Substantiation of the main parameters of a hammer crusher for grinding municipal solid waste

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Abstract: The scientific novelty of the research lies in the determination and substantiation of the rational values of the main parameters of a hammer crusher designed for grinding organic components of municipal solid waste. A method has been developed for calculating the speed and effort, as well as the maximum elastic-plastic deformation of the components of the waste due to the collision of the waste against each other, against the wall of the working chamber of the crusher, as well as against knives welded on the walls of the working chamber at different heights at an angle of 120 degrees with each other. The aim of the study is to develop a hammer crusher design with low energy and material consumption with increased technical and operational performance. As a result of the experimental studies, the dependences of the crusher performance on the number of revolutions of the rotor shaft, on the light area of the grates, and on the diameter of the rotor were obtained. The processing of the obtained experimental data made it possible to obtain a mathematical model that adequately describes the process of crushing the organic components of the waste in a hammer crusher. Design and production of hammer crushers with rational parameters will reduce energy and material consumption by approximately 1.5-2.0 times compared to traditional designs.

1 Introduction

The increase in the urban population, the rapid growth of the economy and the improvement of life in developing countries, as well as the pursuit of excess profits for manufacturers due to the small packaging of goods, have significantly accelerated the rate of quantity and quality of MSW generation, as a result, their negative impact on the environment has increased [1].

Currently, in order to reduce the negative impact of solid waste on the environment, issues related to the crushing of waste in places of accumulation and at waste transfer stations, as well as their use as secondary raw materials, remain relevant. It is known that the crushing operation is a key link in the system of complex waste processing and, in this regard, in many developed countries, special attention is paid to the creation and production of highly efficient and flexible crushing machines with low energy and material consumption. The crushing of MSW components is in demand for a number of reasons: firstly, the efficiency of subsequent operations increases; secondly, due to the crushing of waste, the number of vehicles involved

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will be reduced by approximately 25-30 percent; thirdly, the negative impact of waste on the environment will be significantly reduced; fourthly, shredded waste can serve as a secondary raw material for agriculture. In addition, it is important to note that by reducing the volume of waste disposal, the life of landfills increases, as well as saving land resources used when filling waste, which in turn affects the cost of their disposal [2, 3].

The implementation of large-scale measures aimed at the collection, transportation, crushing and sorting of waste, as well as their disposal at landfills, has begun in the Republic of Uzbekistan. This is evidenced (along with the implementation of measures in the field of ecology to radically improve and develop systems of work related to waste) a number of legal acts adopted by the state that motivate research, organizational and methodological work. In the Development Strategy of New Uzbekistan for the period 2022-2026, the implementation of the following tasks is especially noted “...improving the system for assessing environmental pollution, monitoring the environment, predicting the degree of environmental pollution. Information support of the state environmental control body, monitoring the state of pollution sources and their impact on the environment” and “…increasing the percentage of collection of municipal solid waste up to 100 percent, increasing the percentage of waste recycling by 2026 from 21 percent to 50 percent.” When performing the above tasks, studies related to the crushing of waste, taking into account their morphological and fractional composition, are relevant [4].

A.M. Gonopolsky was engaged in the study of design parameters and the development of criterion relationships from dimensionless complexes based on the methods of the theory of similarity for the calculation and design of ball grinders [5, 6].

Theoretical analysis of the working process and improvement of the design of the shredder-spreader of solid organic fertilizers was devoted by the work of such scientists as A.N. Tseplyaev, V.G. Abezin, V.A. Motorin [7].

In the work of A.Sh. Abdullaeva et al. studied the influence of the speed of rotation of the shaft of the working body of the grinder on the degree of grinding of organic waste, based on the studies, the dependence of the degree of grinding of organic waste on the speed of rotation of the shaft of the working body and on the spacing of the rods was obtained [8].

The work of I. Bondarenko [9] is devoted to the development of a crushing plant with a gravitational-pneumatic drive for the use of alternative energy sources, while the operation of the necessary technological equipment for secondary raw materials management systems has been established. Based on the study of the properties of glass waste, IKECHUKWU O. [10] proposed a modernized design for grinding glass waste with low energy and material consumption.

