Scientific justification of power efficiency of technological process of crushing of forages

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Abstract. The main consumers of feed grain include industries such as livestock, pig and poultry. For the organization of proper feeding of animals and poultry, the rational use of concentrated feeds, the main component of which are grain and leguminous crops, providing about 50% of protein, is important. Currently, the share of concentrated feed in the total feed balance is more than a third. The efficiency of using feed grain without prior preparation is markedly reduced. The quality of the crushed feed in its granulometric composition exceeds the quality of the feed crushed by any hammer mill, due to the increase in the content of the easily digestible animal and bird fraction and the reduction of the dust fraction, which has a negative effect on the animal's body. One of the main ways to prepare grain feed for feeding is grinding. During grinding, conditioning, crushing and other operations, the hard shell is destroyed, the availability of nutrients to the action of digestive juices increases, digestibility is accelerated, and more complete absorption of feed energy occurs. Grinding is the most energy-intensive and time-consuming operation, occupying more than half of the total labour costs in the preparation of animal feed. The article provides the scientific rationale for the energy efficiency of the feed grinding process.

1. Introduction

A correctly selected diet of feed with the necessary set of nutrients allows you to achieve high economic indicators in animal husbandry. High-grade compound feeds include concentrated feed, the preparation of which in the conditions of small farms requires the development of grain crushers with a productivity of 100 ... 300 kg/h with a grinding quality that meets zootechnical requirements with minimal energy costs. Grinding of roughage in modern feed preparation machines occurs as a result of cutting, impact, splitting, crushing and abrasion. It was established that each grinding method individually is suitable only for the destruction of a certain group of materials, depending on the physico-mechanical properties of the crushed feed [1], [2], [3], [4], [5], [6], [7]. The analysis of the current state of coarse forage grinding showed that a number of machines and units designed for grinding stalk crops have been developed and are commercially available by industry. The main disadvantage of these machines is the high energy intensity of the grinding process. Thus, for peasant (farm) and personal homestead households that have small cattle farms, a chopper for coarse fodder, a stalk and corn stalks, a stalk and baskets of sunflower, a branch feed is needed, which ensures the grinding of materials regardless of their physical and mechanical characteristics and possesses high throughput with minimal energy costs.
2. Research results
To solve this problem, a coarse feed chopper has been developed (figures 1, 2) [8], [9].

![Figure 1](image1.jpg)

**Figure 1.** General view of the feed shaft of the chopper of roughage with circulation disks (a) and grinding drums (b).

The drive pulley 3 is rigidly attached to the shaft of the engine 2 and, by means of a V-belt transmission 4, the torque is transmitted to the driven pulley 5, which is rigidly attached to the main shaft 6 with cutting knives 7 resting on the rolling bearings. In parallel with the driven pulley 5, a pulley 8 is rigidly mounted on the shaft 6, which is connected to the driven pulley 9 by means of a V-belt transmission 10. The driven 9 and the driving 11 pulleys are rigidly mounted on the shaft 12, which is attached to the frame 1 by means of a rolling bearing.

![Figure 2](image2.jpg)

**Figure 2.** Kinematic diagram of the mechanism for driving the working bodies of the grinder of roughage: 1 - frame; 2 - engine; 3, 8, 11 - driving pulleys; 4, 10, 14 - V-belt drives; 5, 9, 13 - driven pulleys; 6, 12 - shafts; 7 - grinding drum; 15 - a cylindrical gear reducer; 16, 22 - leading asterisks; 17, 24 - driven stars; 18, 23 - chain transmission; 19, 20 - leading and driven shafts of the conveyor belt; 21 - belt conveyor; 25 - asterisk of a drive of a giving shaft with circulating disks; 26 - an asterisk of a drive of a grinding drum; 27 - an asterisk for regulating the tension of the chain gear; 28 - feed shaft with circulating discs.
Torque from the drive pulley 11 is transmitted to the driven pulley 13 by means of a V-belt transmission 14. The driven pulley 13 is rigidly attached to the drive shaft of a single-stage cylindrical gearbox 15, the housing of which is attached to the frame 1. A drive sprocket 16 is connected to the drive shaft of the single-stage cylindrical gear reducer 15 with a driven sprocket 17 through a chain drive 18. The driven sprocket 17 is rigidly mounted on one end of the drive shaft 19 connected to the driven shaft 20 by means of a conveyor belt Tera 21.

