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ANALYSIS AND ASSESSMENT OF THE PRODUCTIVITY OF JACK AND CONE CRUSHERS DEPENDING ON THE FREQUENCY OF REVOLUTION OF THE WORKING BODIES

ABSTRACT. *The development of the construction industry today is not possible without the participation of energy-efficient machines and equipment. A key role among such machines is occupied by crushing machines, which include jaw, cone, roller, vibrating and impact crushers. The main determining parameters of the energy efficiency of a crushing machine, which at the same time complement each other, are power and productivity. The impact of productivity on energy costs is obvious. There are various approaches to determining productivity, but today there is no systematic analysis of such methods and approaches that could indicate similar and different patterns of the processes of material destruction by the working bodies of crushing machines. The paper considers methods for determining the productivity of jaw and cone crushers. The frequency of oscillations of the working bodies of crushing machines has a significant impact on productivity. Graphs of the dependence of productivity on the frequency of oscillations of the working bodies of crushing machines are presented, which allow a better understanding of the characteristics of productivity changes. A general equation is proposed for determining the productivity of a jaw crusher, which should include functional dependencies on the relevant parameters. The conclusions identify the shortcomings of existing methods for determining productivity and suggest directions for further research.*

Keywords: *crusher, energy efficiency, productivity, oscillation frequency, degree of crushing.*

АНАЛІЗ І ОЦІНКА ПРОДУКТИВНОСТІ ЩОКОВИХ ТА КОНУСНИХ ДРОБАРОК ЗАЛЕЖНО ВІД ЧАСТОТИ ОБЕРТІВ РОБОЧИХ ОРГАНІВ

АНОТАЦІЯ. *Розвиток будівельної галузі на сьогодні не можливий без участі енергоефективних машин та обладнання. Ключову роль серед таких машин займають дробильні машини до яких відносяться щокові, конусні, валкові, вібраційні та ударні дробарки. Головними визначальними параметрами енергоефективності дробильної машини, які одночасно із цим доповнюють один одного, є потужність та продуктивність. Вплив продуктивності на енергозатрати є очевидним. Існують різні підходи до визначення продуктивності, проте на сьогодні відсутній системний аналіз таких методів та підходів, який міг би вказати на подібні та відмінні закономірності процесів руйнування матеріалів робочими органами дробильних машин. В роботі розглянуто методи визначення продуктивності щокових та конусних дробарок. Значний вплив на продуктивність має частота коливань робочих органів дробильних машин. Наведено графіки залежності продуктивності від частоти коливань робочих органів дробильних машин, які дозволяють краще зрозуміти характеристику зміни продуктивності. Запропоноване загальне рівняння для визначення продуктивності щокової дробарки, яке повинно включати функціональні залежності по відповідним параметрам. У висновках встановлено недоліки існуючих методик визначення продуктивності та запропоновано напрямки подальших досліджень.*

Ключові слова: *дробарка, енергоефективність, продуктивність, частота коливань, степінь дроблення.*

1. Problem Statement. The development of the construction industry today is not possible without the participation of energy-efficient machines and equipment. A key role among such machines is occupied by crushing machines, which include jaw, cone, roller, vibrating and impact crushers. The main determining parameters of the energy efficiency of a crushing machine, which at the same time complement each other, are power and productivity. The issue of energy consumption lies in the field of determining the minimum energy required for the destruction of material in the crushing chamber [9],[10]. In addition, in research and creation of methods for applying load in order to minimize energy consumption. One of such areas is the selective disintegration method [11],[12]. The impact of productivity on energy consumption is obvious. There are different approaches to determining productivity, but today there is no systematic analysis of such methods and approaches, which could indicate similar and different patterns of the processes of destruction of materials by the working bodies of crushing machines.

2. Review of Recent Studies and Publications. In work [1], in parallel with the study of energy consumption in crushing machines, the productivity is determined as a mass balance depending on the inlet and outlet. That is, the influence of the material feed parameters and individual crusher parameters on energy efficiency is established. The work defines three types of crushing machines: jaw crusher, vertical shaft impact crusher and high-pressure roller crusher. The influence of the crusher outlet and material feed rate on productivity is considered in more detail. An analysis of the influence of the crushing process parameters on productivity is performed in work [2], however, this work does not currently take into account the design features of modern crushing equipment. In works [3] and [4], the maximum productivity of a jaw crusher is considered based on an empirical dependence to determine the critical rotation speed. In work [5], an assessment and analysis of crushing machines based on mechanical mode parameters, which include productivity, is performed. However, the work does not determine the functional influence of machine, process and working environment parameters on productivity.

3. Purpose of work. Analysis of approaches and methods for determining the productivity of cone and jaw crushers. Assessment of the influence of the frequency of rotation of the crusher working elements on their productivity.

4. Materials and methods. The main materials for the analysis are scientific, technical and reference literature on domestic and foreign samples of modern crushing equipment. The main methods used in the work are the use of mathematical analysis in calculating the parameters of the mechanical mode of crushing machines. To perform calculations and plot graphs, software was used Wolfram Mathematica.

