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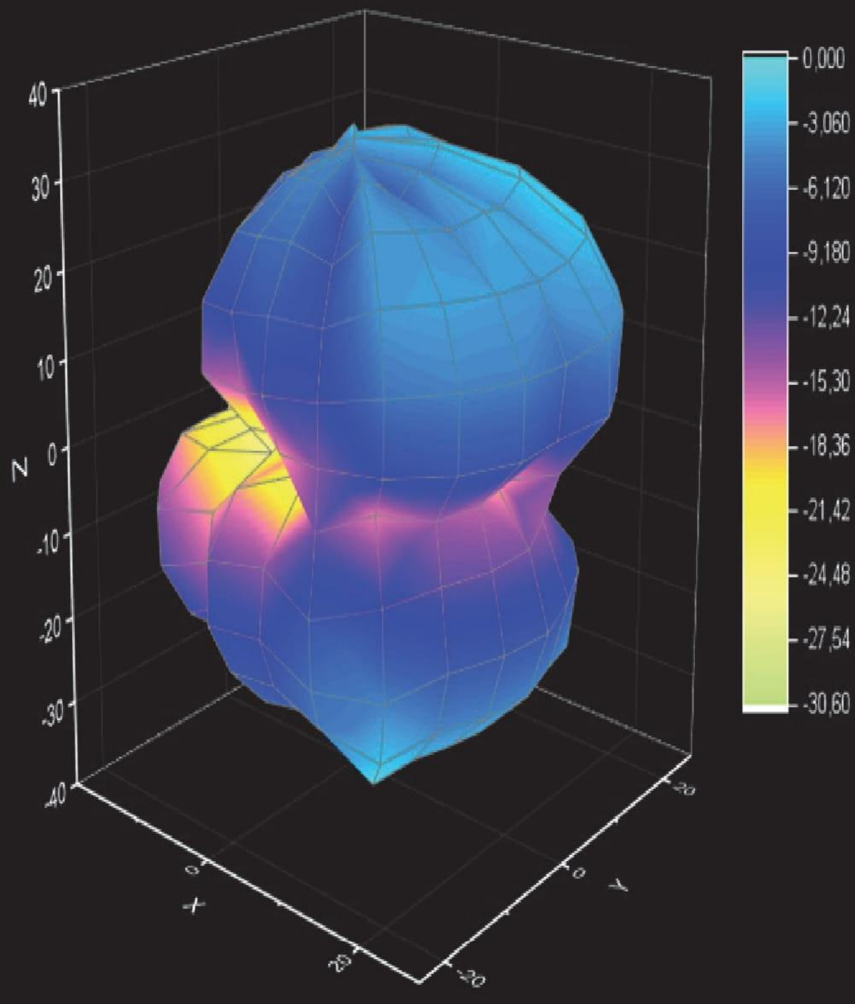

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Multicriteria compromise optimization of feed grain grinding process

Abstract. *Optimization of the feed grinding process by a vibrating rotary crusher was carried out and shown in the article: a multifactor experiment was carried out, a statistical analysis of the results was carried out using the software "Statistica 10.0", mathematical models were obtained in the form of multiple regression of the second order and their adequacy was checked by the Fisher criterion. Rational operating parameters were obtained by Cramer's method using the "Mathcad 15.0" software.*

Streszczenie. Przeprowadzono i przedstawiono w artykule optymalizację procesu rozdrabniania ziarna przez wibracyjną kruszarkę obrotową: przeprowadzono eksperyment wieloczynnikowy, przeprowadzono analizę statystyczną wyników za pomocą programu „Statistica 10.0", modele matematyczne uzyskano w forma regresji wielokrotnej drugiego rzędu i ich adekwatność sprawdzono za pomocą kryterium Fishera. Racjonalne parametry pracy uzyskano metodą Cramera przy użyciu programu „Mathcad 15.0". (***Wielokryterialna optymalizacja procesu mielenia ziarna paszowego***)

Keywords: statistical analysis, multifactor experiment, rotatable central-compositional planning, functional dependence.
Słowa kluczowe: optymalizacja, kruszenie ziarna, , optymalizacja wielokryterialna.

Introduction

Feeds make up most of the cost of livestock products and determine its quality, and one of the most important and energy-intensive operations is grinding of grain, especially substandard (wheat, barley, peas, corn, etc.) [1, 2]. The need for grinding grain feed is conditioned by the physiological characteristics of animals [3, 4], as the rate of processing feed with gastric juice is directly proportional to its surface area [5, 6]. At the same time, in the technological process of feed preparation, the share of energy consumption for grinding can reach 65% [2, 7, 8]. Therefore, the effective functioning of farms in modern conditions requires development and implementation of technologies that meet international standards and reducing energy intensity of the process is an urgent task.

