Development of a root crop grinder

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Abstract. The article presents design of the developed root crop grinder, and also compares theoretical and laboratory studies of the root crop grinding process. The article describes a number of dependences: the power spent on root crop grinding, idling and cutting on the rotational speed of the chopper drum, throughput capacity on rotational speed of the chopping drum and grinding specific energy consumption on the cutting speed. The research results can be used in design development of root crop grinders for livestock enterprises.

1. Introduction

Food security of the state is impossible without animal breeding development. An increase of livestock production is possible only with joint development with crop production, since feed grains, annual and perennial grasses and feed vegetables are the basis of the diet of cattle, pigs, chickens and other farm animals.

An important reserve for productivity increase of cows in agricultural dairy enterprises is application of succulent feed in their ration, primarily root crops, the share of which can reach 10 ... 15% of the daily diet, especially in winter period. The share of root crops can reach 35% in pig rations. In addition, the cost of a feed unit of root crops is much lower than that of cereals, oilseeds and their processing products [1].

To improve the digestibility, eatability, and consequently, productivity of animals, root crops must be prepared for feeding. One of the energy-consuming technological processes in preparation of root crops for feeding is their grinding.

For root crop grinding, factories and companies in different countries produce a large number of different grinders, which are based on different principles of feed crushing. Except energy costs for feed grinding, an important parameter of grinders is the compliance of the grinded product with the requirements for ready-made feed, namely: fractional composition and intensity of juice separation.

Root grinding machines most often operate on the chopping principle, which significantly increases energy costs. However, academician V.P. Goryachkin determined that the sliding (lateral) movement of the knife is of decisive importance in the process of cutting with a blade, since it lowers the normal pressure limit on the material, which is necessary to initiate the cutting process and provides a better cut. Sliding cut is the least energy intensive but it is difficult to implement due to large values of root crop angle of friction on the edge of the metal wedge. Therefore, sloping cutting is used most often in root crop grinders, which provides lower energy consumption and good grinding quality [2].

Among the choppers produced by our industry, the most common are machines that function on the cutting principle, since this principle is less energy-intensive than other types of feed destruction, such
as impact or crushing. In addition, when destructive elements strike root crops, cell fluid is released, which contradicts zootechnical requirements [3].

However, presently, the problem of reducing energy consumption of root crop grinding, while maintaining the quality of the chopped product that meets zootechnical requirements, has not been fully solved.

2. Materials and methods
As a result of the analysis of the well-known root crop grinders at the Department of Service and Mechanics of Ulyanovsk State Agrarian University, a root crop grinder was developed (figure 1).

Figure 1 shows a laboratory unit consisting of a root crop grinder 1, a feed conveyor 2, a current rectifier 3, a voltage regulator 4, a packet switch 5, two electric engines 6 and 7, a worm gear 8, a set of measuring instruments 9, an interface converter 10 and a computer 11.

![Figure 1. Laboratory unit for studying the process of root crop grinding (symbols are in the text).](image)

The root crop grinder (figure 2) contains a hopper 2 located on the frame 1, in the form of a truncated cone tapering downward with a closed bottom base. There is an adjustable anti-cut on the inner side surface of the hopper. There is a discharge window 3 in the lower part of the hopper. Inside the hopper, there is a shaft 4, where the chopping drum cover 5, the chopping drum 6, the discharge blades 7 and the pulley 8 are attached. The chopping drum 6 is in the form of a hollow cylinder with an open bottom base. Windows 9 are cut on the cylindrical surface of the chopping drum 6, they are located at an inclination of 35 ° to the vertical line, knives 10 are fixed over the windows 9. Rotation of the chopping drum 6 is carried out with an electric motor 13 and a V-belt transmission.

The principle of grinder operation. Root crops enter the hopper 2, then they are jammed between the anti-cut and the chopping drum 6 and are chopped with knives 10. The chopped feed falls into the chopping drum 6 through the windows 9. Due to rotation of the shaft 4, on which the chopping drum 6 and the discharge blades 7 are fixed, the chopped feed is thrown out with the blades 7 through the discharge window 3, made in the lower part of the hopper.

3. Results
Energy efficiency of grinders is assessed by specific energy consumption for root crop grinding [4].

\[ q = \frac{N_{gr}}{W} \]  

(1)

Where \( N_{gr} \) is the power consumed by the grinder, kW; 
\( W \) is throughput capacity of the grinder, t / h.
Figure 2. Root grinder: 1 - a frame; 2 - a hopper; 3 - a discharge window; 4 - a shaft; 5 - a chopping drum cover; 6 - a chopping drum; 7 - discharge blades; 8 – a pulley; 9 - windows; 10 - a knife; 11 - holes for adjusting the angle of the anti-cut; 12 – a tightening roller; 13 - an electric motor.