5. Results.

Analysis of methods for determining the productivity of jaw crushers. Let us consider methods for determining the productivity of jaw crushers. In general, the productivity of a jaw crusher can be written as a dependence on a number of the following parameters:

$$\Pi = \left(n, L, S, d, \alpha, \mu, i\right), \tag{1}$$

where n – frequency of oscillation of the moving cheek, oscillations/time period; L – length of the crushing chamber of the crusher, m; S – movement of the movable cheek, m; d – average size of the crushed product, m; α – angle of capture; μ - the coefficient of loosening of the mass of material that fell out of the crusher outlet slot; i – degree of crushing.

There are several different approaches to determining the productivity of a jaw crusher. The classic approach states that the productivity of a jaw crusher is determined by the condition that for each jaw movement or one rotation of the main shaft, a finished product in the form of a prism of trapezoidal cross-section is discharged from the crushing chamber. In the source [6], in the case of n complete swings of the moving jaw in 1 s, the crusher productivity is determined as follows, m^3/sec:

$$\Pi_1 = \frac{3600 nLSd\mu}{tg\alpha}, \tag{2}$$

The average crushing product is determined based on the following relationship:

$$d = \frac{d_{max} + d_{min}}{2} = \frac{2e + S}{2}, \tag{3}$$

where e – width of the discharge opening.

An important role in the productivity of the crusher is played by the speed of movement of the movable jaw, for which there is a specific optimal range. If the rotation frequency significantly exceeds some optimal value, then the piece of material will not have time to fall out of the crusher and will repeatedly contact the crushing plates. Under the condition that the rotation frequency is less than the required optimal value, the speed of movement of the pieces through the crushing chamber will decrease. This, in turn, can lead to clogging of the crushing chamber and, accordingly, a decrease in productivity.

The rotational speed of the eccentric shaft is determined from the condition that during the deflection $t_{від}$ movable cheek at a distance S under the action of gravity over time $t_{вип}$ pieces of crushed material fall out, having a height of h.

Based on the above, we can write:

$$\omega = \frac{\pi}{\sqrt{\frac{2S}{gtg\alpha}}} , \tag{4}$$

where g – acceleration of free fall, м/с.

Considering that ω=2πn and α = 20^0 we will get:

$$n = \frac{0,707}{\sqrt{S}} , \tag{5}$$

Formula (4) does not take into account the influence of friction forces on armor plates during material movement, therefore the value of the speed is taken 5-10% lower. Formula 5 is suitable for determining the speed of small and medium crushing crushers. For large crushers, the speed is taken lower due to the occurrence of significant dynamic loads that occur during the operation of large crushers. For this purpose, the coefficient is introduced into dependence (5) k=0,6…0,75.

In the source [7] it is proposed to determine the productivity of a jaw crusher taking into account the factor that the material unloading can occur not only when the crushing jaw departs, but also when it approaches the stationary jaw. Based on this, the following dependence was proposed:

$$\Pi = \frac{Vn}{n_1} , \tag{6}$$

where V – crushing chamber volume, m^3; n – number of revolutions of the eccentric shaft; n_1 – the number of revolutions of the eccentric shaft of the crusher, during which one volume of the entire crushing chamber is unloaded.

Expanding the terms of dependence (6), the formula for determining productivity will have the following form, m^3/sec:

$$\Pi = \frac{KcSLL_{max} n\left(B + L_{max}\right)}{2Btg\alpha} , \tag{7}$$

where K – coefficient that takes into account the size of the crusher and depends on the size of the loading hole; c – kinematics coefficient, which takes into account the nature of the trajectory of the moving cheek; L_{max} – the largest width of the discharge opening, m; B – loading opening width.

The productivity of crushers calculated on the basis of dependencies (2) and (7) may differ significantly from the actual data, since they do not take into account the influence of the intensity and uniformity of the machine power supply, the shape and size of the crushing plates and their operation. Additionally, it should be noted that the coefficients μ, K, c contribute their share of uncertainty, since on the one hand they have a wide range of changes, and on the other hand the ranges of coefficient values were adopted on the basis of studies of domestic samples of crushing machines, which have differences in comparison with modern foreign samples.

Considering the influence of the eccentric shaft rotation frequency in formulas (2) and (5), it is linear. Based on the linear dependence, it is difficult to analyze a qualitative picture of the optimal range of change in the eccentric shaft oscillation frequency.

An equally important parameter is the angle of engagement. Different sources give different optimal values for the angle – $\alpha=19^0$ or $\alpha=20^0$. With an increased gripping angle, the crusher's productivity decreases. Reducing the gripping angle has no significant effect on productivity. An analysis of the influence of the gripping angle on the operation of a vibrating jaw crusher is considered in the source [8].

Next, we will consider approaches to determining productivity based on foreign research. Thus, in [13] the following dependence is proposed for determining the productivity of a jaw crusher:

$$\Pi = 59.8\left[\frac{S\left(2L_{min}+S\right)LBn\rho K}{\left(B-L_{min}\right)}\right], \qquad (8)$$

where L_{min} – minimum size of the crusher outlet gap; ρ – density of the destructible material.

