SUBSTANTIATION OF THE CONSTRUCTIVE AND MODE PARAMETERS OF VIBRATORY DISC CRUSHER FOR THE FARM ANIMALS COMPOUND FEEDS PRODUCTION

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Abstract. The research is based on the tasks of applied research on the topic: «Development of a complex of energy-efficient and resource-saving equipment and promising technologies for feeding farm animals of the AIC of Ukraine», state registration number 0121U108589. The authors' research is aimed at solving current problems of technological renewal and development of the agro-industrial complex of Ukraine. In the laboratory of the theory of mechanisms and machines of the department of general technical disciplines and labor protection of Vinnitsa National Agrarian University, a vibratory disk crusher was designed to increase the level of technical support for the livestock industry. The crusher uses a more efficient method of grinding feed grain – a combination of impact and cutting, in contrast to a hammer mill that grinds with a free impact of hammers. The research results of grinding soybeans grain into feed by a vibratory disk crusher are presented in the article. An experimental prototype of the developed machine was used as an object of research. To register the input and output parameters of grinding, we used the material and technical base of the department of technological processes and equipment of processing and food industries.

1. Introduction

Taking into consideration current realities and various factors, which create difficulties for the effective functioning of Ukraine's national economic system, the Agro-Industrial Complex of Ukraine acts as the most stable part of

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it, that is characterized by conservatism and is one of the main and stable cross-sectoral formations due to revenues. However, despite the strategic priority of the AIC, the high level of energy consumption by domestic producers does not enable providing an appropriate level of competitiveness of Ukraine's AIC in domestic and foreign markets, at the same time the rationalisation of energy use necessitates the substantiation of the energy-saving variant of its development by implementing energy-efficient machines and technologies in the system of feed preparation and feeding animals.

Full-fledged animal feeding is the basis for the successful functioning and effective development of the livestock production industry and can be ensured only if a sufficient amount of feed is produced, the loss of their nutritional value during their harvesting, storage, and also the correct preparation of feed for feeding is reduced. Grain feeds used at concentrated feed. They contain a large amount of nutrients that are easily absorbed. Their use in the feeding system allows you to balance the rations of animals in terms of energy, protein, amino acids.

The compilation and selection of components of feed rations is carried out by technologists depending on the species, age group, morphological and biological indicators of animals and many other factors. At the same time, regardless of the technology and feeding scheme chosen by the specialist, concentrated feed based on wheat, barley, peas, corn, soybeans and other agricultural crops that have undergone preliminary technological processing remains an indispensable source of nutrients for animals. Moreover, a particularly important indicator that affects the productivity of animals is the quality of grinding concentrated feed. As a result of grinding feed, a significant number of parts are created from a larger surface area, which helps to speed up digestion and increase the absorption of nutrients.

The need for grinding grain feed is conditioned by the physiological characteristics of animals, as the rate of processing feed with gastric juice is directly proportional to its surface area [1]. At the same time, in the technological process of feed preparation, the share of energy consumption for grinding can reach 65% [2]. Therefore, the effective functioning of farms in modern conditions requires development and implementation of technologies that meet international standards and reduce excessive energy losses [3; 4]. Thus, profitability and competitiveness of the livestock industry largely depends on the energy efficiency of this technological operation, and reducing energy intensity of the process is an urgent task.

2. Analysis of recent research and publications

Nowadays, hammer crushers have become widely used on livestock farms and feed mills [5; 6]. In these technological machines, the destruction of the material occurs in the course of the successive stages: application of a distributed load on the flat face of the articulated-suspended hammer, emergence of various deformations and stresses in the body, reaching the limits of stresses and strains, breaking the bonds of atoms and molecules [5].

In the process of crushing mainly brittle and plastic destruction takes place. Brittle destruction is characterized by a slight deformation of the material, and after the fracture there observed no residual deformations. The applied energy is spent on overcoming the forces of mutual adhesion of the body particles, i.e. on formation of a new surface. During the destruction of plastic materials, energy is expended both on the breaking structural ties and on significant plastic deformations. Moreover, the energy expended on deformation is converted into heat.

The tensile strength of the material and its ultimate deformation is determined by the structural and mechanical characteristics of the grain and depends on the variety, size, density, moisture content, temperature, etc. Thus, with moisture content increase there is a decrease in brittleness and tensile strength with a simultaneous increase in plasticity and absolute deformation, which the grain can aquire before the destruction.

Grinding brittle materials consumes much less energy than plastic ones. As already been mentioned, the brittleness and plasticity of some materials are determined by their physical state, thus in terms of energy consumption the material should be grinded in a brittle state.

Experience shows that for the production of feed, mainly fodder grain with a moisture content exceeding the basic conditions is used. This is due to both material aspects (market price of raw grain is much lower) and production capacity of a particular enterprise.

From the point of cost reduction, introduction of machines for grinding grain, proposed by Sergeev N.S. [7], Abramov A.A. [8], Nanka O.V. [9; 10], the principle of which is based on a combination of cutting and spalling methods, is quite promising. The advantage of such a combination is the local overvoltage of surface microvolumes in places of load application. In the process of cutting the knife blade is wedged into the product and near the contact surface a specific pressure sufficient to destroy the body is created.

On the basis of the Department of Technological Processes and Equipment for Food and Processing Industries of Vinnytsia National Agrarian University laboratory a vibratory disk crusher has been developed (Figure 1), in which, when the electric motor 5 is turned on, the torque through the clutch 6 is transmitted to the kinematic shaft 7 with counterweights 8, the rotation of which leads to the creation of a combined power and moment imbalance of the rotor 9, placed on it, with axes and disk-shaped beaters 10 [11].

The processed material is continuously being fed through the loading neck 2 and crushed due to the rotational and oscillating motion of the disc beaters 10. With particle size reduction, the crushed material under the influence of centrifugal forces and alternating loads, through the sieve surface, undergoes intensive classification: particles equal to or smaller than the diameter of the sieve 4 holes are unloaded through the neck 3, the rest goes for re-grinding [12].

This combination of grinding methods (impact and cutting) makes it possible to process substandard raw materials with a high moisture content while reducing energy consumption for this technological operation, which was confirmed by the results of the experimental research.

However, in order to achieve high energy efficiency, it is necessary to substantiate the rational modes of operation for the suggested equipment.

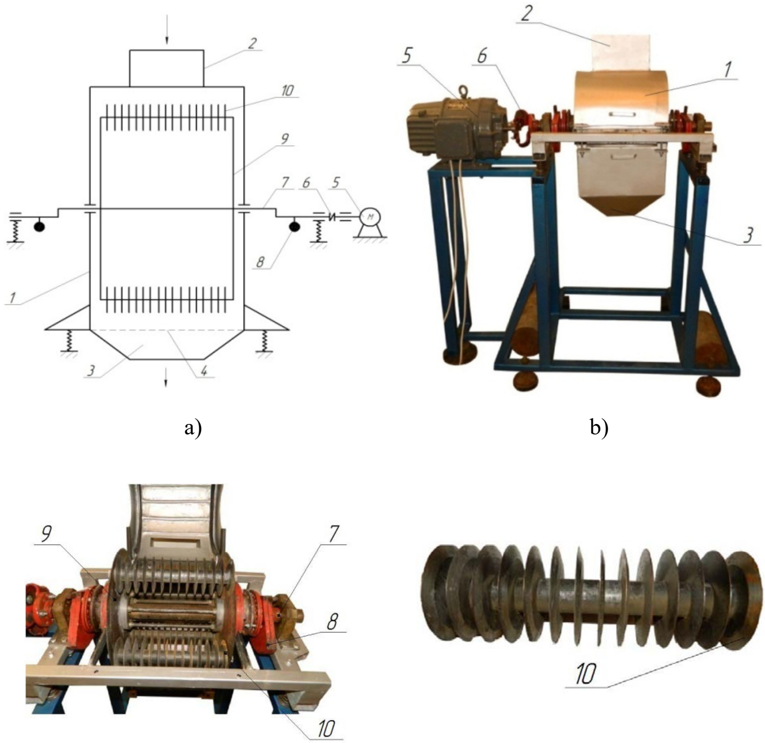
3. Purpose and objectives

The purpose of the researhes is to substantiate energy-efficient and resource-saving modes of operation of the vibratory disk crusher based on the analysis of quality and energy performance of the process of grinding feed grain.

