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Satbayev University

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ИЗВЕСТИЯ

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РЕСПУБЛИКИ КАЗАХСТАН
Satbayev University

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DETERMINATION OF ENERGY CONSUMPTION OF HIGH-SPEED ROCK DIGGING

Abstract. Increasing the productivity of continuous machines with increasing volumes of overburden and mining of rocks is one of the most urgent tasks. The complicated mining conditions required the development and application of advanced technologies based on the introduction of high-performance high-capacity equipment, which would improve the technical and economic performance of open operations. In this regard, the working body of a full-turn rotary excavator must satisfy the following requirements arising from the process of its interaction with rock: to have a low specific energy intensity of cutting, to ensure the required lumpiness of rocks and insignificant dynamics of external load.

All these tasks can be solved by the use of new effective methods for the development of rocks by excavation machines with an inertial lower unloading rotor (ILUR).

In the present work, the authors present the results of studies of high-speed digging and propose a method for determining the energy consumption of the process of transportation of rocks by an inertial rotor (IR) taking into account the influence of speed.

The work shows a graph of the specific energy intensity of the digging process against the speed during the development of the face. It can be seen from the graph that within the limits of rotor speed variation from 2 to 9 m/s the specific energy intensity of the digging process (two rows of knives) increases by 84%, the cutting process (one row of knives) increases by 58%.

In the work, the authors also proved that the most promising working tool is ILUR, the OS advantage of which is the development of an array when rotating the rotor "from top to bottom" with a hoop of cut rock. Theoretical dependencies of determination of power consumption for transportation of rocks by inertial rotor.

Key words: Bucket rotor, Duck less rotor, Knife rotor, Inertial rotor, Cutting and transport elements, Excavation machines, Digging energy capacity.

Introduction. One of the most important directions of the development of the open method of mining rocks at the present stage is the expansion of the field of application of continuous operation technology using high-performance rotary excavators, reloaders, landfills and conveyors. The use of this equipment allows to ensure the conditioning lumpiness of the mineral, a significant increase in labor productivity, rhythmicity and better organization of work at the enterprise. Therefore, today there is a tendency to use rotary excavators for the development of stronger, stronger rocks and coals without explosive preparation at the quarries of mining and open pits in Kazakhstan and Russia /1,2/.

Increasing the speed of the main working processes is one of the promising ways to achieve the highest productivity of mining machines. In this regard, in recent years, work has been underway to create working bodies of these machines that allow working at increased speeds.

However, the issues of the influence of speed on the main indicators of the process of digging rocks have not yet been studied enough. Research results show that with increasing speed, the specific energy intensity of the rock digging process also increases. But at the same time, the nature of this dependence, established by various researchers, varies. In addition, most studies have been carried out with simple cutting elements and their results cannot be extended to the working organs of machines /3,4/. The energy costs of the digging process in most studies are considered as a whole, without dividing into constituent elements, which does not allow to identify the degree of influence of individual factors on the digging process. Existing methods for separately determining the energy costs of the digging process are mainly limited, not accurate enough and not widespread /5,6/.

Digging of rocks is a complex process, all the factors of which theoretically it is not yet possible to take into account. With high-speed digging, there are additional influencing factors that make it even more difficult to study the digging process. This problem is even more complicated when operating at higher speeds, when choosing rational shapes of cutting elements (teeth, knives), and even more so when investigating the effect of cutting speed on the wear of cutting edges /7,8/.

Depending on the properties of the materials, the cutting and transport elements (RTE) of the inertial rotors (IR) are made bucket and sheave-free (knife) (Figure 1). Special calculations have established that the reserve of kinetic energy cut by the rotor (falling down) of the excavated rock is not enough to move the latter "gravity" through the receiving device to the conveyor. Based on this, and taking into account the low connectivity of many bulk rocks, determined by low humidity (less than 5 6%), it is more advisable to provide bucket rotor structures. This should take into account the scale factor - the possibility of using the height of the cutting elements, at which some limitation can be used in the supply of rock movement to the conveyor (in the case of a seamless rotor), as was observed when studying machines with centrifugal working elements /9,10,11,12/.