The work of Luo,S. and others is devoted to the development of a new technology for grinding organic waste. The characteristics of the grinder, such as the influence of the rotor speed on the granulometric composition of the product and specific energy, have been studied [11].

The research of Sothea, K. et al. is devoted to the development of the design of a multifunctional machine that is capable of grinding organic waste in one chamber, and mixing the crushed waste with ingredients in the other in order to obtain a composite brick [12]. Osvaldo, E. et al. report a crusher design made from local raw materials. The conducted studies allowed to establish rational parameters of the crusher [13].

The work of Lopatina N.A. is devoted to the study of the choice of an effective design of a crusher for crushing concrete waste. and others. Based on the analysis of technical and operational indicators of various designs of crushers, the design of a jaw crusher was chosen, which proved to be multifunctional and reliable [14]. In addition, such scientists as N. Huaxun Ma, Lei Sun [15], B. Kosimbetov, S.Komilov [16], Sh.S.Tursunov[17], F.B.Teshome [18].

Despite the large number of studies devoted to the development of crusher designs and
the substantiation of the main parameters, the question of substantiating the main parameters of hammer crushers is still open and, accordingly, is considered open.

The creation of efficient sorting devices for low energy and material consumption causes significant difficulties: firstly, the waste is a very diverse physical and mechanical properties of the agglomerate containing fibrous inclusions (paper, wood, leather, etc.), fragile components (bones, stones, etc.), as well as food waste; secondly, it is connected with the issues of rational layout of the device nodes relative to each other [19-24].

In addition, it should be noted that the methods for calculating the main parameters of crushers based on the energy hypotheses of crushing [25] satisfactorily describe the process of crushing elastic-brittle materials, and when crushing the organic components of municipal solid waste, these calculated dependences have large errors.

In this regard, it is relevant to determine and justify the limit value of the impact force of organic components with each other and with the wall of the working chamber, as well as the main design parameters of the crusher.

In addition, these crushers must meet very stringent energy, environmental and economic requirements, which are as follows: low energy and material consumption; minimum percentage of ballast inclusions; minimal emission of harmful substances into the atmosphere; simplicity of design and reliability in operation [ 26, 27].

2 Methods

In connection with the goal of determining and substantiating the rational values of the main parameters of a hammer crusher designed for grinding organic components of household waste and experimental confirmation of the results obtained, a prototype hammer crusher has been developed. The general view and structural diagram of the crusher is shown in Figure 1.

![Hammer crusher: a) general view of the hammer crusher, b) structural diagram of the hammer crusher: 1-bunker; 2-working chamber; 3-knife rotating; 4-hammer; 5-rotor; 6- side grate; 7-lower grate; 8-frame crusher; 9-knife fixed; 10-electric motor; 11- V-belt.](image)

The hammer crusher consists of a hopper 1, which consists of steel sheets welded with a thickness of 3.0 mm in the shape of an isosceles trapezoid, the lower ends of which are welded to a disk with a diameter of 300 mm, which in turn serves as a cover for the working chamber 2. The working chamber 2 is made of a cast-iron pipe with a diameter of 300 mm, the lower
end of which is welded to the frame 8 of the crusher, and in the upper part of the working chamber four through holes are drilled in a circle, the hopper 1 of the crusher is attached to them with bolts. The electric motor 10 is bolted to the frame 8 of the hammer mill. It is positioned so that crusher wash water or liquid waste does not enter the electrical part of the electric motor. To do this, a pulley is installed in the lower part of the working chamber, which is rigidly mounted on the shaft. A pulley is fixed to the output shaft of the electric motor 10 by means of a key, which is connected to the pulley of the working chamber 2 by means of a V-belt drive. A cruciform working body is mounted on dowels to the upper part of the shaft of the working chamber. A rotor 5 is welded onto a sleeve with a diameter of 20 mm from the bottom side. On the outer side of which hammers 4 are welded. A rotating knife 3 is also welded to the upper part of the sleeve, the ends of which are pointed for better grinding. To obtain crushed waste to the desired size, a side grate 6 is installed in the lower side part of the working chamber 2. In addition, to improve the efficiency of grinding the organic components of the waste, lower grates 7 are drilled along the periphery . For better grinding of waste on the walls working chamber 2 fixed knives 9 are welded.