To achieve this goal it is necessary to perform the following tasks:

– to study the amplitude-frequency characteristics of the developed machine depending on the angular velocity of the drive shaft and with different mode of feeding the material into the working chamber;

– to determine power consumption of the electric motor of the machine depending on the angular velocity of the rotor, the mode of the material in-feed, the diameter of the separation surface perforation;



a) b)

c) d)

Figure 1. Vibratory disc crusher: a) schematic diagram; b) general view; c) actuator; d) disk beaters; 1 – housing; 2, 3 – loading and unloading neck; 4 – sieve; 5 – electric motor; 6 – elastic clutch; 7 – kinematic shaft; 8 – counterweights; 9 – rotor; 10 – disk-type beaters

– to establish the dependence of the productivity of the developed machine on the angular velocity of the drive shaft, the diameter of separation surface perforation and moisture content of the processed material;

– to evaluate the dispersion of the out-put material by specific passage through the control sieve depending on the angular velocity of the drive shaft and the diameter of the separation surface perforation;

– to establish rational parameters of the grinding process in the vibration field on the basis of regression analysis of the obtained experimental data.

4. Equipment and methods

Experimental part of the work was performed on the base of the Department of Technological Processes and Equipment for Food and Processing Industries of Vinnytsia National Agrarian University laboratories on the stand (Figure 2) and experimental sample of the vibratory disk crusher [11] (Figure 1).

To record the amplitude-frequency characteristics of the vibratory disk crusher, a sensor based on the ST Microelectronics LIS3DH accelerometer was developed (Figure 3), which has the following characteristics: ultra-low power consumption – 2 μA; voltage consumption 1.71-3.6 V; adjustable acceleration measurement range: ±4g; ±8g; ±16g; SPI/I2C interface for reading data; built-in self-testing module [13; 14].

The principle of operation of the developed sensor is as follows: after connecting sensor 7 to the surface of the container (Figure 2), the drive mechanism is to be turned on, creating alternating oscillations of the vibratory disk crusher activator, which initiates the built-in accelerometer, which starts the registration of the amplitude-frequency characteristics and through the connected adaptive cord read the amplitude frequency response, which is interpreted as graphical dependencies and data digital matrix on a personal computer 2. The developed software allows to analyze vibration acceleration, vibration velocity, vibration displacement and frequency of oscilations.

In order to register the speed of the drive shaft a wireless tachometer UNI-T UT372 (Figure 4) was used, the principles and procedures of operation of which are described in the technological documents.

To control and change the rotation speed of the electric motor shaft autotransformer AOCH-20-220-75 (Figure 5) was used designed to work with alternating current.

To determine power characteristics of the studied machine the EMF-1 electronic wattmeter was used (Figure 6), intended to measure power consumption in the 220 V network, 16A (maximum), connected through a household outlet [13]. The device measured the following parameters: utility supply voltage, frequency and power of alternating

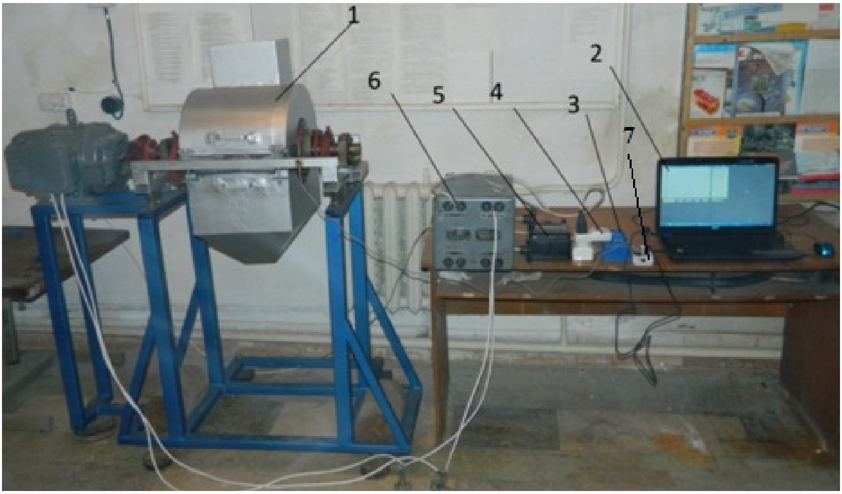


Figure 2. Experimental stand: 1 – experimental sample of the vibratory disk crusher; 2 – personal computer; 3 – switch; 4 – EMF-1 electronic wattmeter; 5 – secondary electromechanical wattmeter; 6 – AOCH-20-220-75 laboratory transformer; 7 – accelerometer

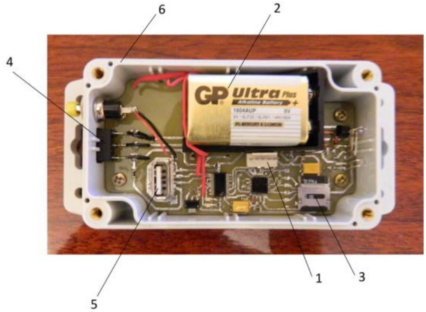


Figure 3. Accelerometer: 1 – microport for the accelerometer sensor connection; 2 – power supply battery; 3 – memory card; 4 – power button; 5 – adaptive microport for data reading; 6 – accelerometer housing

Figure 4. UNI-T UT372 frequency meter: 1 – laser reader; 2 – digital indicator; 3 – control panel

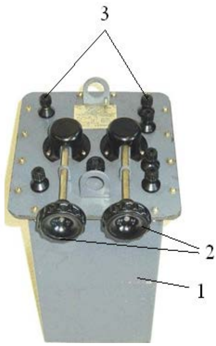


Figure 5. AOCH-20-220-75 laboratory autotransformer: 1 – outer casing; 2 – voltage regulators; 3 – input and output terminals

Figure 6. EMF-1 electronic wattmeter: 1 – wattmeter housing; 2 – control panel; 3 – indicator display

current, the consumed power, coefficient of performance (100% for active load), equipment operating time and total power consumption for the whole period of the machine operation (kW/h).

The crusher separation surface perforation diameter was changed by installing appropriate sieves with round holes of the following sizes: d=1 mm; 1.25 mm; 1.4 mm; 1.6 mm; 1.8 mm; 2 mm [14].