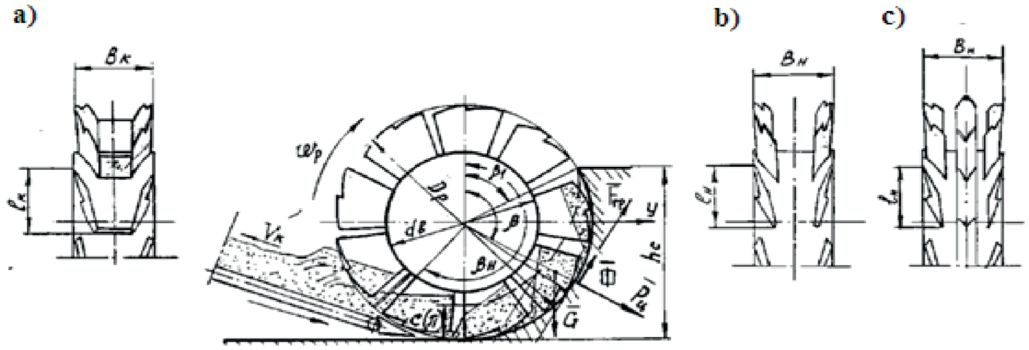


Figure 1 - Diagrams of bucket (a) and bucket-free (b and c) inertial rotors for excavation of bulk (b) and dense (c) rocks.

The speed digging proposed by the authors of the IR, unlike the existing ones, rotates, cuts the rock "from top to bottom" partially communicating it. Under the action of centrifugal force, excavated rock enters the belt conveyor located under the rotor. A receiving tray is installed at the end of the conveyor, which constantly contacts the developed face and prevents rock spilling.

In the IR in question, the buckets are replaced by a pair of knives located at an angle of 65 67 degrees to the generatrix shell. The main advantages of the new inertial rotor in comparison with the traditional design of gravitational, direct-flow and centrifugal rotors include /13,14/:

- possibility of carrying out the working process in a large speed range and obtaining high productivity;
- significant reduction of specific energy intensity of the digging process, in which oblique cutting occurs with chipping and partial collapse of cut rock;
- small weight of inertial rotor and reduction of total weight of excavator (due to change of reaction direction from cutting forces), which allows to reduce overturning moment and main loads on excavator;
- automatic cleaning of knives by cut rock;
- a significant initial rate of rock discharge from the rotor in the direction of the belt movement of the receiving conveyor.

Materials and methods. This work presents the results of further studies of high-speed digging of rocks and proposes a methodology for determining the energy consumption (specific energy intensity) of the digging process by an inertial rotor of lower unloading (IRNR) taking into account speed.

Considering the features of IR operation on the principle of "top-down" with collapse of cut rock and its transportation along the face surface by paired rows of knives with continuous flow, it can be assumed that at any moment of time the volume of excavated rock from angle β_p to R can be constant. Then this volume of rock cut and transported by the rotor can be considered as a solid, which is influenced by gravity and friction of the rock against the surface of the developed layer, so the theorem on changing the moment of the amount of motion /14,15/ can be applied. The volume of rock transported by the rotor will be broken into two parts from β_p to π and from π to β_p, r, and the parameters related to these parts, respectively, are marked with numbers 1 and 2 and we define their centers of gravity. Given that this volume of excavated rock is a constant value, it is sufficient to determine the center of gravity of the flat figures in the plane of rotation of the rotor (Figure 2).

In Figure 2, we select the elementary site and define its area as

$$dS_k = C(\beta)R_p d\beta \qquad (1)$$

Then the elementary volume of the detachable chips in the natural state dV_o can be compared with the elementary volume in the stress-free state dV_c through K_p the loosening factor: $dV_o = dV_c K_p$;

$$B_c R_p d\beta_c (C(\beta)) = K_p v_b dt S_0 \sin\beta d\beta;$$

Where $dt = \frac{d\beta}{w_p}$.