Hammer crusher works as follows. The waste arriving for grinding enters the loading hopper 1. Then the waste enters the working chamber 2, where it is accelerated to a rotation speed equal to the nominal rotation speed of the electric motor 10 due to the creation of air pressure by means of a hammer 4. Accelerated waste to the nominal rotation speed of the electric motor 10 is crushed due to the collision of waste with knives 9 rigidly welded to the walls of the working chamber 2. In addition, the waste is crushed by colliding with the grate 5.

To study the influence of the shape and installation angle of the hammers relative to the axis passing through the length of the crushing machine rotor on the crushing efficiency, a series of preliminary experiments were carried out.

![Fig.2](image)

Fig.2. Designs of rotors with different hammers: a) straight hammers located along the rotor axis; b) hammers located at an angle of 45 degrees to the rotor axis; c) parabolic hammers

### 3 Materials

The non-linear elastoplastic model of Hertz was used to determine the main ratios of the impact of MSW components with each other and with the wall of the working chamber. The model is based on two main concepts: firstly, in the interaction of colliding bodies, local deformations in the contact zone are significant, and the general deformations of the colliding bodies are small compared to local ones and can be neglected; secondly, the dependence of the contact force on the contact deformation during impact remains the same as in the case of static compression of bodies [27,28,29].

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The following designations have been adopted: the masses of the colliding components of the waste are denoted by \( m_1 \) and \( m_2 \), respectively; the speeds of the components of municipal solid waste at the moment of impact are equal to \( \dot{\theta}_{10} \) and \( \dot{\theta}_{20} \), respectively. Assumptions and restrictions introduced to describe the process of crushing organic components of MSW in the process of collision of waste components: the speeds of colliding organic components of waste have the ratio \( \dot{\theta}_{10} > \dot{\theta}_{20} \); the velocity vectors of the organic components of the waste coincide with the line passing through the centers of gravity of the colliding bodies; the shaping of waste components in the contact zone is elastic-plastic in nature; the force parameter can be described by a one-term empirical dependence.

The calculation scheme for determining the main parameters of the process of collision of MSW components is shown in Fig.3.

![Fig.3. Calculation scheme for determining the main parameters of the impact between the organic components of the waste: 1,2 - organic components of MSW.](image)

Let us first consider the solution of this problem without taking into account the wave oscillations of bodies. The equations of motion of the colliding components of the waste in this case will have the form

\[
m_1 \frac{d^2 x_1}{dt^2} = -P(x) \quad m_2 \frac{d^2 x_2}{dt^2} = -P(x) \quad m_1 \frac{d\theta_1}{dt} = -P(x) \quad m_2 \frac{d\theta_2}{dt} = -P(x)
\]

(1)

where \( x_1 \) and \( x_2 \) are the coordinates of the centers of gravity of the organic components of the waste in the process of impact, \( m \); \( \dot{\theta}_1, \dot{\theta}_2 \)- the speed of the centers of gravity of the organic components of the waste during the impact, m/s. The coordinates of the centers of gravity of the organic components of the waste in the process of impact have the following dependence components of waste during impact, m/s. The coordinates of the centers of gravity of the organic components of the waste in the process of impact have the following dependence

\[
x_1 + x_2 = x
\]

(2)

Consequently, the shape change of the organic components of the waste in the process of collision determines the convergence of the coordinates of the centers of gravity of the waste

\[
\frac{dx_1}{dt} + \frac{dx_2}{dt} = \dot{\theta}_1 + \dot{\theta}_2 = \dot{\theta}
\]

(3)

where \( \dot{\theta} = \frac{dx}{dt} \) - the speed of convergence of the coordinates of the centers of gravity of
the organic components of the waste, m/s.