To change the mode of the feed-in of the material FV-2 mobile vibrating dispenser was used (Figure 7), in which the loaded into the hopper 1 material through the unloading hole, partially closed by the sliding shutter 2, falls on the tray 4 and under the forced oscillation action of the latter, caused by electromagnetic vibrator 3, moves along it and is unloaded through the neck 6.

To determine the moisture content of the material a Wile 55 moisture meter (Figure 8) was used, intended to measure the relative humidity of various types of grains and seeds, characteristics of which are stored in the device memory.

Productivity evaluation was done by weighing the crushed material that passed through the crusher over a time interval [14]. The BTA-60/30-5-T electronic laboratory technical scales were used to determine the mass (Figure 9).

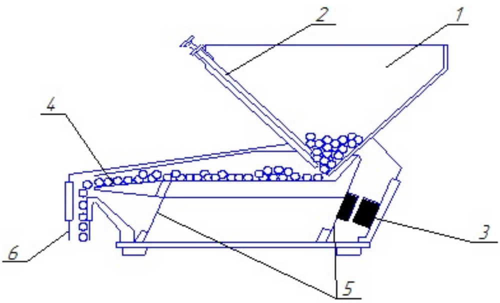


Figure 7. Model of the ПГ-2 vibrating feeder: 1 – loading hopper; 2 – sliding shutter; 3 – electromagnetic vibration excitor; 4 – conveying tray; 5 – springs; 6 – unloading neck

Figure 8. Wile-55 moisture meter: 1 – case cover; 2 – digital indicator; 3 – control panel; 4 – test sample container

Dispersivity of the material was determined by the method of mechanical separation of particles – sieve analysis. The material was loaded on a sieve with holes of certain size and by oscillating motion was separated into two parts: the separated material and the remaining residue. Sieves with a hole size of 1; 0.8; 0.6; 0.4; 0.2 mm were used. The experimental material was passed through the A-20 laboratory sieve analyzer (Figure 10) [15].

During sample aquisition by the spot sampling method, a laboratory sampler was used to analyze the quality of grinding (Figure 11).

For the quality assessment of the crushed material, the rate of extraction or the proportion of its passage through the control sieve was assumed. By extraction we mean the number of particles in the product after grinding, expressed as a percentage over weight of the sample taken for the analysis. The technology of feeding farm animals supposes the dispersion of the compound feed particles in the range of 0.5-3.5 mm, depending on the animal kind, age and method of keeping [12; 13]. Given the ability of a vibratory disc crusher to obtain particles of different sizes, as a control indicator of the quality of grinding we took the following conditions: the finished product particle size should not exceed 1 mm; the proportion of the

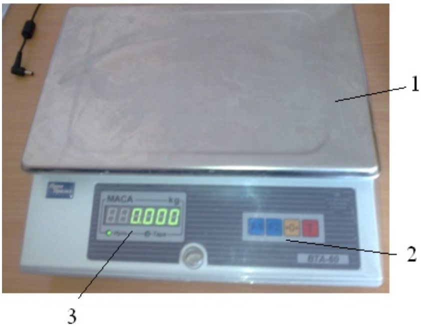


Figure 9. The BTA-60/30-5-T electronic laboratory technical scales: 1 – weighing pan; 2 – calibration panel; 3 – indicator display

Figure 10. A-20 sieve analyzer: 1 – vibrating platform; 2 – sieve block; 3 – fixing screws; 4 – dustproof surface; 5 – control panel

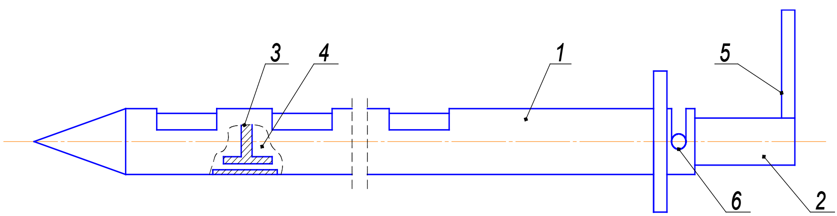


Figure 11. Model of a tubular sampler: 1 – external branch pipe; 2 – internal branch pipe; 3 – valve; 4 – camera; 5 – the lever; 6 – locking valve

material with particle size not more than 1 mm should be not less than 85% of the total weight of the crushed product [16].

Statistical analysis of the experimental data array, aimed at receiving functional dependence in the form of multiple regression of the second order was obtained using rotatable central-compositional planning (RCCP) of a multifactorial experiment [17].

The RCCP method makes it possible to obtain a more accurate mathematical description of the data distribution by increasing the number of experiments at the central points of the plan matrix and a special choice of the "star value". Processing of the experimental data was carried out in the statistical environment STATISTICA 10.0. and Mathcad 15.

5. Results of the research

In the study of the developed equipment grinding process technological characteristics, a number of experiments were performed to change the dispersed properties of the processed material (soybeans) under the action of impact-cutting action of the working bodies in the "vibratory field".

The first part of the experimental research was based on the analysis of the amplitude-frequency characteristics of the actuator and the consumed energy for driving the machine. The second part was devoted to the determining the technological parameters of the studied process, in particular the assessment of the equipment performance and dispersion of the obtained material. Comprehensive statistical analysis of those parameters allows finding rational modes of the machine operation, which provide maximum efficiency of the process of grinding grain while ensuring the desired dispersion of the finished product.

5.1. Estimation of the amplitude-frequency and energy parameters

Figure 12a demonstrates experimental dependences of the amplitude of oscillations on the angular velocity of the rotor and the volume of the material feed-in, which shows that at idling (without material feed), together with angular velocity ω increase, graphical curves of the amplitude of oscillations of the container A become divided into three zones: subresonance, in which the amplitude A=4 mm gradually increases in the range of values of the angular velocity ω=0… 45 rad/s; resonance, where the maximum value of the amplitude A=4.6 mm at ω 45… 100 rad/s is observed; super-resonance, where stabilization of the amplitude of oscillations in the range of A=3.35… 3.4 mm occurs [11].

With the entry of the material into the working chamber of the crusher (at ω=100 rad/s) due to the increase of oscillating masses, there is an increase in the amplitude of oscillations in the range of 3.2… 3.5 mm (inversely proportional to the loaded mass), and the super-resonance zone shifts to the right on the abscissa axis and occurs at the ω=120… 125 rad/s angular velocity. With the the increase of the material feed-in, the values of the amplitude of oscillations in the super-resonance period decrease due to the growth of the dissipative forces of the technological environment and is A=2.8… 3.3 mm.

Analysis of the experimental dependence of the vibration velocity v of the crusher actuator on the angular speed of the rotor (Figure 12b) and the volume of the material detected 270 mm/s in the resonance zone at 65 rad/s, after which the dependence becomes linear with 340… 360 mm/s at the operating mode.

The experimental dependence of vibration acceleration a and vibration intensity I of the crusher actuator (Figure 13a; 13b) was also determined, which clearly shows that after passing the resonance zone (at ω=45… 100 rad/s) the dependences acquire linear character of growth, and their value at the operating mode of 120..125 rad/s are a=40-46 m/s^2 and I = 18-21 m^2/s^3 respectively.