From where:

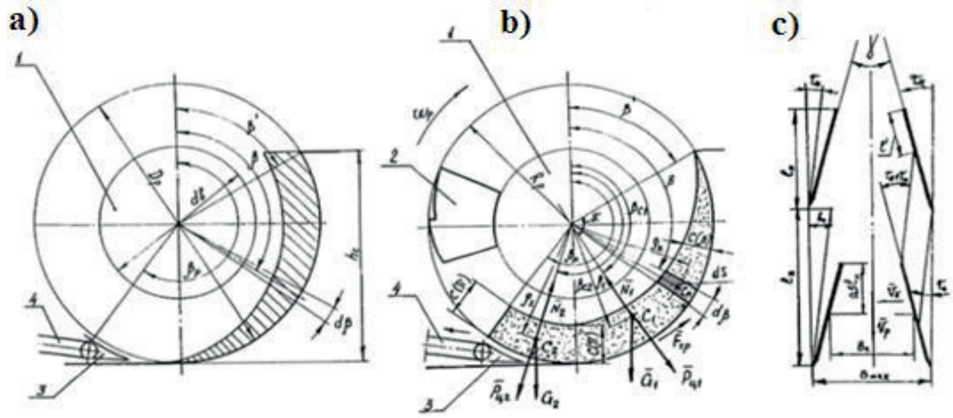
$$C(\beta) = \frac{K_p V_b S_o}{R_c B_c w_p} \sin\beta d\beta, \qquad (2)$$

where: B_c-average distance between cutting elements (RE); V_b- rotor lateral feed; S_o- maximum thickness of detachable chips; w_p- rotor angular rotation speed; K_p- rock loosening factor.

Using the expression (2) for $C(\beta)$, we obtain:

$$S_1 = R_p e[\sin\beta' + (\pi - \beta')\cos\beta']; \qquad (3)$$

where $e = V_b S_o (R_p B_c w_p)^{-1}$ – dimensionless factor.



1-rotor; 2-knife; 3-tray; 4-conveyor

Figure 2- Diagram of development (a), transport of rock cut by knives with a steam less (b) inertial rotor and diagram of RTE in plan (c)

Then, in the polar coordinate system, the center of gravity of the transported rock in the area from β' to π (3) can be defined as:

$$rc_1 = \left[\int_{\beta'}^{\pi} r_k C(\beta) R_p d\beta\right] S_1^{-1} \quad \text{and} \quad \beta c_1 = \left[\int_{\beta'}^{\pi}\left(\beta + \frac{d\beta}{2}\right) C(\beta) R_p d\beta\right] S_1^{-1} \qquad (4)$$

where r_k and $\left(\beta + \frac{d\beta}{2}\right)$ - coordinates of the center of gravity of the elementary site.

$$r_k = R_p - \frac{C(\beta)}{2}.$$

Substituting the expressions of all values included in formula (4) and integrating, we obtain:

$$r_{c1} = R_p\left[1 - \frac{1}{2}\cdot e \cdot \frac{0,75\cdot\sin 2\beta' + (\pi - \beta')\cdot(0,5 + \cos^2\beta')}{\sin\beta' + (\pi - \beta)\cdot\cos\beta'}\right] \qquad (5)$$

$$\beta_{c1} = \frac{1 + \beta'\sin\beta' + \{1 + 0,5\cdot[\pi^2 - (\beta')^2]\}\cdot\cos\beta'}{\sin\beta' + (\pi - \beta)'\cdot\cos\beta'}. \qquad (6)$$

In the second section from π to β_p rock with a center of gravity C_2 is thrown onto a tray with a constant height $C(\pi)$, so we have:

$$r_{c2} = R_p - 0{,}5C(\pi); \qquad \beta_{c2} = (\beta_p - \pi)0{,}5 \qquad S_2 = C(\pi)R_p(\beta_p p - \pi) \tag{7}$$