Dependence (8) according to a number of authors [14] is acceptable when determining the productivity in the destruction of soft rocks. The search for a universal method for determining productivity led to the consideration of productivity depending on the time and distance that a particle must travel between two opposite surfaces of the working bodies of crushing machines [15]. The maximum particle size will be determined based on the maximum distance between the surfaces of the working bodies in the lower part of the crushing chamber. In turn, the speed of lowering the particle to the unloading gap of the crusher will depend on how often the surfaces of the working bodies of the crusher will approach and move away from each other. Fig. 1 shows a calculation scheme for determining productivity. In this case, the following statement is accepted if n_c – number of cycles per minute, then the time of one cycle per second will be $60/n_c$, in turn, half of the cycle during which the moving cheek moves away from the fixed cheek will be - $60/2n_c$.

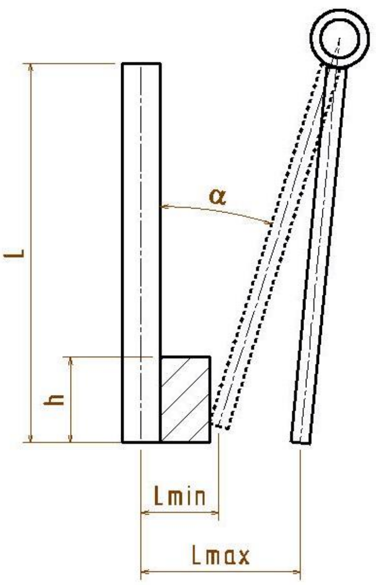


Рис. 1. Розрахункова схема до визначення продуктивності

Fig. 1. Calculation scheme for determining productivity

Thus, the distance that the material will travel in the crushing chamber will be:

$$h = \frac{1}{2} g \left(\frac{30}{n_c}\right)^2 = \frac{4414.5}{n_c^2}, \qquad (9)$$

Then the oscillation frequency

$$n_c = \frac{66.4}{\sqrt{h}} \ , \qquad (10)$$

Thus, for the movement of material in the crushing chamber in the direction of unloading, a necessary condition is that the frequency of oscillation of the jaws does not exceed the frequency determined by the relationship (10). The distance h can be determined from the angle of engagement as follows, Fig. 1:

$$h = \frac{\left(L_{max} - L_{min}\right)}{tg\alpha} \ , \qquad (15)$$

Here it is necessary to mention one more characteristic of the operation of the jaw crusher. It turns out that at a low frequency of oscillation of the crushing jaw, the productivity is directly proportional to the frequency of oscillation up to some optimal value, on the basis of which the formula for determining the productivity has the form [16]:

$$П_Н = 3600 S n_c L \left(2L_{min} + S\right)\left(\frac{i}{i-1}\right), \qquad (16)$$

where $S=L_{max}-L_{min}$ – difference between the maximum and minimum outlet clearance values; i = B/e – the reduction ratio of the material size after it passes through the crushing chamber.

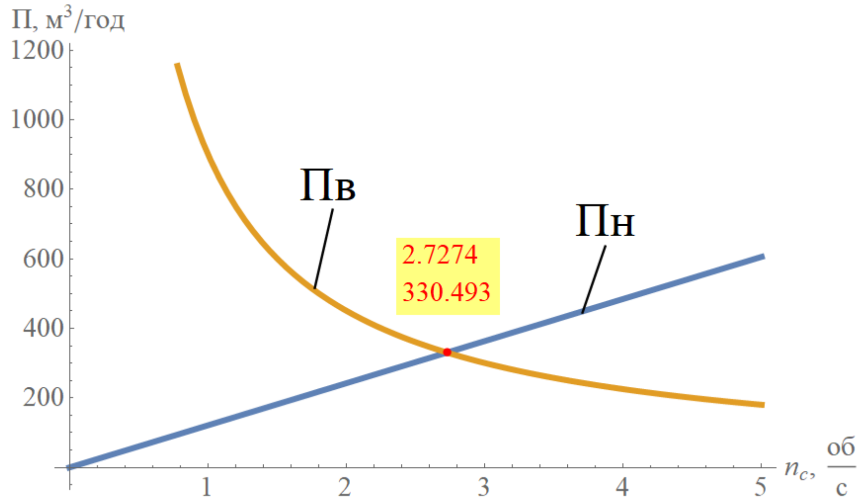


Рис. 2. Графік залежності частоти обертів ексцентрикового валу від продуктивності щокової дробарки на основі залежностей (16) та (17)
Fig. 2. Graph of the dependence of the eccentric shaft speed on the productivity of the jaw crusher based on the dependencies (16) and (17)

However, at significant frequencies of oscillation of the crushing jaw, it was found that the productivity becomes inversely proportional to the frequency of oscillation. Based on which, the dependence (16) is written as follows:

$$П_В = 1606 L \left(2L_{min} + S\right)\left(\frac{1}{n_c}\right), \qquad (17)$$

Thus, the dependencies (16) and (17) make it possible to establish the optimal range of oscillation frequency of the moving jaw of the jaw crusher. For example, let's take the Metso C120 jaw crusher with the following parameters – S = 0.0245 м, L=1.2 м, L_{min} = 0.1505 м, i=4,65. Using dependencies (16) and (17) and the determined parameter values, we will construct the corresponding graph, fig.2.