From the above dependencies between the coordinates of the centers of gravity and the velocities of the organic components of the waste, the main impact ratio has been developed

\[
\frac{d\theta}{dt} = \frac{d^2x}{dt^2} = -P(x)/m,
\]

(4)

where \( m = (m_1 m_2)/(m_1 + m_2) \) – generalized mass of colliding components of the waste, kg.

This equation is obtained by summing equations (1) and dividing them term by term into the corresponding masses. Of most interest is the nature and properties of the impact force, which determine the values of accelerations in the process of impact and the duration of their contact. In addition, knowledge of the contact force makes it possible, if the body has a relatively simple configuration, to determine the stresses arising in the process of collision, guided by well-known calculation methods.

The impact of waste constituents can be conditionally considered in two stages. The first stage can be called active, the second - passive.

During the active stage, the force characteristic increases, and the shape change of the colliding components of the waste in the contact zone is elastic-plastic in nature, i.e. during the first stage of the impact, the colliding bodies receive additional loads; during this period, the coordinates of the centers of gravity of the colliding components of the waste approach and the stresses that arise at the contact site will exceed the strength limits of the components of the waste, and thus the crushing process will occur.

The end of the active stage, as it were, merges with the passive stage, and in this interval, the organic components of the waste are crushed into several parts and the crushed waste is removed with an air-product mixture to the outside through the grates. In this regard, the active stage of impact is of the greatest interest. Therefore, we will consider it in more detail.

The initial phase of the impact (active stage) is obtained by substituting the value of the impact force characteristic into the main equation of the elastoplastic impact process

\[
\frac{\theta}{n} \frac{d\theta}{nx} = -\frac{1}{m}kx^n,
\]

(5)

At the initial stage, when \( t=0 \), \( \alpha = 0 \) and \( \theta = \theta_0 = \theta_{10} + \theta_{20} \), solving the last equation (5) we get

\[
\theta = \theta_0(1 - \frac{2k}{m\theta_0 n+1} \frac{x^{n+1}}{n+1})^2,
\]

(6)

From equation (6) it is possible to calculate the largest index of elastic-plastic deformation, at

\[
\theta = 0 \quad x_{max} = \left[\frac{2(n+1)k}{m\theta_0} \right]^{\frac{1}{n+1}},
\]

(7)

and correspondingly

\[
P_{max} = \left[\frac{2(n+1)k^{n+2}}{m\theta_0} \right]^{\frac{1}{n+1}} = \left[\frac{(n+1)k^{n+2}}{E_0} \right]^{\frac{1}{n+1}},
\]

(8)

where \( E_0 = \frac{m\theta_0^2}{2} \) - reduced kinetic energy of MSW constituents.

An analysis of the morphological composition of MSW entering the crusher showed that the waste contains stones, bones, rags, food waste, wood, etc. Therefore, for the efficient
The operation of the crushing machine, the design and operating parameters of the crushing machine should be selected based on the percentage of organic components, for example, food waste as a percentage of organic waste ranges from 90-95%, therefore, the technological parameters of the crusher are set based on the properties food waste, and the stones that take place in the waste will perform a grinding function. Therefore, the coefficients $k$ and $n$ in formulas (5-8), based on the properties of the components of the waste, as well as on the nature of the impact, can be determined

$$n = \frac{2}{3} \; n \; \quad \quad k = \frac{4}{3\pi} \cdot \frac{1}{\delta_1 + \delta_2} \cdot \frac{R_1 R_2}{R_1 + R_2},$$  \hspace{1cm} (9)$$

where $\delta_1, \delta_2$ — coefficients taking into account the properties of materials, $\frac{m^2}{H}$; $R_1, R_2$ — averaged reduced radii of colliding bodies, m. Taking into account (9), we obtain the impact velocity of the waste components

$$\vartheta = \vartheta_0 \sqrt{1 - \frac{1}{3(\delta_1 + \delta_2)} \cdot \frac{R_1 R_2}{R_1 + R_2} \cdot \frac{1}{x^{5/2}}},$$  \hspace{1cm} (10)$$