Thus, in this case, the expressions for the moments of gravity and friction are simplified and have the form:

$$M_{B1} = -\gamma \cdot B_c \cdot R_p^2 \cdot e \cdot [\sin\beta' + (\pi - \beta')\cdot\cos\beta'] \cdot r_c \cdot \sin\beta_{c1};$$

$$M_{B2} = -\gamma \cdot B_c \cdot R_p^3 \cdot e \cdot [1 - 0{,}5 \cdot e \cdot (1+\cos\beta')](\beta_p - \pi)\cdot(1+\cos\beta')\cdot\cos(0{,}5\cdot\beta_p);$$

$$M_{TP1} = \gamma \cdot B_c \cdot R_p^3 \cdot e \cdot [\sin\beta' + (\pi - \beta')\cdot\cos\beta'](R_p \cdot \omega^2 \cdot g^{-1} + \cos\beta_c);$$

$$M_{TP2} = -\gamma \cdot B_c \cdot R_p^3 \cdot e \cdot (\beta_p - \pi)\cdot(1+\cos\beta')\cdot[R_p \cdot \omega^2 \cdot g^{-1} + \sin(0{,}5\cdot\beta_p)].$$

Substituting all these obtained values into the expression of the theorem on changing the kinetic moment, we obtain a formula for determining the total torque on the rotor shaft spent on transporting excavated rock with an inertia-no-roof rotor:

$$M_{kp} = -\gamma \cdot B_c \cdot R_p^3 \cdot e\langle[\sin\beta' + (\pi - \beta')\cos\beta'] \cdot [A\sin\beta_{c1} + (\cos\beta_{c2} - R_p \cdot \omega_p^2 \cdot g^{-1})\mu_r] + (\beta_p - \pi)\cdot(1+\cos\beta)\times$$
$$\times\{[1 - 0{,}5e(1+\cos\beta')]\cos 0{,}5\beta_p - (\sin 0{,}5\beta_p + R_p \cdot \omega_p^2 \cdot g^{-1})\cdot\mu_r\} + R_p \cdot \omega_p^2 \cdot g^{-1} \cdot [1 - 0{,}5e(1+\cos\beta')]^3 \cdot (1+\cos\beta')\rangle \tag{8}$$

where $A = 1 - 0{,}5e \cdot [0{,}75\sin^2\beta' + (\pi - \beta')(0{,}5 + \cos^2\beta')] \cdot [\sin\beta' + (\pi - \beta')\cos\beta']^{-1}$.

Due to the complexity of the derived dependencies, more simplified formulas are needed for practical application. Taking into account the experience of operation of rotary excavators and their calculation methodology, values can be taken $\beta = 60^0$; $\beta_p = 125^0$; coefficients of internal and external friction $\mu = \mu_r = 0{,}7$, as well as taking dimensionless coefficients

$$e = V_b S_o (B_c \cdot \omega_p \cdot R_a)^{-1} = S_o \cdot tg\tau_o \cdot B_c^{-1}, \tag{9}$$

and

$$C_v = V_p^2 \cdot (gR_p)^{-1} = R_p \cdot \omega_p^2 \cdot g^{-1}$$

after transformations of formula (8) we obtain:

$$M_{kp} = -\gamma B_c R_p^3 e[1{,}08 - 0{,}98e - 2{,}84\mu_r C_v - 2{,}22\mu_r + C_v \cdot (1{,}52 - 3{,}4e + 2{,}54e^2 + 0{,}64e^3)]. \tag{10}$$

Results. Experimental studies of a number of machine models in production conditions found $z = 8 \div 12$ that with pairs of knives with angles of installation $\tau_H = 15^0 \div 16^0$, cutting $\tau_0 = 7^0 \div 8^0$, as well as their height coefficient $K_\varepsilon = 1{,}35 \div 1{,}4$, which determines the ratio of rotor radius to RE height, almost all rock cut by knives is taken by them to the receiving conveyor. At the same time, (85 95)% - filling of the volume between paired knives was observed, determined by the coefficient of geometric capacity of RTE IR $K_q = 0{,}85 \div 0{,}95$ (less value is determined for connected rocks, more - for disconnected ones). Therefore, to determine the dimensions of RTE and their placement on the rotor shell, it is necessary to proceed from the equality of the geometric volume between the knives to the volume of shredded chips with the coefficient of rock loosening $K_p = 1{,}35 \div 1{,}5$:

$$B_c h_\varepsilon l_H k_q = S_o b h_c k_p \tag{11}$$

where h_ε and l_H – respectively height and length of pairs of knives diverging at an angle $90^0 - 2\tau_H$ towards rotor rotation; b and h_c – width and maximum height of cut chips, respectively.