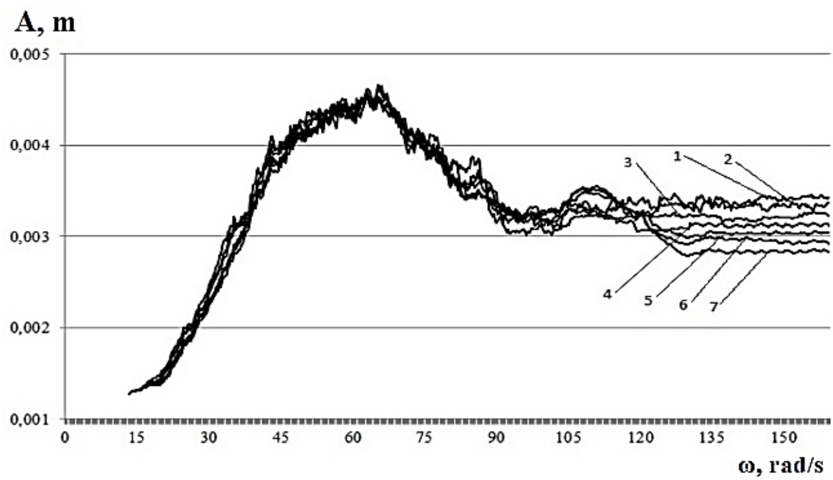
In the general case, the main energy parameters of vibration include the work of urging forces or moments and internal resistance forces of the oscillating system [17].

The work of external forces is created by unbalanced masses and is spent on overcoming the forces of resistance of the system and ensuring the oscillating motion of the working bodies of the vibratory technological machine with the specified parameters. The internal resistance forces of the oscillating system are the forces of reactive and dissipative resistance [18].

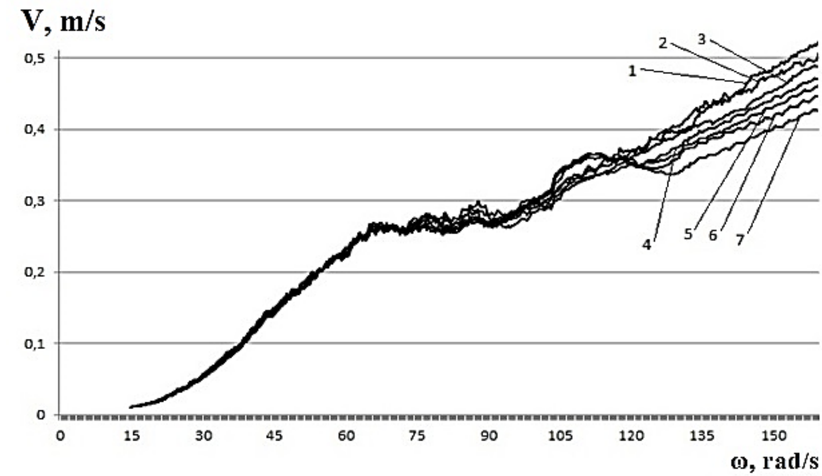
Figure 14 demonstrates the experimental dependence of the crusher drive consumed energy on the angular velocity of the drive shaft and the material feed-in at the separating surface holes diameter d=2 mm.

From the given dependence it is seen that when the machine is operated without material feed-in with the frequency ω growth, the consumed power N increases almost proportionally. When there is an increase in the degree of loading of the working chamber (material feed-in rises), the amplitude of oscillations of the container decreases, and power consumption increases.

However, when the frequency exceeds ω=128…130 rad/s, almost quadratic increase in N is observed, indicating growth of reactive and dissipative resistance of the material due to its recirculation and untimely removal from the working area. At the operating frequency of the machine ω=120-125 rad/s the consumed power of the electric motor, at material feed-in Q = 100…600 kg/h, makes: N = 740… 1160 W.

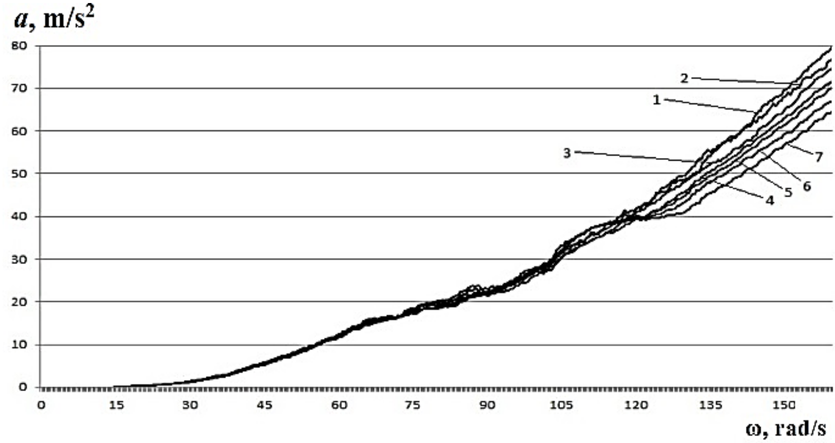


a

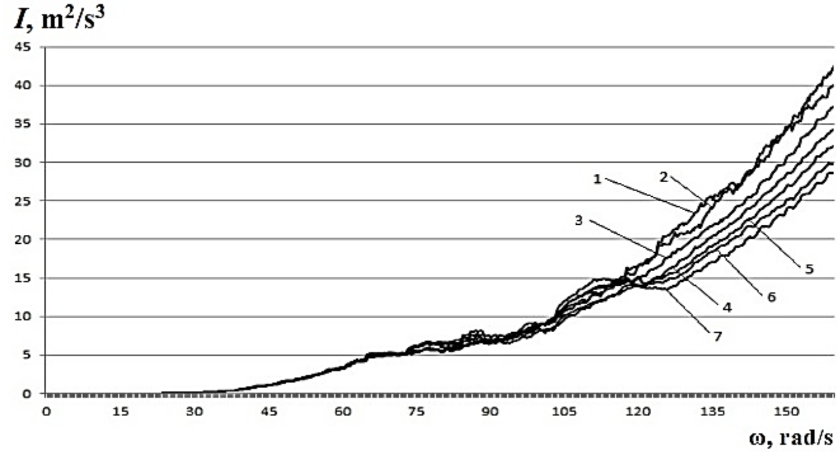


b

Figure 12. Dependence of the amplitude (a) and vibration velocity (b) on the angular velocity of the drive shaft: 1 – without material feed-in; 2 – at 100 kg/h feed-in; 3 – at 200 kg/h feed-in; 4 – at 300 kg/h feed-in; 5 – at 400 kg/h feed-in; 6 – at 500 kg/h feed-in; 7 – at 600 kg/h feed-in



a



b

Figure 13. Dependence of the vibration acceleration (a) and intensity of oscillations (b) on the angular velocity of the drive shaft: 1 – without material feed-in; 2 – at 100 kg/h feed-in; 3 – at 200 kg/h feed-in; 4 – at 300 kg/h feed-in; 5 – at 400 kg/h feed-in; 6 – at 500 kg/h feed-in; 7 – at 600 kg/h feed-in