Maximum value of elastoplastic deformation

$$x_{max} = \left[ 2.12 \frac{m \vartheta_0^2 (\delta_1 + \delta_2)}{R_1 R_2 (R_1 + R_2)} \right]^{2/5},$$  \hspace{1cm} (11)$$

Max contact force

$$P_{max} = \left[ 4 \frac{m \vartheta_0^2 (\delta_1 + \delta_2)}{3\pi (\delta_1 + \delta_2)} \cdot \frac{R_1 R_2}{R_1 + R_2} \right]^{7/5},$$  \hspace{1cm} (12)$$

The developed mathematical model (formulas (10)-(12) made it possible to determine the rational values of the design and technological parameters of machines that ensure the efficiency of the process of crushing the organic components of MSW.

When developing a mathematical model of the process of grinding MSW components due to impact on the walls of the crushing chamber, a number of assumptions were made:
- the movement of the components of the waste in the process of impact on the knives and rotor blades occurs in a plane parallel to the bottom of the crushing chamber;
- the movement of waste components in the axial direction is neglected.

One of the main parameters of the process of impact of the components of the waste, affecting the impact force, is the speed of impact of the components of the waste against the wall of the crushing chamber.

The design scheme for determining the main impact parameters is shown in Fig. 4.
The grinding of the components of the waste against the wall of the working chamber occurs due to the maximum value of the contact force, which in turn is determined by the normal component of the pre-shock

\[ \vartheta_n = k_1 \sigma_p \cos \beta, \]  

where \( \beta \) — angle between the pre-impact velocity vector and the normal to the impact surface of the components of the waste, degree.

From the first equation of the law of conservation of momentum in projections onto the normal, we obtain

\[ \vartheta_n^* = \frac{s_n}{m} - \vartheta_n = \frac{p_c'}{m} - k_1 \sigma_p \cos \beta, \]  

where \( P_c' \) - average value of the contact force, H; \( t \) - impact duration, sec.

Since the maximum value of the impact force is of great interest, the relationship between the average and maximum values of the impact force has the following form

\[ P_{cp}' = \frac{1}{2} \bar{P}_{max}(t/2) = \frac{1}{2} \cdot \frac{1.140k_2m(\vartheta_n^*)^2}{x_{max}} \cdot \sin \left( \frac{1.068\vartheta_n^*}{x_{max}} \right) \cdot \frac{\pi x_{max}}{2 \cdot 1.068\vartheta_n^*} = \frac{1.140k_2m(\vartheta_n^*)^2}{2x_{max}}, \]  

It is known that the impact duration is determined by the following dependence

\[ t = \frac{\pi x_{max}}{1.068\vartheta_n^*}. \]  

After substituting (15), (16) into (14) and after some simple transformations, we obtain

\[ \vartheta_n^* = \frac{2k_1\sigma_p \cos \beta}{1.1\pi k_2 - 2} = \frac{k_1\sigma_p \cos \beta}{0.55\pi k_2 - 1}, \]  

where \( k_2 \) - coefficient taking into account the deviation of the shapes of the components from the sphere.

Therefore, the value of the impact force of the constituent wastes on the wall of the working chamber of the crusher has the form
\[
\begin{align*}
P &= \frac{1.140m(\theta_n^*)^2}{x_{\text{max}}} \sin \frac{1.068\theta_n^* t}{x_{\text{max}}}, \quad 0 \leq t \leq \frac{\pi x_{\text{max}}}{1.068\theta_n^*} \\
P &= 0, \quad t > \frac{\pi x_{\text{max}}}{1.068\theta_n^*}, \tag{18}
\end{align*}
\]

An analysis of the obtained dependences (12) and (18) shows that the impact force depends on the impact velocity and inert properties of the material, as well as on the impact conditions. The data of a priori information and several conducted installation experiments made it possible to clarify the factors that significantly affect the performance of the crusher at fixed values of the above parameters:

- frequency of rotation of the rotor shaft, \( n_p \), rpm;
- light area of the grate, \( F_c \), cm\(^2\);
- rotor diameter, \( D_r \), cm.