Having accepted $h_c = 1{,}5R_p$; $S_0 = 0{,}8h_\varepsilon$; $b = 2\pi R_p V_b (z v_p)^{-1}$ and performing transformations can be written according to the figure 2,c:

$$B_c = 2{,}4\pi K_p R_p^2 tg\tau_o (z l_H K_q)^{-1}, \tag{12}$$

$$l_{H\min} = 2\pi R_p tg\tau_o [z(tg\tau_H + tg\tau_o)]^{-1}. \tag{13}$$

The value (13) should be increased by 2 2,5 times, since almost by this value it can exceed the calculated one as a result of oscillatory movements of the boom in the horizontal plane during the development of dense rocks.

Using the experimental data obtained K_p, K_q, τ_o and τ_H knife sizes can be determined for rocks /7/:

for two-row knives:

$B_c = (0{,}21 \div 0{,}31)D_p$; $l_H = (0{,}21 \div 0{,}32)D_p$ and $B_{\max} = (0{,}22 \div 0{,}34)D_p$;

for three-row knives:

$$B_c = (0{,}22 \div 0{,}32)D_p;\quad l_H = (0{,}21 \div 0{,}32)D_p \text{ and } B_{\max} = (0{,}23 \div 0{,}35)D_p; \tag{14}$$

where a smaller value is taken for $z = 12$ at $K_\varepsilon = 4$; and more for $z = 8$ at $K_\varepsilon = 2$. Then the values of the dimensionless coefficient $e = 0{,}06$ at $K_\varepsilon = 4$ and $e = 0{,}08$ at $K_\varepsilon = 2$.

Using formulae (8 and 14) and experimental data (9), considering the transport stream as a constant mass on the tray cutoff surfaces, we obtain:

-at $K_\varepsilon = R_p \cdot h_\varepsilon^{-1} = 4{,}0$ and $e = 0{,}06$

$$M_{kp} = \gamma \cdot B_c \cdot R_p^3 e(0{,}57 + 0{,}59C_v); \tag{15}$$

-at $K_\varepsilon = R_p \cdot h_\varepsilon^{-1} = 2{,}0$ and $e = 0{,}08$

$$M_{kp} = \gamma \cdot B_c \cdot R_p^s e(0{,}58 + 0{,}6C_v). \tag{16}$$

Thus, by performing a number of transformations, with some assumptions, a simple formula is obtained for determining the torque for transporting the cut rock with isotope knives, dimensional values and the location of RTE on the rotor shell for preliminary engineering calculations.

In addition, the expression for the specific energy intensity of the digging process by the inertial rotor, taking into account the influence of speed, can be obtained in the form

$$E_k = K_v E_p + E_m; \tag{17}$$

and

$$E_k = K_v E_p \pm E_b + E_{mp} + E_{raz} + E_{rea}, \tag{18}$$

where E_i – specific energy consumption by cost elements.

The k_v, values obtained from these rock experiments are shown in Table 1.

Discussion. Description of benches, measurement system, list of used equipment and procedure of experimental studies are given in works /13,14/ and are not given in this article.

In these works, the development of the face was carried out with vertical chips "from top to bottom" when working with two rows of knives (16 pieces), the excavated rock was transported along the face and unloaded along the rotor, when cutting with one row of knives (8 pieces), the cut rock collapsed to the bottom of the face.

Table 1 - Factor to take into account the effect of cutting speed

Cutting speed	v_p	1	2	3	4	5	6	7	8	9
Factor to account for the effect of cutting speed	k_v	1,00	1,00	1,07	1,09	1,22	1,29	1,39	1,48	1,58

Studies were carried out at the same size of chips in rocks with a natural humidity of 23 25%, a volume weight of 1.95 t/m^3 an angle of internal friction of 20 °.