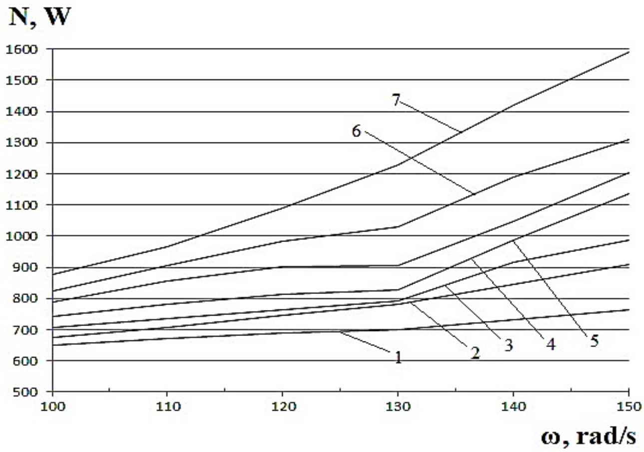


Figure 14. Dependence of the consumed power of the electric motor on the angular velocity of the drive shaft: 1 – in the absence of the material feed-in; 2 – at 100 kg/h; 3 – at 200 kg/h; 4 – at 300 kg/h; 5 – at 400 kg/h; 6 – at 500 kg/h; 7 – at 600 kg/h

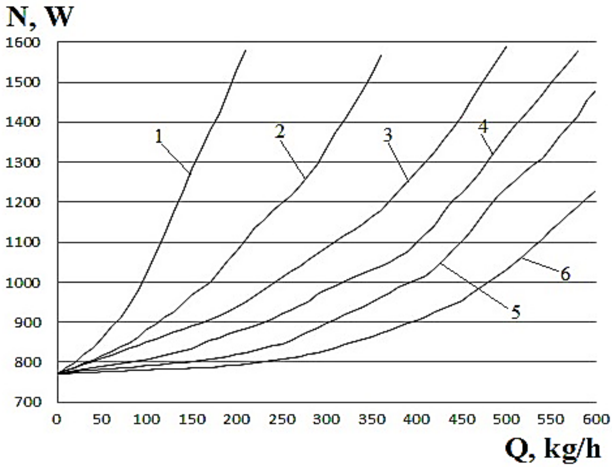


Figure 15. Dependence of the consumed power of the electric motor on the material feed-in: 1 – at d=1 mm; 2 – at d=1.25 mm; 3 – at d=1.4 mm; 4 – at d= 1.6 mm; 5 – at d=1.8 mm; 6 – at d=2 mm

Herewith, as can be seen from Figure 15, the increase in the feed-in of the material at a constant angular frequency ω=130 rad/s is accompanied by the almost quadratic increase in the power N consumed by the electric drive from the power network, which is caused by energy dissipation in the treated medium. However, there is a direct relationship between the separation surface holes diameter increase and the radius of curvature of the section of the parabola N (Q), which indicates the increase in energy intensity intended to overcome the resistance of the material retained in the crushing chamber due to the decrease of the throughput capacity of the sieve at its holes diameter reduction.

5.2. Characterization of the studied process technological parameters

Figure 16 displays the change in productivity of the machine depending on the angular velocity of the drive shaft and the diameter of the holes of the separation surface.

Having analyzed the obtained dependence, we can conclude that productivity *P* grows with the the rotor angular velocity ω increase, however, when the angular velocity ω=125-135 rad/s and more, there is a decrease in productivity, which indicates excessive recycling of the already crushed material.

The results of the experimental studies of the equipment *P* productivity on the angular velocity of the drive shaft ω and moisture content *W*, are shown on Figure 17, wherefrom it can be concluded that the productivity is significantly affected by the moisture content of the material, in particular at equal angular velocity of the rotor (ω=130 rad/s) productivity decreased by more than 25%, namely from 450 kg/h to 325 kg/h at grinding material with moisture content of 13-14% and 25-26%, respectively.

To determine the influence of the angular velocity of the crusher drive shaft and the separation surface holes diameter on the specific passage through the control sieve, a number of experiments were performed, on the base of which graphical dependences were (Figure 18).

From the dependences it is can be seen that the curves that characterize the specific share of the material at different holes diameters of the installed sieves, change in two phases, depending on the angular velocity of the rotor. In the first phase, there is an increase in the “passage” through the control

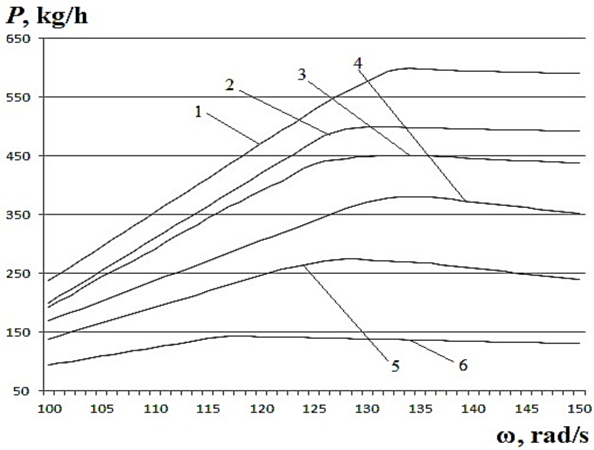


Figure 16. Dependence of the productivity on angular velocity of the drive shaft: 1 – at d=2 mm; 2 – at d=1.8 mm; 3 – at d= 1.6 mm; 4 – at d=1.4 mm; 5 – at d=1.25 mm; 6 – at d=1 mm

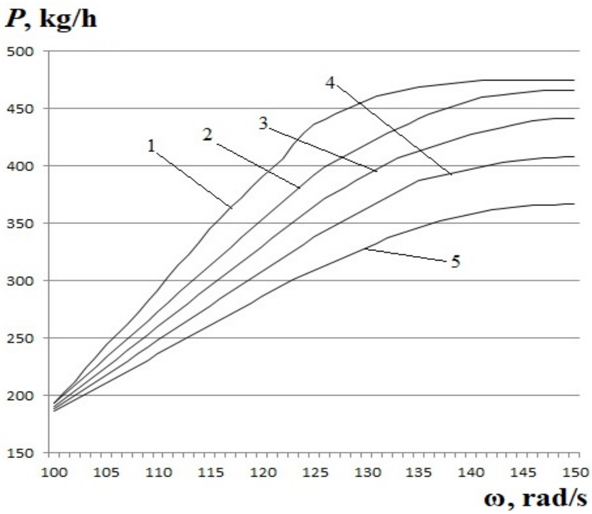


Figure 17. Dependence of the productivity on angular velocity of the drive shaft: 1 – at W= 13-14%; 2 – at W=16-17%; 3 – at W=19-20%; 4 – at W=22-23%; 5 – at W=25-26%

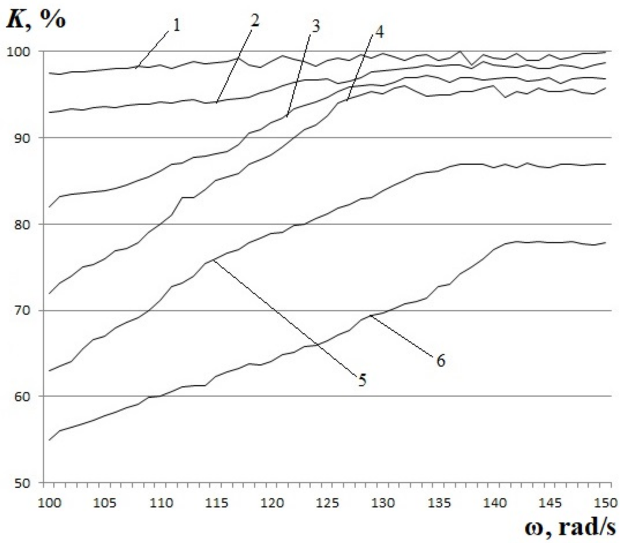


Figure 18. Specific share of the material depending on the angular velocity of the drive shaft: 1 – at d= 1 mm; 2 – at d=1.25 mm; 3 – at d=1.4 mm; 4 – at d=1.6 mm; 5 – at d=1.8 mm; 6 – at d=2 mm

sieve proportionally to the angular velocity, in the second – the curve is aquilizing, and the increase tends to zero. In addition, as can be seen from the graphs, when the diameter of the holes of the separation surface d=2 mm, specific share of the material passed through the control sieve is 78-79% at the angular velocity of the rotor from ω=140 rad/s, what does not meet conditions described above.