The drive and driven shafts 19 and 20 are supported by rolling bearings, the housings of which are attached to the frame 1. At the other end of the drive shaft 19, a drive sprocket 22 is attached, which is connected via a chain gear 23 to the driven sprocket 24.

The chain drive 23 drives the sprockets 25 and 26 to rotate. The sprocket 25 is rigidly mounted on the feed shaft with circulation discs 28. The shaft 28 is supported by rolling bearings, the housings of which are attached to the upper part of the frame 1. The sprocket 26 is rigidly attached to the feed shaft with counter knives 29 which relies on rolling bearings. The sprocket 27 performs the function of tensioning the chain gear 23 and is attached to the frame 1 with the possibility of rotation in a vertical plane.

Grinding of roughage in modern feed preparation machines occurs as a result of cutting, impact, splitting, crushing and abrasion. It was found that each grinding method individually is suitable only for the destruction of a certain group of materials, depending on the physico-mechanical properties of the crushed feed.

Theoretical studies have shown that increasing the energy efficiency of grinding coarse fodder is possible due to the use of two parallel shafts in the unit: the main and feed shafts, on the cylindrical surface of which six teeth are cut along the entire length of 0.02 m wide and 0.04 m long, which are located at an angle of 60° relative to each other and distributed along the entire length of the cylindrical surface of the shafts in increments of 5 cm, which mesh with each other with a gap of 0.01 m. In this case, one main shaft with cutting knives grows with a frequency of 2000 ... 2011 min⁻¹ in a clockwise direction, and the feed shaft with opposing knives - with a frequency of 80 ... 90 min⁻¹, providing high-quality grinding indicators corresponding to zootechnical requirements.

Experimental studies of the technological process of the coarse feed chopper were carried out with the aim of checking the theoretical conclusions, identifying the most significant factors and the influence of each of them on the energy consumption of coarse feed grinding, obtaining sufficient information about the technological process to establish the main dependencies and evaluating its energy efficiency [10].

An analysis of the factors affecting the energy consumption of grinding coarse feeds by the proposed grinder showed that the greatest influence on these indicators is exerted by the number of revolutions of the cutting knives, the gap between the cutting and counter knives, and the feed rate of the starting material (table 1).

| Factors Value | Speed of cutting knives, \(n_{\text{RN}}\), min⁻¹ | Clearance between cutting and counter knives, \(S_{N}\), m | Feed rate, \(V_{\text{fm}}\), m/s |
|---------------|-----------------------------------|------------------|------------------|
| Coded (dimensionless) | \(X_1\) | \(X_2\) | \(X_3\) |
| -1 | 0 | +1 | -1 | 0 | +1 |
| Natural | \(n_{\text{RN}}\), min⁻¹ | \(S_{N}\), m | \(V_{\text{fm}}\), m/s |
| 1500 | 2000 | 2500 | 0.005 | 0.01 | 0.015 | 0.04 | 0.08 | 0.12 |

Table 1. Factors and levels of their variation.
After conducting the experiment and processing the experimental data, the regression equations were obtained:
- in coded form:
  \[
  Y_{E_{12}} = 3.5333 + 0.3888X_1 - 0.9963X_2 - 2.225X_3 + 0.165X_1X_2 + \\
  + 0.143X_1X_3 + 0.0925X_2X_3 + 4.3084X_1^2 + 3.3584X_2^2 + 4.3809X_3^2;
  \]
  (1)
- in natural form:
  \[
  E_{12} = 111.142 - 0.0694n_{RN} - 3054.98S_N - 512.59V_{IM} + 0.066n_{RN}S_N + \\
  + 0.0071n_{RN}V_{IM} + 462.5S_NV_{IM} + 0.000017n_{RN}^2 + 134336S_N^2 + 2738.06V_{IM}^2.
  \]
  (2)