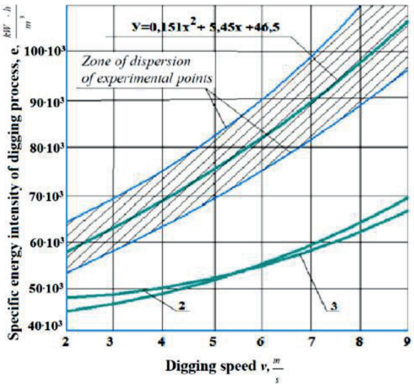
The obtained experimental curves of dependence of specific energy intensity of the process and its components on rotor speed are described in the form

$$y = Ax^2 + Bx + C. \tag{19}$$

which corresponds to the results of studies by other authors.

As can be seen from Figure 3, within the limits of the rotor speed variation from 2 to 9 m/s, the specific energy intensity of the digging process (two rows of knives) increases by 84%, the cutting process (one row of knives) increases by 58%, (curves 1 and 2).

Considering that the inertial rotor output increases in proportion to the increase in the digging speed, the productivity of the rotor can be substantially increased by increasing the rotor rotation speed with a slight increase in specific energy costs and thereby achieving a more efficient use thereof.



1 - rotor with two rows of knives; 2-rotor with one row of knives; 3 - rotor with two rows of knives minus power consumption for transportation of cut rock, obtained analytically.
Figure 3 - Dependence of specific energy intensity of digging process on speed during face development.

Close coincidence of specific energy intensity of transportation calculated analytically (curve 3) with experimental values confirms correctness of proposed method of calculation of energy consumption for transportation taking into account variability of mass of excavated rock.

As in field studies, the analysis of curves 1, 2 and 3 shows that the experimental costs of the specific energy intensity of the excavated mass transportation process by the inertial rotor are significant and account for 20 33%of the total energy consumption of the company and confirm the acceptability of analytical methods for calculating these dependencies proposed by the authors.

The obtained calculation values show that the power consumption increases significantly with increasing speed and diameter of the rotor. Thus, the minimum percentage of discrepancies calculated above (2 0,5)% is observed at the diameter of the rotor $D_p = (4 \div 6)$ m, $V_p = (4 \div 5)$ m/s and $K_\varepsilon = 2{,}0$, and the maximum - at the same parameters is respectively (6 2,9)%. Such small discrepancies between them indicate that the method produced for determining the energy consumption for transporting excavated rock with an inertial rotor is acceptable for practical use.

Conclusion. The results of the studies make it possible to draw the following conclusions:

- it was established that the most promising working tool is ILUR, the main advantage of which is considered the development of the array when the rotor rotates “from top to bottom” with the collapse of the cut rock;
- theoretical dependencies of determination of energy consumption of rock transportation by inertial rotor, dimensional values and location of RTE on rotor shell are established;
- studies of a number of machines in production conditions have established that when excavating rocks to a speed of 2,0 m/s, its specific energy intensity practically does not depend on the digging speed. Further increase in digging speed leads to an intensive increase in specific energy intensity, which should be taken into account when selecting engines and calculating the energy costs of excavation machine drives.

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ТАУ ЖЫНЫСТАРЫН ЖЫЛДАМ ҚАЗУДЫҢ ЭНЕРГИЯ ШЫҒЫНДАРЫН АНЫҚТАУ

Аннотация. Тау жыныстарын аршу және өндіру жұмыстарының көлемі өскен сайын үздіксіз жұмыс істейтін машиналардың өнімділігін арттыру ең өзекті мәселелердің бірі болып табылады. Күрделі таукен-техникалық жағдайлар ашық жұмыстардың техникалық-экономикалық көрсеткіштерін жақсартуға мүмкіндік беретін жоғары қуатты әрі жоғары өнімді техниканы енгізу негізінде прогрессивті технологияларды әзірлеуді және қолдануды талап етеді. Осыған байланысты, толық айналмалы роторлы экскаватордың жұмыс органы оның тау жынысымен өзара әрекеттесу процесінде туындайтын келесі талаптарды қанағаттандыруы керек: кесудің төмен энергия сыйымдылығына ие болу, тау жыныстарының қажетті кесектілігін және сыртқы жүктеменің динамикалылығын қамтамасыз ету.