The throughput capacity of the root grinder can be determined using the expression:

$$W = q \cdot n \cdot z,$$

(2)

Where $q$ is the supply of root crops for one cut of a knife, kg; $n$ is the rotational speed of the chopping drum, $s^{-1}$; $z$ is the number of knives on the chopping drum.

The amount of root crop supply per a knife cut:

$$q = (R - r_d) l_{kn} \cdot l_{cos} \cdot \rho_b \cdot K_{kn.us.} \cdot \sin \alpha,$$

(3)

Where $R$ is the radius made by the knife blades, m; $r_d$ is the radius of the chopping drum, m; $l_{cos}$ is the length of cossettes, m; $l_{kn}$ is knife length, m; $\rho_b$ is bulk density of root crops, kg / m$^3$; $l_c$ is length of the cutting part of the knife, m. $K_{kn.us.} = l_c / l_{kn}$ is knife utilization factor (for comb knives it is 0.5 ... 0.6, for tooth knives - 0.9); $\alpha$ is inclination angle of knives on the surface of the chopping drum in relation to its axis, degr.

The amount of supply per one cut depends on design parameters of the grinder and on physical and mechanical properties of root crops. The design parameters of the grinder include the length of the knife $l_{kn}$, the length of the cutting part of the knife $l_c$, the inclination angle of the knife blade of the chopping drum $\alpha$, the distance between the edge of the knife blade and the surface of the chopping drum $(R - r_d)$. The parameters $l_{kn}$ and $l_c$ can be changed within wide limits, but the angle $\alpha$ is limited by the design features of the grinder, and the parameter $(R - r_d)$ is taken considering the required cutting thickness for a particular type of animal.

The expression for determining the capacity of the grinder has the following form:

$$W = (R - r_d) l_{kn} \cdot l_{cos} \cdot \rho_b \cdot K_{kn.us.} \cdot n \cdot z \cdot \sin \alpha,$$

(4)

The power consumed by the grinder is spent on root crop cutting $N_{cut}$, transporting the grinded feed $N_{transp}$, idling $N_{idl}$, and to overcome the frictional force of the grinded product on the working bodies of the grinder $N_{frict\_force}$:

$$N = N_{cut} + N_{transp} + N_{idl} + N_{frict\_force},$$

(5)

The power spent on cutting is determined by the formula [5]:

...


\[ N_{\text{cut}} = P \cdot S_c \cdot z \cdot n, \]  

(6) Where \( P \) is specific resistance to cutting, \( N / m \); \( S_c = l_c \cdot \cos \alpha \cdot (R - r_d) \) is surface area of one cut, \( m^2 \). Then:

\[ N_{\text{cut}} = P \cdot z \cdot n \cdot l_c \cdot \sin \alpha \cdot (R - r_d) \]  

(7) Power spent on transportation of the grinded product:

\[ N_{\text{transp}} = m \cdot g \cdot v_d \cdot K_r, \]  

(8) Where \( v_d \) is rotational speed of the chopping drum, \( m / s \); \( m \) is the mass of the transported grinded product, kg; \( K_r \) is the coefficient of resistance to movement, taking into account the friction of the grinded product on the inner surface of the hopper, including jamming of the product between the discharge blade and the surface of the hopper.

The idle power [6-7]:

\[ N_{\text{idle}} = N_{\text{ac}} + N_a, \]  

(9) Where \( N_{\text{ac}} \) is the power spent on acceleration of the chopping drum, kW; \( N_a \) is the power spent on overcoming the force of air resistance to the movement of the discharge blades, kW.

The determine the power:

\[ N_{\text{ac}} = J_z \cdot \omega^2 \cdot 2 \cdot t_{ac}, \]  

(10) Where \( J_z \) is inertia moment of the grinder working body, \( kg \cdot m^2 \); \( t_{ac} \) is acceleration time of the chopping drum, s; \( \omega \) is angular speed of the chopping drum, \( s^{-1} \).

Air resistance force:

\[ F_a = 0.5 \cdot C_d \cdot \rho_a \cdot v_d^2 \cdot S_b, \]  

(11) Where \( C_d \) is the drag coefficient, determined experimentally; \( \rho_a \) is air density, \( kg / m^3 \); \( S_b = 2 \cdot l_{db} \cdot b_{db} \) is cross-section of discharge blades, \( m^2 \); \( l_{db} \) is length of the discharge blade, m; \( b_{db} \) is width of the discharge blade, m.