In order to determine the interval of variation of factors, as well as ranking the factors by significance, a series of experiments were carried out.

**Fig.5.** Dependence of the performance of a hammer crusher on the drive power at different values of the rotor shaft speed: 1 - at a frequency of rotation of the rotor shaft equal to \( n_p = 1250 \) rpm; 2 - at a frequency of rotation of the rotor shaft equal to \( n_p = 1750 \) rpm; 3 - at a frequency of rotation of the rotor shaft equal to \( n_p = 1500 \) rpm.

Analysis of the graphs presented in Fig. 4 shows that when the drive power is equal in the range from 0.25 to 0.5 kW, there is a jamming of the rotor shaft due to lack of power to overcome the resistance forces that arise from the components of the waste, as well as to overcome the static resistance forces. It can be seen from the graphs that the highest performance value is achieved at a rotor shaft speed equal to \( n_p = 1500 \) rpm, which corresponds to the nominal speed of the rotor shaft of the electric motor. In addition, when the rotor shaft speed is equal to \( n_p = 1500 \) rpm, the minimum specific energy value.

At values of the rotational speed of the rotor shaft equal to \( n_p = 1750 \) rpm (line 3) and \( n_p = 1250 \) rpm (line 1) the crusher has a higher value of specific energy consumption. In addition, an increase in speed leads to a decrease in torque, as a result of which a decrease in the performance value occurs. At \( n_p = 1250 \) rpm (line 1), the waste components will not be able to acquire the speed value necessary for efficient grinding.
Fig. 6. Dependence of the hammer crusher productivity on the drive power at different values of the light area of the grate: 1- at values of the light area of the grate $F_c = 250 \text{ cm}^2$; 2- at values of the light area of the grate $F_c = 350 \text{ cm}^2$; 3- at values of the light area of the grate $F_c = 300 \text{ cm}^2$.

The best performance values coincide with the value of the light area equal to $F_c = 300 \text{ cm}^2$ (line 3). The reason for the relatively low performance value of the hammer crusher at $F_c = 350 \text{ cm}^2$ (line 2) due to the fact that the crushed waste begins to scatter in different directions, polluting the environment, and when installing an unloading device, the periphery of the inner part will be clogged with waste and the performance value will be low.

Fig. 7. Dependence of the hammer crusher performance on the drive power for various values of the rotor diameter: 1- at a value of the rotor diameter $D_r = 24 \text{ cm}$; 2- at a value of the rotor diameter $D_r = 27 \text{ cm}$; 3- at a value of the rotor diameter $D_r = 30 \text{ cm}$.

An analysis of the graphs presented in Fig. 6 shows that when $D_r = 30 \text{ cm}$ (line 3) crusher performance has the best values, this is due to the fact that at this value of the rotor diameter there is no influence of boundary conditions, i.e. there is a complete coverage of the array of waste located at the wall of the working chamber. Full coverage of the mass of waste allows you to achieve the maximum value. In the other two cases, there will be a mast effect of boundary conditions, when the mass of waste pressed against the wall will have zero speed,
which will result in a low productivity value. Based on the methods of theories of mathematical statistics, by preliminary distribution, taking into account the review and the results of single-factor experiments, the main factors determining the crushing process are established. The dependence of crusher performance on the main process parameters in an implicit form.

\[ Y = f(n_p, F_c, D_p), \]  \hspace{1cm} (19)

where \( n_p \) - number of revolutions of the rotor shaft, rpm; \( F_c \) - light area of the grate, cm\(^2\); \( D_p \) - rotor shaft diameter, cm; \( Y \) - crusher performance, kg/h.

The implicit relationship between optimization factors and parameters is as follows

\[ Y = a_0 + \sum a_i x_i + \sum a_{ij} x_{ij} + \sum a_i x_i^2, \]  \hspace{1cm} (20)

where \( Y \) - the value of the considered optimization indicator; \( x_i \) - encrypted value of factors (\( i = 1, 2, 3 \)); \( a_i \) - the value of the coefficient characterizing the contribution \( i \)th factor; \( a_{ij} \) - coefficient value, characterizing the interaction of factors.