Analysis of literary sources and problem statement

To reduce the energy intensity of this process the experimental model Vibrating-Rotor Crusher [7, 9, 10] has been developed, in which the 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 [8].

On the base of the Department of Technological Processes and Equipment for Food and Processing Industries of Vinnytsia National Agrarian University laboratories the ranges of amplitude-frequency characteristics of Vibrating-Rotor Crusher on the angular velocity of the drive shaft were researched [11].

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

Purpose and tasks of research

The purpose of the article 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 performed the multifactors experiments to change the dispersed properties of the processed material (corn) under the action of impact-cutting action of the disk-type beaters.

Materials 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 (Fig. 1) and experimental model of the vibratory crusher [9, 11]. The first part of the experimental research was based on the analysis of the amplitude-frequency characteristics [11, 12] of the actuator and the consumed energy [8, 13, 14] 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 [7] and dispersion of the obtained material [15].

Comprehensive statistical analysis [16, 17] 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.

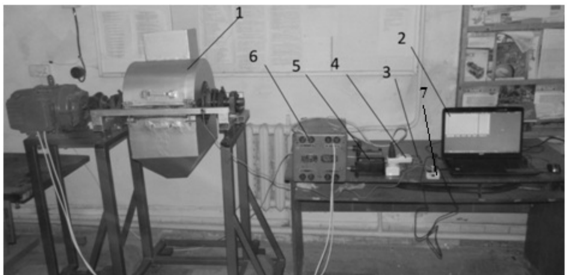


Fig. 1. Experimental stand: 1 – experimental sample of the vibratory disk crusher; 2 – personal computer; 3 – switch; 4 – EMF-1 electronic wattmeter; 5 – secondary electromechanical wattmeter; 6 – AOCH-20-220-75 laboratory transformer; 7 – accelerometer.

To record the amplitude-frequency characteristics of the vibratory disk crusher, a sensor based on the ST Microelectronics LIS3DH accelerometer was developed (Fig. 2) [11, 18].

In order to register the frequency of the drive shaft a wireless tachometer UNI-T UT372 (Fig. 3a) was used, the principles and procedures of operation of which are described in the technological documents [7, 11].

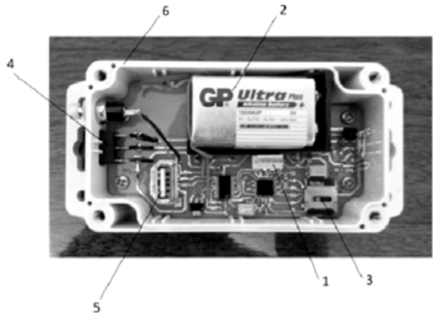
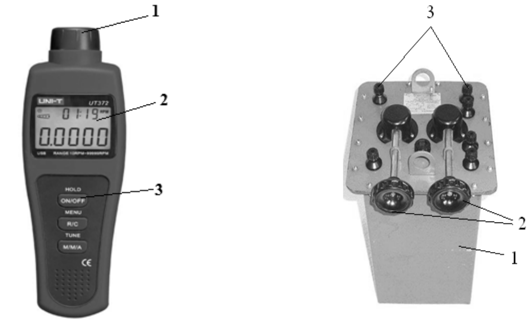


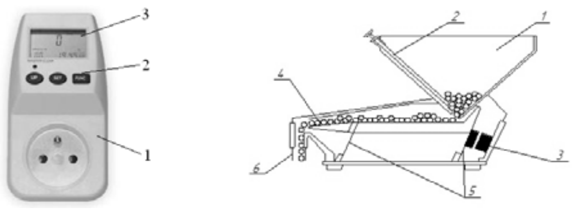
Fig. 2. Accelerometer (general view of the device): 1 – microport for the accelerometer sensor connection; 2 – power supply battery; 3 – memory card; 4 – power button; 5 – adaptive microport for data reading; 6 – accelerometer housing

To control and change the rotation speed of the electric motor shaft autotransformer AOCH-20-220-75 (Fig. 3b) was used designed to work with alternating current [7, 8, 11].



a) b)

Fig. 3. Devices for velocity control of the drive shaft:
a) UNI-T UT372 frequency meter: 1 – laser reader; 2 – digital indicator; 3 – control panel;
b) AOCH-20-220-75 laboratory autotransformer: 1 – outer casing; 2 – voltage regulators; 3 – input and output terminals.