5.3. Regression analysis of the experimental data obtained

Qualitative and energy parameters of optimization of the studied process are determined as: productivity ***P***, kg/h; specific passage through the control sieve *K*, %; *N* – consumed energy, W. Based on our own experience and having analyzed other scientists research results [1–4; 7; 8; 16], vibration acceleration *a*, m/s^2; the separation surface holes diameter d, mm; amount of the material feed-in *Q*, kg/h; moisture content of the material *W*, % are determined as the factors that have the greatest impact on the defined optimization parameters:

$$П = f(a,Q,W,d)\,; \tag{1}$$

$$К = f(a,Q,W,d)\,; \tag{2}$$

$$N = f(a,Q,W,d)\,. \tag{3}$$

The number of factors (RCCP) is:

$$k = k_я + 2n + k_0\,, \tag{4}$$

where $k_я$ is the number of factors in the core of the plan; n – number of factors; $2n$ – the number of studies in star points; k_0 – the number of factors in the center of the plan with coordinates (0.0… 0). The rotatability of the compositional plan is acquired provided that the size of the star arm α is selected from the interval $\alpha = 2^{\frac{n}{4}}$ at $n \le 5$, i.e. for a four-factor experiment $\alpha = 2$.

Analysis of the statistical characteristics of the obtained data showed that the coefficients of their asymmetry go to zero, i.e. the distribution of experimental data is symmetric and is approximated by the normal law.

All factors included in functions (1-3) are the parameters that have different dimensions and orders. Therefore, in order to obtain the response surface of these functions, a factor coding operation was performed, which is a linear transformation of the factor space. The following values of factor levels are set in a conditional scale: minimum "–1", average "0", maximum "+1" and star values "$-\alpha$", "$+\alpha$". The true values of the factors of the RCCP matrix are established on the basis of the results of experimental studies described above and are shown in table 1.

Table 1

Levels of factors and intervals of variation

Factors	**Levels of factors**					**Interval of variation**
	- α	**-1**	**0**	**+1**	**+ α**	
x_1 – vibration acceleration, м/с^2	30	35	40	45	50	5
x_2 – feed-in, кг/год	200	300	400	500	600	100
x_3 – material moisture content, %	14	17	20	23	26	3
x_4 – sieve hole diameter, mm	1,2	1,4	1,6	1,8	2	0,2

To carry out the RCPC of a four-factor experiment, a matrix of experiments planning was compiled, which is presented in table 2.

It is planned to obtain the 2nd order multiple regression equation:

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ij} x_i^2 + \sum_{i=1}^{n} b_{ij} x_{ij} x_{ij} , \quad (5)$$

where y is one of the qualitative functions *P*, *K*, *N*; b_0, b_i, b_{ij} – regression coefficients obtained by the method of least squares.

After processing the experimental data in the statistical environment STATISTICA 10.0, the coefficients of complex multiple regression equations of the 2nd order were obtained:

– for productivity:

$$P = 380 - 11.5a - 0.4Q + 7M - 24.8d + 0.24a^2 - 0.5W^2 - 11.3d^2 + \\ + 0.02aQ - 0.06aM - 5.3ad - 0.05QW + 0.16Qd + 16.7Wd; \quad (6)$$

– for the specific passage:

$$K = 81.83 - 1.3a + 0.07Q + 1.48W + 12.62d + \\ + 0.03a^2 - 0.05W^2 - 3.2d^2 + 0.04aQ - 0.25ad - 1.7Wd; \quad (7)$$

– for the consumed energy:

$$N = 1042.7 - 19.7a - 1.5Q - 11.2W - 78d + 0.42a2 - 1.05W2 - \\ 178d2 + 0.096aQ + 0.74aW - 18.2ad - 0.2QW - 0.8Qd + 13.62Wd. \quad (8)$$

The adequacy of the obtained mathematical models was evaluated according to Fisher's criterion, which showed that the calculated values are much lower than the critical ones, thus, the obtained regression models adequately describe the response surfaces and can be used for the investigated process optimization [16].

The response surfaces were constructed as well (Figure 19, 20, 21, 22, 23, 24) and the rational parameters of the grain grinding process with a vibratory disk crusher were determined (Table 3), the compromise values of which were obtained by Cramer's method in the "Mathcad 15" mathematical environment.

It was also determined that at these parameters the qualitative and energy characteristics of the process of grinding grain raw material by the vibratory disk crusher acquire their optimal values: productivity is 320… 450 kg/h, specific passage through the control sieve – 85… 95% at the energy consumption 1.2… 1.5 kW for the crusher drive.

Table 2

Four-factor matrix for the optimal parameters of the grinding process characterization

Serial no. of the experiment	Factors									Parameters		
	x_1	x_2	x_3	x_4	$F(x_1\ x_2\ x_3\ x_4)$	a, m/s²	Q, kg/h	W, %	d, mm	П, kg/h	К, %	N, W
1	+	+	+	+	+	45	500	20	1,8	387	80,9	1335
2	-	+	+	+	-	35	500	20	1,8	321	70,7	928
3	+	-	+	+	-	45	300	20	1,8	297	81,3	997
4	-	-	+	+	+	35	300	20	1,8	271	67	804
5	+	+	-	+	-	45	500	16	1,8	455	81,2	1276
6	-	+	-	+	+	35	500	16	1,8	311	71,2	917
7	+	-	-	+	+	45	300	16	1,8	299	81,8	935
8	-	-	-	+	-	35	300	16	1,8	283	67,5	793
9	+	+	+	-	-	45	500	20	1,4	343	93	1570
10	-	+	+	-	+	35	500	20	1,4	230	85,1	945
11	+	-	+	-	+	45	300	20	1,4	279	94	1186
12	-	-	+	-	-	35	300	20	1,4	236	85	854
13	+	+	-	-	+	45	500	16	1,4	376	91	1520
14	-	+	-	-	-	35	500	16	1,4	269	86	934
15	+	-	-	-	-	45	300	16	1,4	299	91,3	1102
16	-	-	-	-	+	35	300	16	1,4	281	86,3	867
17	+A	0	0	0	0	50	400	18	1,6	399	93	1101
18	-A	0	0	0	0	30	400	18	1,6	260	72	815
19	0	+A	0	0	0	40	600	18	1,6	392	93,2	1595
20	0	-A	0	0	0	40	200	18	1,6	330	93,6	877
21	0	0	+A	0	0	40	400	22	1,6	300	91	1320
22	0	0	-A	0	0	40	400	14	1,6	400	95,6	1070
23	0	0	0	+A	0	40	400	18	2	398	66,7	910
24	0	0	0	-A	0	40	400	18	1,2	282	94,2	1595
25	0	0	0	0	0	40	400	18	1,6	344	93,5	1200
26	0	0	0	0	0	40	400	18	1,6	340	93,6	1205