Analyzing graph 2, it can be noted that a certain optimum speed for the Metso C120 jaw crusher will be within the point n_c = 2.72 rpm. Based on the above statements, it can be assumed that in this case the performance will decrease if the oscillation frequency is exceeded, i.e. the value n_c = 2.72 rpm. Based on the real picture of the operation of crushing machines, it can be concluded that the optimal speed of large-sized jaw crushers and jaw crushers with a simple jaw movement lies approximately within the limits indicated in the graph, Fig. 2. However, for jaw crushers with a complex jaw movement and which at the same time have small dimensions, the optimal speed is somewhat higher. Among the features of the method for calculating productivity according to dependence (17), the following can be noted - the angle of engagement is increased to 45 degrees, based on the fact that the jaw, as stated in the source [16], can significantly change the angle during the crushing of the material.

Based on the dependencies (16) and (17), the formula for determining the optimal rotational speed of the eccentric shaft is written as:

$$n_c = 47\sqrt{\frac{\left(\frac{i-1}{i}\right)}{S}} \ . \quad (18)$$

Considering the real values of the parameters of the recommended rotational speed of the eccentric shaft of the Metso C120 crusher, which is equal to n_c = 230 rpm = 3,83 rps and based on the specified maximum performance, it can be concluded that the graph 2 reflects a slightly shifted optimum point. This can be explained by the fact that dependencies (16) and (17) do not take into account additional process parameters. For example, during the passage of the crushing chamber, the bulk density of the material is constantly changing. In turn, dependency (2) takes into account the bulk density using the loosening coefficient, but this value is constant. In addition, dependency (7) takes into account the crusher size coefficient and its kinematics coefficient, which also affect the optimal productivity value.

In addition to the main parameters that are included in the dependences (16) and (17) on the productivity of the jaw crusher, the following additional parameters have an impact: 1) the distribution of material particles over the volume of the crushing chamber (packing characteristics); 2) the physical properties of the rock (strong, brittle, viscous rocks, etc.); 3) the bulk density of the material; 4) the geometry of the particle surface and the surface of the crushing plate. Based on these parameters, the general expression for determining the productivity of the jaw crusher will have the following form:

$$\begin{aligned}\Pi_з &= 60SL\left(2L_{min}+S\right)\left(\frac{i}{i-1}\right)47\sqrt{\frac{\left(\frac{i-1}{i}\right)}{S}}\rho f\left(x_1\right)f\left(x_2\right)f\left(x_3\right) = \\ &= 2820\sqrt{S\left(\frac{i-1}{i}\right)}L\left(2L_{min}+S\right)\rho f\left(x_1\right)f\left(x_2\right)f\left(x_3\right)\end{aligned}, \quad (19)$$

where ρ – density of a particle of material; $f(x_1)$ – function of distributing material particles throughout the volume of the crushing chamber; $f(x_2)$ – surface function of material particles; $f(x_3)$ – function of the surface geometry of the crushing plate.

In general, similar transformations based on direct and inverse proportionality between the frequency of oscillation of the crusher jaw and productivity can be performed for dependence (2). In this case, the inversely proportional form of formula (2) will be as follows:

$$\Pi_2 = \frac{4414.5Ld\mu}{n} \ . \quad (20)$$

Similarly to the graph in Fig. 2, we construct a graph of the dependence of productivity on the frequency of oscillations of the movable jaw of the crusher based on expressions (2) and (20). The determined parameters for the C120 crusher remain the same.

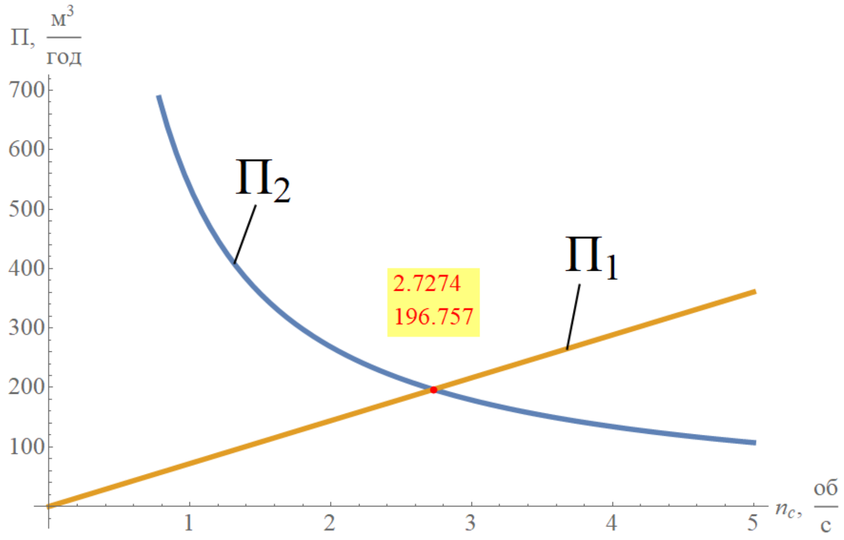


Рис. 3. Графік залежності частоти обертів ексцентрикового валу від продуктивності щокової дробарки на основі залежностей (2) та (20)
Fig. 3. Graph of the dependence of the eccentric shaft speed on the productivity of the jaw crusher based on the dependencies (2) and (20)