The dependence of the grinding energy intensity on the pairwise influence of the studied parameters is presented using equal level lines obtained from the regression equation (2). The regression equation at a zero level of the feed rate of the source material \((V_{IM} = 0.08 \text{ m/s})\) has the form:
  \[
  E_{12} = 87.6584 - 0.0688n_{RN} - 3017.98S_N + 0.066n_{RN}S_N + 0.000017n_{RN}^2 + \\
  + 134336S_N^2.
  \]
  (3)

The response surface when changing the number of revolutions of the shaft and the gap between the cutting and opposing knives (at a zero level of the feed rate of the source material) is shown in figure 3.

![Figure 3](image)

**Figure 3.** Response surface of \(f(n_{RN}, S_N)\) at \(V_{IM} = 0.08 \text{ m/s}\).

The regression equation at a zero level of the gap between the cutting and the opposing knives \((S_N = 0.01 \text{ m})\) has the form:
  \[
  E_{12} = 94.0258 - 0.0687n_{RN} - 507.965V_{IM} + 0.0071n_{RN}V_{IM} + 0.000017n_{RN}^2 + \\
  + 2738.06V_{IM}^2.
  \]
  (4)
The response surface when changing the number of revolutions of the shaft and the feed rate of the starting material (at a zero level of the gap between the cutting and counter-cutting knives) is shown in figure 4.

Regression equation at zero shaft speed \((n_{RN} = 2000 \text{ min}^{-1})\) has the following form:

\[
E_{t_2} = 40,342 - 2922.98S_N - 498.39V_{IM} + 462.58S_NV_{IM} + 13433.6S_N^2 + 2738.06V_{IM}^2. \tag{5}
\]

The response surface when changing the clearance between the shafts and the feed rate of the source material (at a zero level of the number of revolutions of the cutting knives) is presented in figure 5.

Based on the results of a multifactor experiment, we can conclude that the minimum value of the optimization criterion is 3.17 kWh/t, for which the energy consumption of grinding is taken, is ensured for the following values of the main factors: frequency of revolutions of the cutting knives \(n_{RN} = 1974 \text{ min}^{-1}\), the gap between the cutting and the contradictory knives \(S_N = 0.011 \text{ m}\) and feed rate \(V_{IM} = 0.09 \text{ m/s}\).

![Figure 4. Response surface of \(f(n_{RN}, V_{IM})\) at \(S_N = 0.01 \text{ m}\).](image)

![Figure 5. Response surface of \(f(S_N, V_{IM})\) at \(n_{RN} = 2000 \text{ min}^{-1}\).](image)
3. Conclusion

As a result of experimental studies, it was found that the proposed design of the feed conveyor provides the required uniformity of the flow of the crushed material to the working bodies of the grinder in the range of rotation frequencies of 80 ... 90 min⁻¹.

The maximum grinder productivity of 0.7 ... 0.9 t/h is achieved at a revolution frequency of the working body of 2000 min⁻¹.

It has been established that the greatest influence on the energy consumption of grinding coarse fodder is exerted by the rotational speed of the cutting knives, the gap between the cutting and the counter knives, and the feed rate of the starting material.

The optimal values of the parameters of the grinder of roughage, at which the cutting length meets the zootechnical requirements: the frequency of rotation of the cutting knives 1974 min⁻¹, the gap between the cutting and the opposing knives 0.011 m, the feed rate of the source material of 0.09 m/s. With these values, the minimum energy consumption of grinding coarse feed is ensured (3.17 kW·h/t).

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