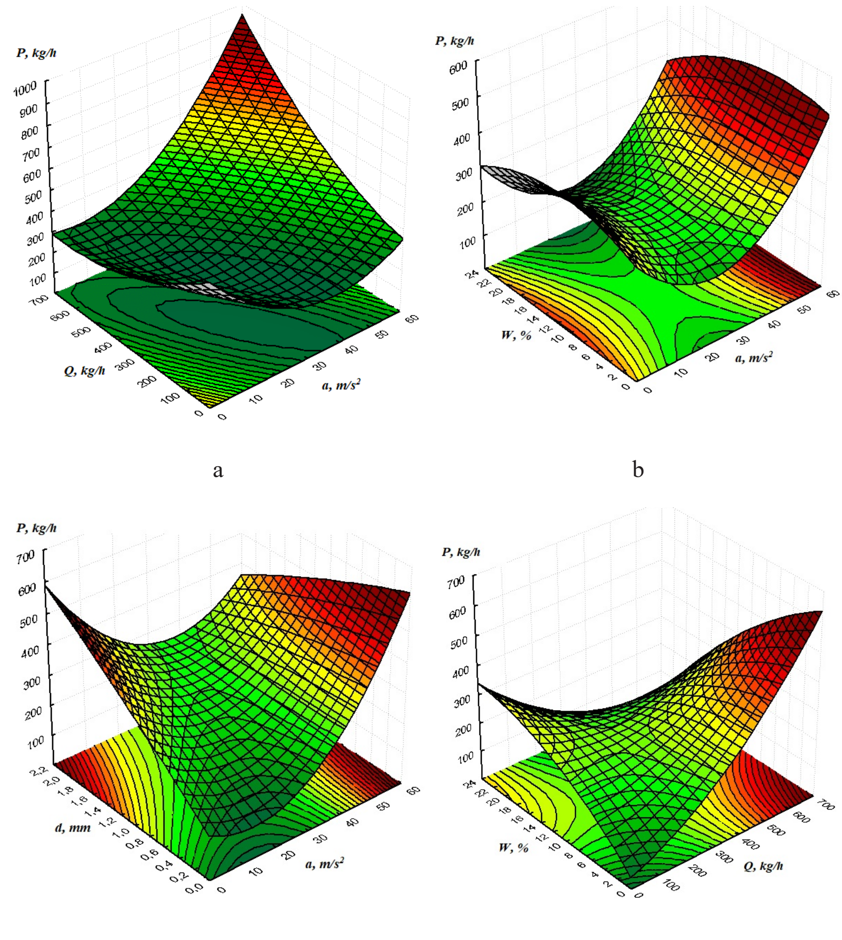
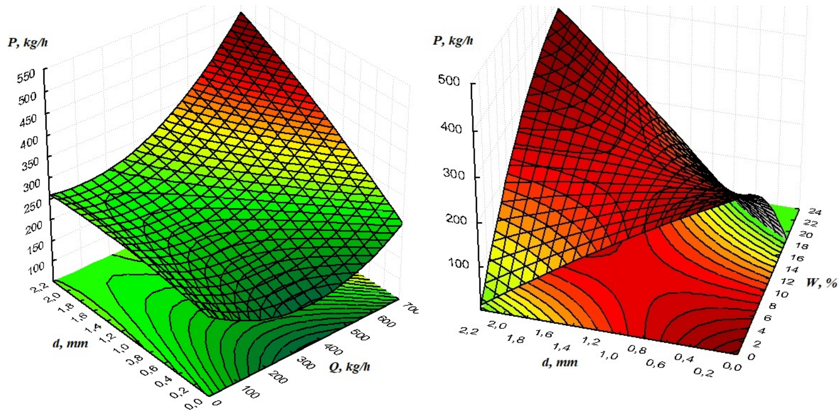
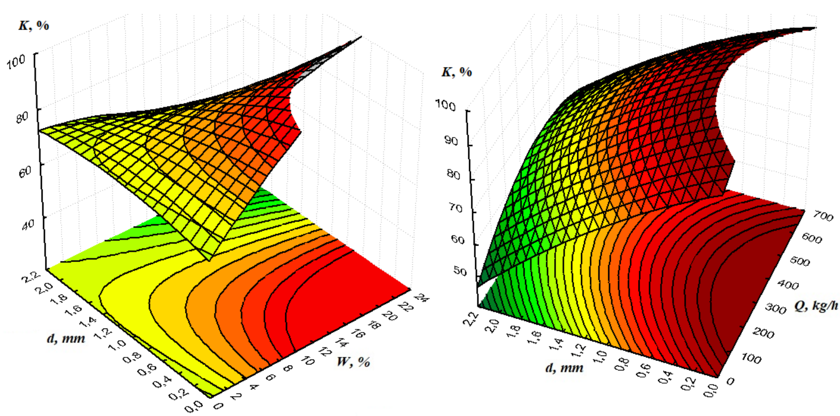


Figure 19. Response surfaces and their projections for productivity in pair interaction of the main factors: a) – vibration acceleration and material feed-in; b) – vibration acceleration and moisture content of the material; c) – vibration acceleration and the separation surface holes diameter; d) – material moisture content and feed-in



a b

Figure 20. Response surfaces and their projections for productivity in pair interaction of the main factors: a) – material feed-in and the separation surface holes diameter; b) – moisture content of the material and the diameter of the holes of the separation surface



a b

Figure 21. Response surfaces and their projections for the specific passage through the control sieve in pair interaction of the main factors: a) – moisture content of the material and the separation surface holes diameter; b) – material feed-in and the separation surface holes diameter

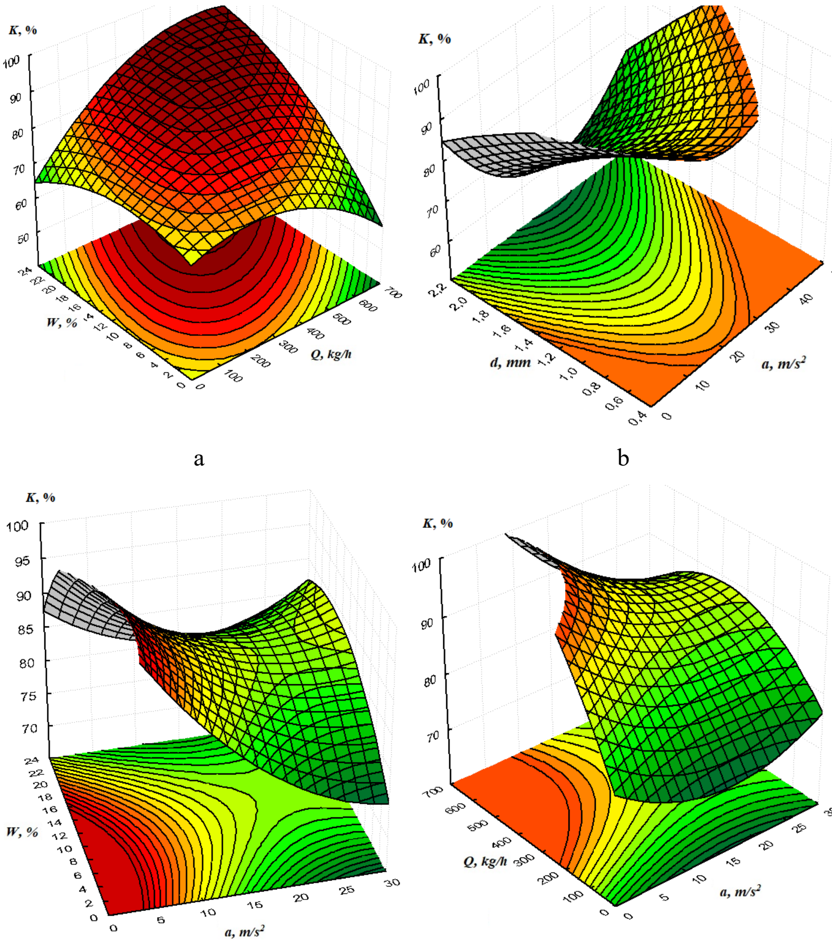


Figure 22. Response surfaces and their projections for the specific passage through the control sieve in pair interaction of the main factors: a) – moisture content and material feed-in; b) – vibration acceleration and the separation surface holes diameter; c) – material moisture content and vibration acceleration; d) – vibration acceleration and material feed-in