As can be seen from the graph of Fig. 3, the productivity value is closer to the productivity of the real C120 crusher compared to the graph of Fig. 2. However, the optimal speed in both graphs is the same. Again, the difference in productivity lies in the presence in formula (2) of the material loosening coefficient and the parameter of the weighted average size of the material. It should also be noted that the angle of engagement was taken equal to 20 degrees. In general, it can be noted that the dependences (2) and (20) still give inflated productivity values compared to their real values.

An excellent approach to determining the productivity of a jaw crusher relative to those considered above is given in the source [17]. This approach consists in taking into account the coefficient of reduction of the size of the material and additionally the coefficients of the process conditions. When the material enters the crushing chamber, some of it may be smaller than the output size of the CSS crusher. That is, this part of the material is almost not destroyed and simply passes through the crushing chamber. In turn, reducing the maximum size of the input material will lead to an increase in the amount of material, the dimensions of which are smaller than the CSS crusher. Taking into account the above in the source [17], [18] the following dependence was proposed for determining the productivity:

$$П_T = П \times i_{80}, \tag{21}$$

where П – crusher performance; $П_T$ – crusher performance based on the degree of material destruction; $i_{80} = K_{in80}/K_{out80}$ – material size reduction ratio based on 80% feed screen pass and corresponding crushing product.

To take into account the physical properties of different materials, the corresponding coefficients were additionally introduced into the dependence (21). Thus, the dependence (21) will take the following form:

$$П_T = П i_{80} k_p k_в k_ж, \tag{22}$$

where k_p – coefficient that characterizes the fracture properties of a material; $k_в$ – coefficient that takes into account moisture content; $k_ж$ – coefficient that characterizes power conditions.

In sources [19] and [20], the productivity of a jaw crusher is determined based on the gravitational flow of material through the open space of the crushing chamber, t/h:

$$\Pi = \frac{7.037 \times 10^5 Lk\left(L_{min} + S\right)}{v}, \tag{23}$$

where k – cheek geometry coefficient (k = 0.18-0.3 – for a straight cheek profile, k = 0.32-0.45 – for curved cheek profile). Dependence (23) is valid for a material with a specific density 2,65 kg/m^3.

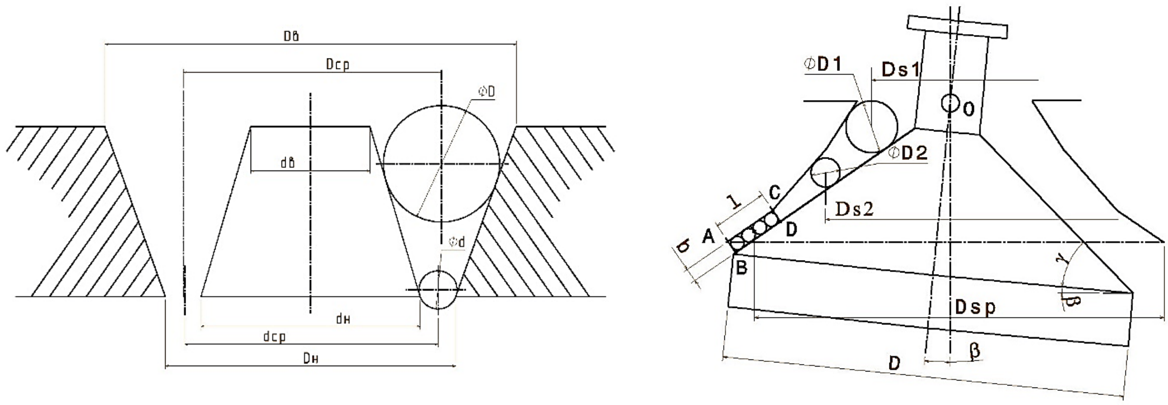
Returning to the optimal speed of rotation of the eccentric shaft in the source [21], problems were identified with the dependence (18), which assumes underestimated speed values when the gap of the crusher inlet is too large or too small. Based on which the following empirical dependence was proposed:

$$v = 280e^{\left(-0.212B^3\right)} \pm 20\%, \tag{24}$$

Thus, we see that the productivity of a jaw crusher depends on a significant number of parameters and today the methods for calculating productivity still include empirical dependencies. For further research, I see a scientifically sound basis for the approach implemented on the basis of (2) taking into account the functions that include dependency (19).

Analysis of methods for determining cone crusher performance. The main parameters of cone crushers are: 1) angle of engagement; 2) rotational speed of the moving cone; 3) productivity; 4) power; 5) crushing force.

Due to the peculiarities of the movement of the inner cone relative to the outer cone and the design features, the calculation of the crushing force of a coarse-crushing cone crusher differs from the calculations of the crushing force of medium- and fine-crushing cone crushers. Fig. 4 shows the calculation diagram of a cone crusher.