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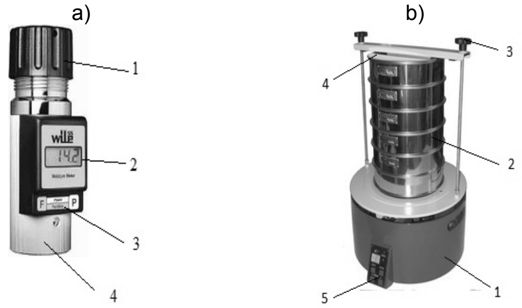


c) d)

Fig. 4. Devices for research the technological parameters:
a) EMF-1 electronic wattmeter: 1 – wattmeter housing; 2 – control panel; 3 – indicator display.
a) PG-2 vibrating feeder: 1 – loading hopper; 2 – sliding shutter; 3 – electromagnetic vibration excitor; 4 – conveying tray; 5 – springs; 6 – unloading neck.
c) Wile-55 moisture meter: 1 – case cover; 2 – digital indicator; 3 – control panel; 4 – test sample container.
d) A-20 sieve analyzer: 1 – vibrating platform; 2 – sieve block; 3 – fixing screws; 4 – dustproof surface; 5 – control panel.

To determine power characteristics the EMF-1 electronic wattmeter was used (Fig. 4a) [8]. The device measured the following parameters: utility supply voltage, frequency and power of alternating 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 [9].

To change the mode of the feed-in of the material PG-2 mobile vibrating dispenser was used (Fig. 4b) [19], 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 (Fig. 4c) was used, intended to measure the relative humidity of various types of grains and seeds, characteristics of which are stored in the device memory [8].

Productivity evaluation was done by weighing the crushed material that passed through the crusher over a time interval [7].

Dispersity of the material was determined by the method of mechanical separation of particles – sieve analysis. The experimental material was passed through the A-20 laboratory sieve analyzer (Fig. 4d) [15]. Sieves with a hole size of 1; 0.8; 0.6; 0.4; 0.2 mm were used.

For the quality assessment of the crushed material, the rate of extraction or the proportion of its passage through the control sieve was assumed [20]. 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 suppose 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 [1]. 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 [2, 3]; the proportion of the material with particle size not more than 1 mm should be not less than 85% of the total weight of the crushed product [4].

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 [21]. 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" [18]. Processing of the experimental data was carried out in the statistical environment "Statistica 10.0." and "Mathcad 15.0" [21].

Qualitative and energy parameters of optimization of the studied process are determined as: productivity P, $kg \cdot h^{-1}$; specific passage through the control sieve (holes diameter d_c=1.0 mm) K, %; consumed energy N, W. Based on our own experience [2, 7, 8, 11, 12] and having analyzed other scientists research results [1, 5, 6, 10, 19], vibration acceleration a, $m \cdot s^{-2}$; the separation surface holes diameter d, mm; amount of the material feed-in Q, $kg \cdot h^{-1}$; moisture content of the material M,% are determined as the factors that have the greatest impact on the defined optimization parameters:

(1) $P=f(a, Q, M, d)$;
(2) $K=f(a, Q, M, d)$;
(3) $N=f(a, Q, M, d)$.

The number of factors (RCCP) is:

(4) $k=k_c+2n+k_0$,

where k_c 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 $\alpha = 2$.

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 "-α", "+α". 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				
	-α	-1	0	+1	+α
x_1 – vibration acceleration, m·s^{-2}	30	35	40	45	50
x_2 – feed-in, kg·h^{-1}	200	300	400	500	600
x_3 – material moisture content,%	14	17	20	23	26
x_4 – sieve hole diameter, mm	1.2	1.4	1.6	1.8	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 [20]:

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

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.

Table 2 – Four-factor matrix to performed the multifactors experiment (encoded)

№	x_1	x_2	x_3	x_4	$F(x_1, x_2, x_3, x_4)$
1	+	+	+	+	+
2	-	+	+	+	-
3	+	-	+	+	-
4	-	-	+	+	+
5	+	+	-	+	-
6	-	+	-	+	+
7	+	-	-	+	+
8	-	-	-	+	-
9	+	+	+	-	-
10	-	+	+	-	+
11	+	-	+	-	+
12	-	-	+	-	-
13	+	+	-	-	+
14	-	+	-	-	-
15	+	-	-	-	-
16	-	-	-	-	+
17	+α	0	0	0	0
18	-α	0	0	0	0
19	0	+α	0	0	0
20	0	-α	0	0	0
21	0	0	+α	0	0
22	0	0	-α	0	0
23	0	0	0	+α	0
24	0	0	0	-α	0
25	0	0	0	0	0
26	0	0	0	0	0

Research results

The results of experimental studies are shown in table 3.