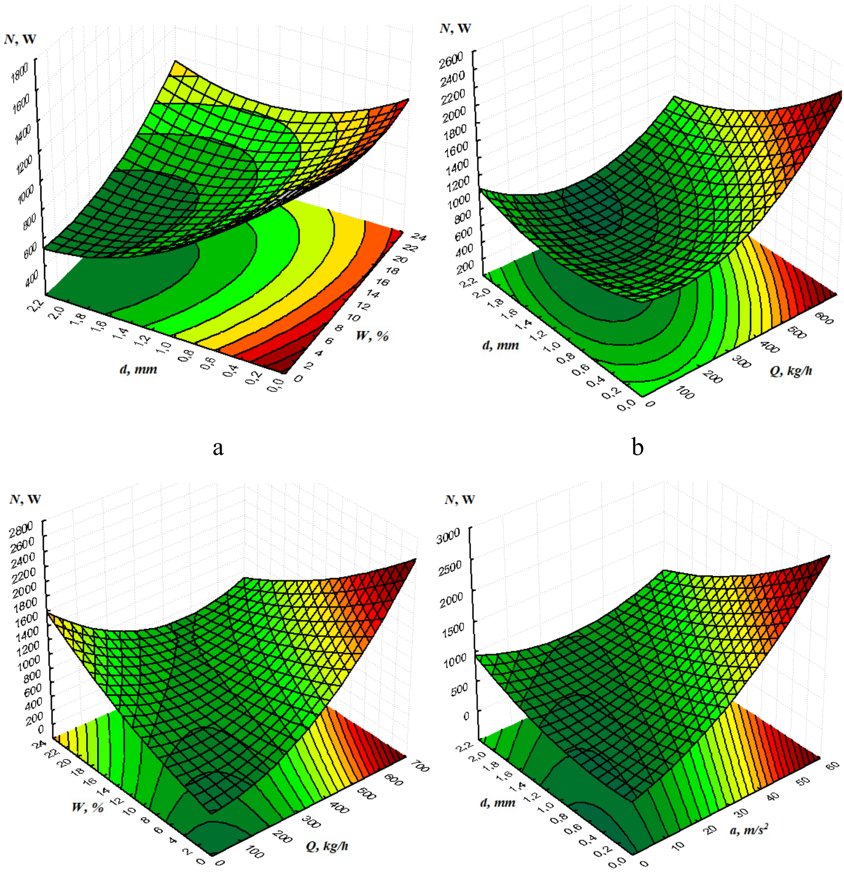
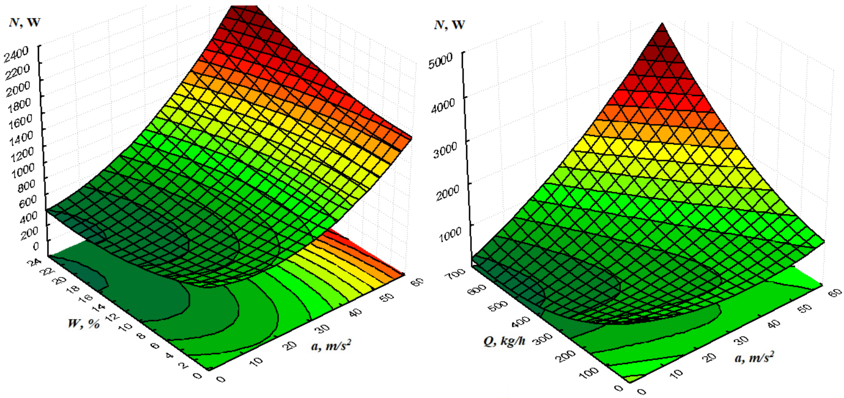


Figure 23. Surface responses and their projections for the consumed energy in the pair interaction of the main factors: a) – moisture content of the material and the separation surface holes diameter; b) – material feed-in and the separation surface holes diameter; c) – material moisture content and feed-in; d) – vibration acceleration and the separation surface holes diameter



a b

Figure 24. Surface responses and their projections for the consumed energy in the pair interaction of the main factors: a) – material moisture content and vibration acceleration; b) – material feed-in and vibration acceleration

Table 3

Rational parameters of the developed equipment and process

Parameters	Rational value
Vibration acceleration, m/s^2	32-38
Material feed-in, kg/h	342-480
Material moisture content, %	16-18
Separation surface holes diameter, mm	1,6-1,8

6. Conclusions

1. Based on the analysis of literature sources, it has been established that the existing methods of grinding grain in the production of feed for farm animals do not fully correspond to modern trends towards reducing energy consumption and increasing the efficiency of the working process. Grinding of high moisture material (feed grain) is energy-intensive. This is caused by an increase in grain ductility and adhesive forces, which causes the material to stick to the sieve.

2. Grinding with the use of combined vibro-centrifugal and impact-cutting impact of hammers on the material is one of the ways to solve the problem of intensification of forage production.

3. Rotary vibratory crusher is developed. The crusher implements the idea of a combined interaction of vibration and rotary motion of the rotor. Disc hammers are also installed on the rotor. All this increases the impact-cutting action and neutralizes the circulation effect of the crushed material in the crushing chamber. The leveling of excessive circulation of the air-product layer contributes to the timely removal of material from the grinding zone. Thus, it can improve the productivity and energy efficiency of the process.

4. As a result of the experimental studies, the amplitude-frequency and energy characteristics for the crusher were obtained. In the operating mode of the rotor frequency ω = 100 ... 125 rad/s and material feed-in Q = 100 ... 600 kg/h: amplitude – A = 2.8 ... 3.3 mm; vibration acceleration – a = 40 ... 46 m/s^2, energy consumption by the drive – N = 740 ... 1160 W.

5. According to the results of a multifactor experiment, mathematical models in the form of second-order multiple regression, which adequately describe the studied process, were obtained. The analysis of the obtained models allowed to receive rational mode parameters of the studied process: operating mode of vibration acceleration – a = 32… 38 m/s^2; geometric parameters of the separation surface – d=1.6…1.8 mm; material feed-in – Q = 342…480 kg/h; moisture content of the material – W = 17-18%. Herewith, the angular velocity of the crusher rotor is ω = 110…113 rad/s, the amplitude – A = 3.15…3.2 mm. In compliance with the specified limits of design and mode parameters, quality and energy characteristics of the process acquire the following values: productivity is 320…450 kg/h, specific passage through the control sieve – 85…95% at energy consumption of 1.2…1.5 kW for the crusher drive.

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