а (a) б (b)

Рис. 4. Розрахункова схема конусної дробарки до визначення її продуктивності:
а – схема до розрахунки об'єму матеріалу конусної дробарки крупного дроблення; б – схема до розрахунки об'єму матеріалу конусної дробарки середнього та мілкого дроблення

Fig. 4. Calculation scheme of a cone crusher before determining its productivity:
a – scheme for calculating the volume of material for a cone crusher for coarse crushing; b – scheme for calculating the volume of material for a cone crusher for medium and fine crushing

The volume of the input material pieces is the sum of the material particles with diameter D, which are placed along the length of a circle with a diameter equal to the average diameter of the loading annular opening D_{cp}. In turn, the volume of the starting material is calculated based on the average diameter of the crushing product. d_{cp}, which is placed along the length of the circle of the discharge annular opening. Then for the volume of material of the coarse crushing crusher we can write the following dependence, fig.4, a [7]:

$$V = \frac{\pi D^3}{6}\frac{\pi D_{cp}}{D} - \frac{\pi d^3}{6}\frac{\pi d_{cp}}{d}. \quad (25)$$

Medium and fine cone crushers differ from coarse cone crushers in the profile of the crushing chamber, i.e. they have a smaller discharge gap and an increased length of the parallel crushing zone.

During one revolution of the eccentric cup, the material passes through a parallel zone of the crushing chamber. Then, during one revolution, the crusher will produce a finished product with a volume of:

$$V = \pi D_{sp} lb, \quad (26)$$

Dependence (26) does not take into account the difference in the sizes of the input and output material, as well as the number of individual particles in each layer. Therefore, expression (30) for the volume of the material can be rewritten as follows, fig.4, b:

$$\Delta V = \frac{\pi D_1^3}{6}N_1 + \frac{\pi D_2^3}{6}N_2 - \frac{\pi d^3}{6}N_3, \quad (27)$$

where D_1, D_2, d – diameters of pieces of material in the upper zone and the parallel zone, m; N_1,N_2,N_3 – number of pieces of material placed in the first and second rows and in the parallel zone. Expressing N in terms of the ratio of the lengths of the corresponding circles and the diameters of the crushed pieces, we have:

$$\Delta V = \frac{\pi D_1^3}{6}\frac{\pi D_{s1}}{D_1} + \frac{\pi D_2^3}{6}\frac{\pi D_{s2}}{D_2} - \frac{\pi d^3}{6}\frac{\pi D_s}{d}\frac{l}{d}. \quad (28)$$

Since there are differences in the designs of cone crushers for coarse crushing (gyration cone crushers) and cone crushers for medium and fine crushing, the determination of productivity according to individual methodologies is somewhat different. Thus, in work [7] for gyratory cone crushers, productivity is determined as follows:

$$П_{к.г.1} = \frac{3600\pi D_{cp} 2r(e+r)n\mu}{tg\alpha_1 + tg\alpha_2}, \quad (29)$$

where α_1 and α_2 – respectively, the angles generated by the fixed and moving cones with the vertical, degree; D_{cp} – average diameter of the crushed stone ring, m; e – size of the crusher discharge gap with the cones close together, m; n – number of revolutions of the inner cone, s^{-1}; μ – finished product fluffing coefficient, μ = 0,35…0,5; r – eccentricity of the vibrations of a moving cone, m.

The calculation of productivity according to the dependence (29) is based on the fact that during one complete oscillation of the moving cone a certain volume of crushed stone falls out of the crusher. The frequency of oscillations of the moving cone is determined on the basis that half the time of the complete oscillation of the moving cone should be equal to the time of falling out of pieces of a certain height from the crushing chamber. Then the optimal angular velocity will be equal to:

$$\omega = 4{,}9\sqrt{\frac{tg\alpha_1 + tg\alpha_2}{r}}, \quad (30)$$

In dependencies (29) and (30) there are parameters that are difficult to determine, so the following values can be taken for them. So, the sum of angles α_1 and α_2 should not exceed the limits of 21…23 degrees. The value of eccentricity can be taken based on the dependency – r = (0,01…0,02)B, where B is the width of the loading hole.

Next, we transform the dependence (30) in such a way as to obtain an inversely proportional dependence of the productivity on the frequency of oscillations of the moving cone. In this case, we can write:

$$\Pi_{к.г.2} = \frac{4410\pi D_{ср}\left(e+r\right)\mu}{n}, \qquad (31)$$

For the analysis, we will use the Kubria G150 cone crusher model with the following parameters: $\alpha_1=11^0$, $\alpha_2=18^0$, $D_{cp}=1.5425$ m, r=0.0075 m, e=0.035 m, B=0.5 m, μ=0.4.

The graph of the dependence of productivity on the rotational speed of the moving cone is shown in Fig. 5. The optimal rotational speed of the moving cone for the Kubria G150 cone crusher is 6.512 rps = 390 rpm. However, it is known that in cone crushers for coarse crushing, the range of speed changes is within 100-300 rpm, most cone crushers for medium and fine crushing operate at frequencies that do not exceed 500-800 rpm. The limitation of speed is associated with many negative effects, such as the imbalance of the significant oscillating mass of the moving cone, which requires a significant increase in the foundation, the danger of the moving cone shaft jamming in the eccentric at idle, and a decrease in the reliability of the lower support of the moving cone.