Analysis of the statistical characteristics (table 4) 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.

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, 18].

Table 3 - The results of a multifactorial experiment

№	Variable factors				Parameters		
	a, m·s^{-2}	Q, kg·h^{-1}	M, %	d, mm	P, kg·h^{-1}	K, %	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	50	400	18	1.6	399	93	1101
18	30	400	18	1.6	260	72	815
19	40	600	18	1.6	392	93.2	1595
20	40	200	18	1.6	330	93.6	877
21	40	400	22	1.6	300	91	1320
22	40	400	14	1.6	400	95.6	1070
23	40	400	18	2	398	66.7	910
24	40	400	18	1.2	282	94.2	1595
25	40	400	18	1.6	344	93.5	1200
26	40	400	18	1.6	340	93.6	1205

Table 4 – Statistical characteristics

Indicator	Parameter values		
	P, kg·h^{-1}	K, %	N, W
number of factors	26	26	26
minimum value	230	66.7	793
maximum value	455	95.6	1595
average value	322.4	84.6	1102
upper limit of the confidence interval	345.6	88.6	1206
lower limit of the confidence interval	299.1	80.7	997
geometric mean	317.6	84	1075
harmonic mean	312.9	83.4	1050
median	305.5	86.2	1034
mode	299	85.3	1595
mode frequency	2	2	2
lower quartile	281	80.9	910
upper quartile	376	93.2	1276
range	225	28.9	802
interquartile range	95	12.3	366
asymmetry	0.493	-0.724	0.739
kurtosis coefficient	-0.462	-0.883	-0.629

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 (6-8):

- for productivity:

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

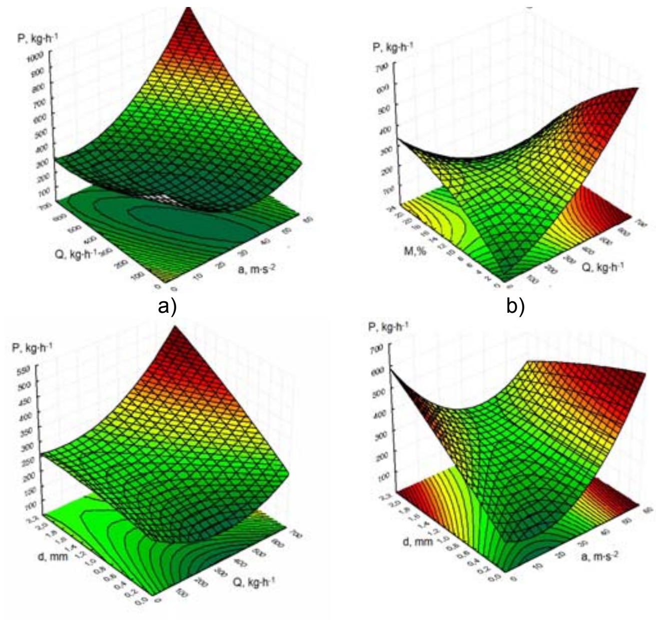
- for the specific passage:

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

- for the consumed energy:

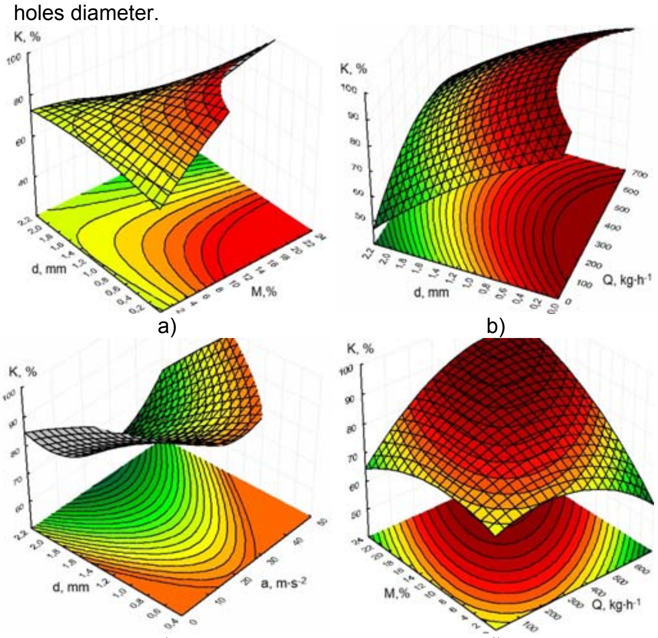
$$N=1042.7-19.7a-1.5Q-11.2M-78d+0.42a^2-1.05M^2-178d^2+0.096aQ+0.74aM-18.2ad-0.2QM-0.8Qd+13.62Md. \quad (8)$$

The response surfaces for this parametrs are shown in fig. 5, fig. 6, fig. 7.



a) b) c) d)

Fig. 5. Productivity in pair interaction of the main factors: a) vibration acceleration and material feed-in; b) material moisture content and feed-in; c) material feed-in and the separation surface holes diameter; d) vibration acceleration and the separation surface holes diameter.