Барлық осы мәселелерді тау жыныстарын төмен қарай қазатын инерциялық роторы бар экскавациялық машиналармен өңдеудің жаңа тиімді әдістерін қолдану арқылы шешуге болады.

Бұл жұмыста авторлар жылдам қазуды зерттеу нәтижелерін келтіреді және жылдамдықтың әсерін ескере отырып, тау жыныстарын инерциялық ротормен (ИР) тасымалдау процесінің энергия шығындарын анықтау әдістемесін ұсынады.

Жұмыста қазу процесінің меншікті энергия сыйымдылығының қазбаны өңдеу кезіндегі жылдамдыққа тәуелділігінің графигін ұсынылған. Бұл графиктен ротор жылдамдығының 2-ден 9 м/сек-қа дейін өзгеруі аралығында қазу процесінің (пышақтар екі қатарлы) меншікті энергия сыйымдылығының 84% - ға, кесу процесінің (пышақтар бір қатарлы) 58% - ға артатынын көруге болады.

Авторлар жұмыста ең перспективалы жұмыс органы жоғарыдан төмен қарай қазатын ИР екенін дәлелдеді, оның басты артықшылығы - ротордың жоғарыдан төмен айналуы кезінде кесілген тау жұмыстарын жаппай құлату арқылы массивті өңдеу болып табылады. Жұмыста сонымен бірге ИР-мен тау жыныстарын тасымалдауда энергия шығындарын анықтаудың теориялық тәуелділігі берілген.

Түйінді сөздер: Шөмішті ротор, Шөмішсіз ротор, Пышақты ротор, Инерциялы ротор, Кесу-тасымалдау элементтері, Экскавациялық машиналар, Қазудың энергия сыйымдылығы.

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ОПРЕДЕЛЕНИЕ ЭНЕРГОЗАТРАТ СКОРОСТНОГО КОПАНИЯ ГОРНЫХ ПОРОД

Аннотация. Повышение производительности машин непрерывного действия при возрастающих объемах вскрышных и добычных работ горных пород является одной из самых неотложных задач. Усложняющиеся горно-технические условия требуют разработку и применения прогрессивных технологий на основе внедрения высокопроизводительной техники большой мощности, которая позволит улучшить технико-экономические показатели открытых работ. В связи с этим рабочий орган полноповоротного роторного экскаватора должен удовлетворить следующие требования, вытекающие из процесса взаимодействия его с горной породой: иметь низкую удельную энергоемкость резания, обеспечивать требуемую кусковатость пород и незначительную динамичность внешней нагрузки.

Все эти задачи могут быть решены применением новых эффективных методов разработки горных пород экскавационными машинами с инерционным ротором нижней разгрузки (ИРНР).

В настоящей работе авторами приводятся результаты исследований скоростного копания и предлагается методика определения энергозатрат процесса транспортирования горных пород инерционным ротором (ИР) с учетом влияния скорости.

В работе приведен график зависимости удельной энергоемкости процесса копания от скорости при разработке забоя. Из графика видно, что в пределах изменения скорости ротора от 2 до 9 м/сек происходит увеличение удельной энергоемкости процесса копания (два ряда ножей) на 84 %, процесса резания (одним рядом ножей) - на 58%.

В работе авторы также доказали, что наиболее перспективным рабочим органом является ИРНР, основным достоинством которого является разработка массива при вращении ротора «сверху вниз» с обрушением срезанной породы. В работе установлены теоретические зависимости определения энергозатрат на транспортирование горных пород инерционным ротором.

Ключевые слова: ротор ковшовый, ротор бесковшовый, ротор ножевой, инерционный ротор, режуще-транспортные элементы, экскавационные машины, энергоемкость копания.

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