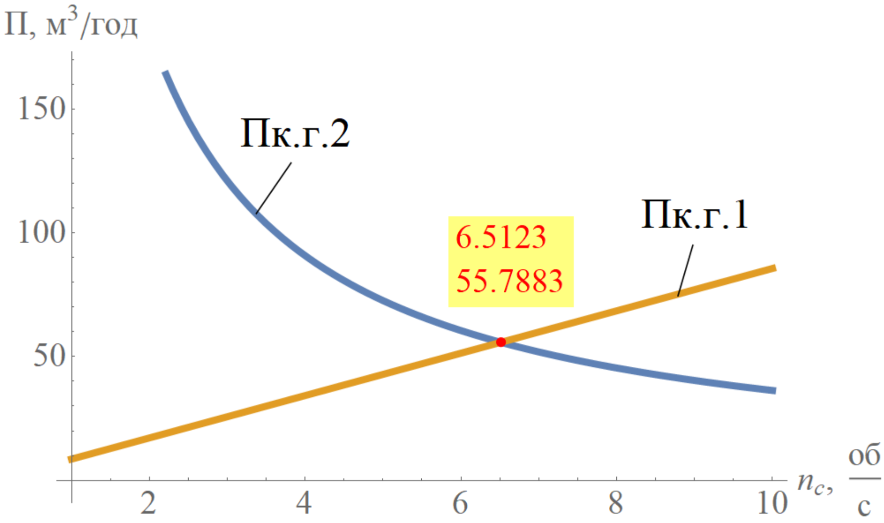


Рис. 5 Графік впливу частоти обертів рухомого конуса на продуктивності конусної дробарки крупного дроблення
Fig. 5 Graph of the influence of the speed of the moving cone on the performance of the coarse crushing cone crusher

It is worth noting the underestimated productivity values with a direct proportional dependence on the speed. For example, for the Kubria G150 crusher, according to the technical characteristics, the maximum productivity is 750 t/h, which at a bulk density of the material of 1.6 t/m^3 will be 468.75 m^3/h. That is, a more realistic picture of productivity is reflected by the inversely proportional dependence. However, in the inversely proportional dependence, inaccuracy is introduced by the productivity values in the vicinity of zero values of the speed. In addition, in dependences (29) and (31), significant uncertainty is introduced by the material loosening coefficient μ, which varies within wide limits.

For medium and shallow cone crushers, the rotational speed of the eccentric cup or the number of oscillations of the moving cone are determined based on the dependence:

$$n \geq 7.5\sqrt{\frac{\sin\gamma - f\cos\gamma}{2l}}, \qquad (32)$$

where γ – angle of inclination of the surface of the crushing cone to the horizon; f – coefficient of friction of crushed stone by material, f=0.36; l =1/(12D)– length of parallel zone for medium crushing cone crushers; D – diameter of the base of the moving cone. In medium and shallow cone crushers, the angle γ >45 degrees.

The productivity of medium and fine crushing crushers will be as follows [10]:

$$\Pi_{к.с.1} = 3600\mu\pi D_{ср} lbn \;, \tag{33}$$

where b – width of parallel zone, m; μ =0.45 – finished product fluffing coefficient.

As an example, let's take the Metso HP400 cone crusher, which has the following parameters: $D_{ср}$ = 1.32 m; b=0.03 m; l = 0.0631 m; μ = 0.45; $\gamma=50^0$, f=0.36.

Productivity in the case of inverse proportionality will have the following form:

$$\Pi_{к.с.2} = \frac{101250\mu\pi D_{ср} b(\sin\gamma - f\cos\gamma)}{n} \;, \tag{34}$$

The graphical dependence of productivity on the speed of rotation for the Metso HP400 cone crusher is presented in Fig. 6.

Based on the graph in Fig. 6, it can be noted that the optimum point is overestimated for this crusher. Thus, the Metso HP400 cone crusher at a speed of 6.9 rps, has productivity 393.75 m^3/h. Thus, the dependences for determining the productivity of cone crushers, similarly to jaw crushers, do not take into account additional parameters that have an impact on the crushing process. In general, the angle of inclination of the straight line in the graphs of Fig. 5 and Fig. 6 should be greater, which will reflect the real picture of the process. After passing the optimum point, the productivity will begin to decrease in an inversely proportional relationship.