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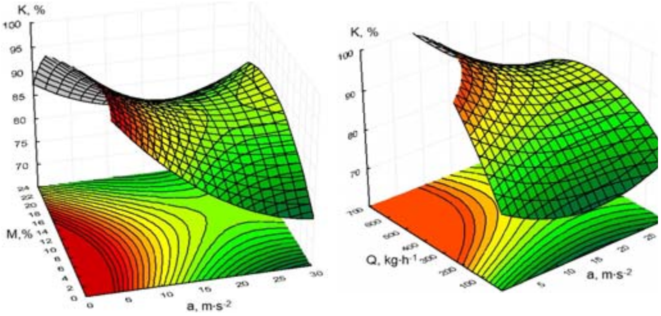
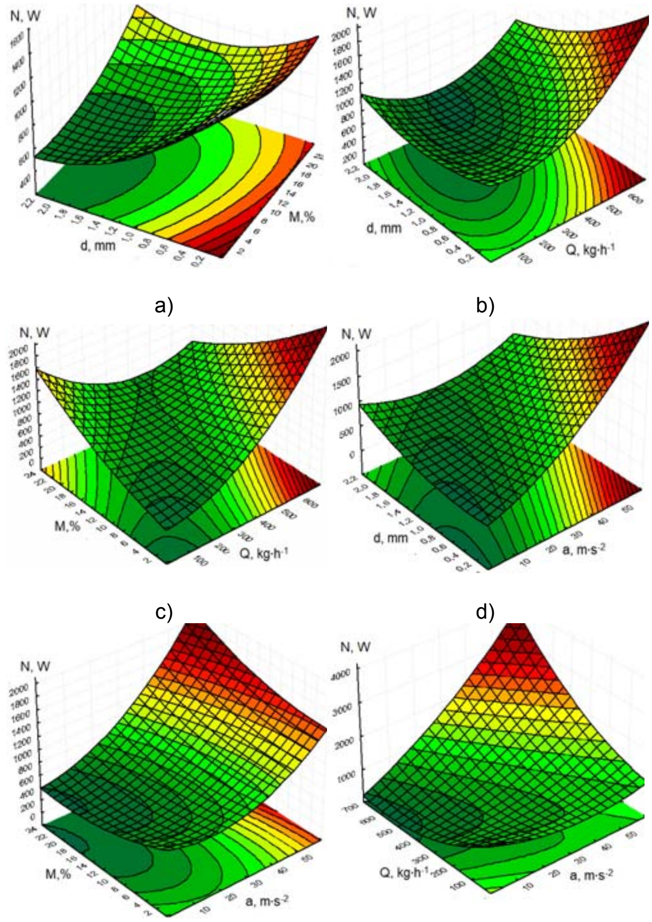


e) f)

Fig. 6. 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; c) vibration acceleration and the separation surface holes diameter; d) moisture content and material feed-in; e) material moisture content and vibration acceleration; f) vibration acceleration and material feed-in.



a) b) c) d) e) f)

Fig. 7. Consumed energy 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; c) material moisture content and feed-in; d) vibration acceleration and the separation surface holes diameter; e) material moisture content and vibration acceleration; f) – material feed-in and vibration acceleration.

The rational values of parameters for grinding process with a vibratory disk crusher were determined by Cramer's method using the "Mathcad 15.0" [21] software (table 5).

Table 5 – Rational values of parameters

Parameters	Values
Vibration acceleration, $m{\cdot}s^{-2}$	32-38
Material feed-in, $kg{\cdot}h^{-1}$	342-480
Material moisture content, %	16-18
Separation surface holes diameter, mm	1,6-1,8

It was also determined that at these parameters the grinding feed grain prosess by the vibratory disk crusher reached compromise values between the criteria of productivity, energy consumption and grinding quality.

Conclusions

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 $m \cdot s^{-2}$; geometric parameters of the separation surface – d=1.6…1.8 mm; material feed-in – Q=342… 480 $kg \cdot h^{-1}$; moisture content of the material – W=16…18 %. 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 $kg \cdot h^{-1}$, specific passage through the control sieve – 85… 95 % at the energy consumption 1.2… 1.5 kW for the crusher drive.

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