to increase the efficiency of hammer crushers is to substantiate the parameters of the hammer rotor and the method of feeding raw materials into the crusher's working chamber. The peripheral feeding compared to the central one and its increase with intensifying the working mechanism speed has been proven as much more beneficial. While at the speed of $v_{m} = 30$ m·s^{-1}, the unevenness of the product output at the central feeding was only 8-14% higher than that of the peripheral one, at $v_{m} = 75$-80 m·s^{-1} this difference reached 20-32%.
2. To boost the productivity of the hammer crusher, it is necessary to increase the rotation frequency of the hammer drum. It has been shown that the value of 60 m·s^{-1} is the rational hammer speed v_{m}

when grinding clover and lupine hay, at which the energy intensity Q_s is minimal, and the grinding modulus M is within 1.0-1.3 mm.

3. While justifying the parameters of a hammer crusher, it should be taken into account that a rise in the diameter of the working chamber, provided that the hammers are at equal speeds, increases the rate of uneven output of ground products across its width.

Author contributions

All the authors have contributed equally to creation of this article.

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