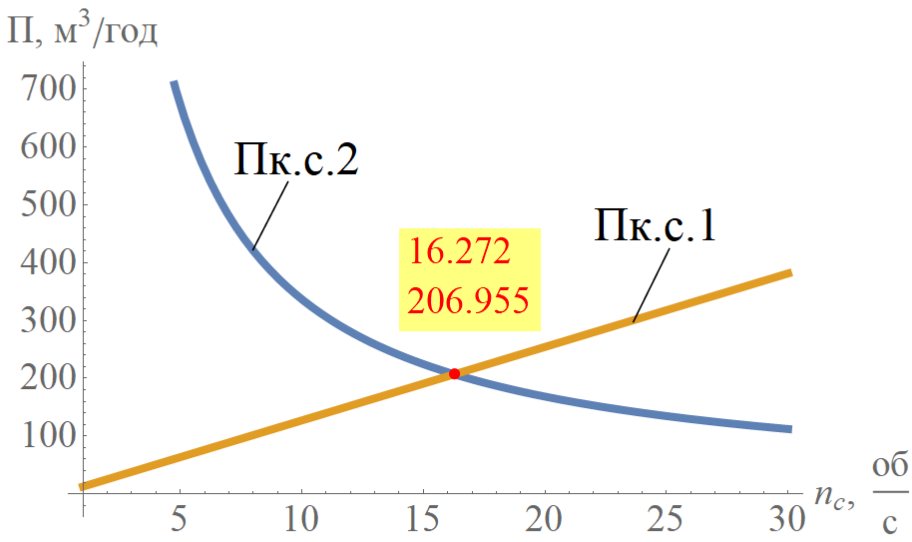


Рис. 6 Графік впливу частоти обертів рухомого конуса на продуктивності конусної дробарки середнього дроблення

Next, we will consider other approaches to determining the productivity and speed of the moving cone. In [22] it is noted that the speed of rotation of the moving cone of a coarse crushing cone crusher is inversely proportional to the size of the feed material:

$$n \geq \frac{665(\sin\gamma - f\cos\gamma)}{\sqrt{d}} \;, \tag{35}$$

where d – input material size, cm.

Determining the performance of a coarse crushing cone crusher in works [14], [15] is proposed as follows:

$$\Pi_k = 0.35\pi \sin\gamma \left(L_{max} + L_{min}\right) gH \left(\sin\gamma - f\cos\gamma\right)^{0.5} , \quad (36)$$

where H – crushing chamber height; L_{max} , L_{min} – maximum minimum unloading distance between the moving cone and the fixed one.

In general, dependence (36) is similar to dependences (29) and (33). In the source [16], an approach to determining productivity is considered similar to that used in jaw crushers. That is, the cross-section of the material layer and the time for which this layer passes the crushing chamber are considered. The dependence is written in the following form:

$$\Pi_b = \frac{\left(D_{зк} - L_{min}\right)\pi L_{min} S60nk}{\tan\alpha} , \quad (37)$$

where $D_{зк}$ – outer diameter of the fixed cone at the point of unloading, m; S – cone stroke length at the unloading point, m; L_{min} – minimum outlet size, m; n- number of revolutions of the moving cone, rpm; k – constant that defines a material characteristic, k=2…3; α – angle of capture.

Another approach to determining the productivity of a cone is considered in [17], which is based on taking into account the Bond work index. The dependence itself has the following form:

$$\Pi_{ip} = \frac{W_i D\rho_m \sqrt{\left(L_{max} - L_{min}\right)}\left(L_{max} + L_{min}\right)k}{2\sqrt{\frac{i}{i-1}}} , \quad (38)$$

where W_i – Bond work index; D – diameter of the bowl in a given cross-section; k – statistical coefficient (k=0.5 – for soft materials, k=1 – for solid materials).

The determination of productivity based on correction factors is discussed in the source [18]. The dependence for determining productivity has the following form:

$$\Pi_м = k_1 k_2 k_3 k_4 D^2 enL_{max} , \quad (39)$$

where k_1 – coefficient, for efficiency k=0.6; k_2 k_3 k_4 – coefficients that take into account feed size, hardness and moisture content of the material; D – diameter of the base of the moving cone; e - lower eccentricity of the axis of the moving cone, m; L_{max} – width of the discharge opening on the open side, m.

6. Discussion. From the analysis and evaluation of various methods for determining the productivity considered in the work, it can be noted that in many cone crushers the process of destruction of large pieces of material occurs when a moving cone applies a load cyclically, after which the material undergoes destruction. A similar situation is observed in jaw crushers. This can be explained by the geometry of the crushing chamber, the kinematic features of the crusher, the physical properties of the material and the uniformity of the material placement in the space of the crushing chamber. In turn, the angles of engagement in the lower zone of the crushing space and the curvilinear profile in the lower part of the crushing chamber have a smaller impact on the productivity, the change of which does not lead to a significant increase in the productivity of the crusher. The angular velocity of the eccentric shaft has a significant impact on the productivity of the crusher. However, the speed of the eccentric shaft is limited due to the design features of the crushing machines.

7. Conclusions. Most of the considered methods for determining the productivity of cone crushers, similarly to jaw crushers, do not take into account the distribution of material in the crushing chamber, the geometry of the material and crushing plates, and the physical characteristics of the material. The absence of these parameters in many dependencies is compensated by the introduction of appropriate correction factors, which cannot fully characterize the process of material destruction within a wide range of its changes.

When using the above-mentioned dependencies to determine productivity, there is a difference from the actual productivity of cone crushers, which indicates the lack of an adequate methodology for determining the theoretical productivity of cone and jaw crushers.

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