Power spent on air resistance:

\[ N_a = F_a \cdot v_d = 0.5 \cdot C_d \cdot \rho_a \cdot v_d^2 \cdot S_b \]  

(12) The power spent on overcoming the friction forces of the chopped product on the grinder working bodies [8-9]:

\[ N_{\text{frict. force}} = N_{fkn} + N_{fbl}, \]  

(13) Where \( N_{fkn} \) is the power spent on overcoming the friction of the product on the knives of the chopping drum, kW; \( N_{fbl} \) is the power spent on overcoming the friction of the product against the body during transportation of the grinded product with a blower, kW:

\[ N_{fkn} = 30 \cdot f_i \cdot m \cdot \omega^3 \cdot r_m^2 \cdot \cos^2(90 - \alpha_0) / \pi = 9.55 \cdot f_i \cdot m \cdot \omega^3 \cdot r_m^2 \cdot \cos^2(90 - \alpha_0), \]  

(14) Where \( r_m \) is the rotation radius of the center of mass of the product portion, m; \( \alpha_0 \) is angle of knife installation to the surface of the chopping drum, degr.; \( f_i \) is friction coefficient of the root crop on the surface of the chopping drum;
N_{f_{HL}} = 9,55 f_2 \cdot m \cdot \omega^3 \cdot r_m^2, \quad (15)

Where \( f_2 \) is friction coefficient of the root crop on the hopper wall.

Considering all the substitutions and transformations, the power consumed by the grinder during cutting can be found by the formula:

\[ N = P \cdot z \cdot n \cdot l_{c} \cdot \sin \alpha \cdot (R-r_d) + m \cdot g \cdot v_d + J \cdot \omega^2 \cdot t_c + 9,55 m \cdot \omega^3 \cdot r_m^2 (f_1 \cdot \cos^2 (90-\alpha_0) + f_2) \quad (16) \]

Thus, the power required for root crop grinding depends on design parameters and operating modes of the grinder, as well as on the properties of the material being ground.

After processing the experiment results of root crop grinding, the following regression equation was obtained:

\[ q = 1,4816 - 0,0531 v_c - 0,0426 \chi + 0,0036 v_c^2 - 0,000097179 v_c \chi + 0,0006 \chi^2, \quad (17) \]

Where \( v_c \) is cutting speed, m / s;
\( \chi \) is jamming angle, degr.

Comparison of theoretical and laboratory studies of the process of root crop grinding is shown in figure 3.

![Figure 3](image-url)

**Figure 3.** Results of theoretical and laboratory studies of the developed root crop grinder: 1 - calculated value of specific energy consumption of root crop grinding by the grinder; 2 - results of laboratory studies to determine specific energy consumption of root crop grinding by the experimental grinder.

**Table 1.** Parameter values for calculating theoretical specific energy consumption of grinding of the experimental root crop grinder.

| P, N/m | l_c, m | R, m | R_{db}, m | Z, pieces. | n, c^{-1} | m, kg | v_d, m/s |
|-------|--------|------|-----------|------------|----------|-------|----------|
| 3500  | 0.48   | 0.175| 0.16      | 4          | f(v_d)   | f(n)  | 1...18   |
| K_r   | J, kg·m² | t_c, s | C_d | B_{db}, m | \chi, degr. | l_{db}, m | \rho_v, kg/m³ | f_l |
| 3.7   | 0.5114 | 5    | 1.28     | 35         | 0.17     | 1.225 | 0.68     |
| f_2   | r_m, m | \alpha_0, degr. | l_{kn}, m | \cos, m | \rho_v, kg/m³ | K_{kn,us} | \alpha, degr |
| 0.68  | 0.17   | 30   | 0.485    | -6\cdot10^{-5} n^2 + 1.1\cdot10^{-3} n + 4.7\cdot10^{-3} | 650      | 0.5   | 60       |
4. Discussion
The given theoretical dependences make it possible to determine the main parameters of drum-type root crop grinders, such as: specific energy consumption of grinding, power consumed by the grinder, and its throughput capacity.

Comparison of the results of laboratory and theoretical studies showed that the result difference does not exceed 8% and is explained by errors in measurements and calculations, as well as heterogeneity of properties of the chopped material, which is also confirmed by studies [10].

Slight discrepancies between laboratory and theoretical results indicate the possibility of using these results of theoretical studies when calculating parameters of drum-type root crop grinders.

5. Conclusion
The regression equation obtained after the tests made it possible to reveal that the most suitable parameters of the root crop grinder, at which the minimum energy consumption of grinding is achieved, equal to 0.5 kW h / t, with a cutting speed of 7.87 m / s and a jamming angle of 34˚ 76 ’.

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