The experiments were carried out according to the Box-Behnken plan. (\( B_3 \) [30], they take into account the complex interplay of factors. Box-Behnken plans are the best system, contain the least susceptibility of coefficient results. In addition, the variation of factors at three levels provides the necessary accuracy of the results at the smallest points of the plan. To control the feasibility of the experiments, to evaluate the hypothesis about the closeness of the values of the variances with the same repetitions, the Cochran test was used, and the role of the empirical coefficients of the regression equation was evaluated using the Student's test with an accuracy of 0.05. The ability to represent the response surface quite well, i.e. the conformity of the accepted model was checked by standard methods.

\[ F_{pac} < F_{tabl}, \]  \hspace{1cm} (21)

Table 1 shows the factors with their levels, as well as their ranges.

**Table 1. Levels of factors and ranges of their change**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Code</th>
<th>Factor levels</th>
<th>Range.</th>
<th>Size.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of revolutions of the rotor shaft</td>
<td>( X_1 )</td>
<td>(-1), ( 0 ), (+1)</td>
<td>( 125, 0, 0 ), ( 150, 0, 0 ), ( 1750, 0 ), ( 250, 0 )</td>
<td>rpm</td>
</tr>
<tr>
<td>Luminous area of the grate</td>
<td>( X_2 )</td>
<td>(-1), ( 0 ), (+1)</td>
<td>( 250, 0 ), ( 300, 0 ), ( 350, 0 ), ( 50 )</td>
<td>cm(^2)</td>
</tr>
<tr>
<td>Rotor shaft diameter</td>
<td>( X_3 )</td>
<td>(-1), ( 0 ), (+1)</td>
<td>( 24, 0 ), ( 27, 0 ), ( 30 ), ( 3 )</td>
<td>cm</td>
</tr>
</tbody>
</table>

Following the production of experimental data and checking the importance of the regression coefficients, a mathematical model of the performance of a prototype crusher was obtained.

\[ Y = 89,2 + 7,4X_1 - 3,4X_2 + 2,7X_3 - 3,3X_1^2 - 2,4X_2^2 + 1,8X_3^2, \]  \hspace{1cm} (22)

Evaluation of the model's compliance by the Fisher criterion showed that with 95% truth, the mathematical model is
To find the best values of the factors, equation (22) was investigated for a maximum, the result of which is given in Table 2

Table 2. Rational values of factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>X₁, mm</th>
<th>X₂, angle</th>
<th>X₃, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coded</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>Natural</td>
<td>1500,0</td>
<td>300</td>
<td>30</td>
</tr>
<tr>
<td>Rounded</td>
<td>1500,0</td>
<td>300</td>
<td>30</td>
</tr>
</tbody>
</table>

Therefore, the best values for the main crusher parameters are:
- frequency of rotation of the rotor shaft
  - \( n_r \approx 1500 \text{ rpm} \);
- light area of the grate
  - \( F_c \approx 300 \text{ cm}^2 \);
- rotor diameter
  - \( D_r \approx 30 \text{ cm} \).

4 Conclusions

1. A mathematical model has been developed that makes it possible to determine the rational values of the design and technological parameters of machines that ensure the efficiency of the process of crushing municipal solid waste.
2. The rational parameters of the impact crushing machine are substantiated:
   - crusher rotor shaft speed
     - \( n_r \approx 1500 \text{ rpm} \);
   - light area of the grate
     - \( F_c \approx 300 \text{ cm}^2 \);
   - rotor diameter
     - \( D_r \approx 30 \text{ cm} \).
3. Using the methods and methods of the theory of similarity and modeling, it is possible, based on the initial data on the values of the volumes of accumulations of MSW, to select a crusher with an appropriate performance with rational values of the main parameters.

References

24. T. Khankelov, et.al., European science review.-Vienna, 2019, 1-2. 80-82.