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STUDY OF THE PARTICLE DYNAMICS IN IMPACT-CENTRIFUGAL MILLS

Abstract. Proceeding from the analysis of operation of impact-centrifugal mills, requiring extremely high energy costs, of particular interest is the search for sources, enabling to minimize these costs. Along with the structural elements and assemblies, as well as the technological service, a great role here is played by the influence of the dynamics of particles, formed during grinding. In its turn, the velocity nature of crushed particles' motion is a function of such variables as the design of impingement elements, the direction of impact, the particle's configuration and the material, to which it belongs, as well as a number of other factors.

The paper presents the analysis of design schemes of impact-throwing type mills with different shape and location of accelerating blades. There is considered the common case of the material's particle motion along the accelerating arc blade, located in the horizontal plane, and there is given the design scheme.There is graphically considered the direction of the total velocity of a particle at different location of blades, and there is suggested the dependence of the particle's impact impulse on the particle's descent angle. There are obtained the laws of material's particle motion in the impact-centrifugal mill with the blades of arc profile of variable radius, there are established the basic laws, permitting to determine the impact impulse and, accordingly, the grinding efficiency, depending on the blade profile.

Keywords: the impact-centrifugal mills,thedesign scheme, the particle**,** the velocity, the motion, the operating device, the rotating rotor, the impact impulse, the profile, the efficiency.

Introduction.

Grinding processes are very common in many industries. These, in particular, include: the production of building materials, food production, pharmacology, recycling.

A. Griffiths and A. Ioffe made a significant contribution to the study of fracture mechanics [1, 2]. Taking into account their work, many researchers studied the physical bases of the processes of destruction [3 – 5], laying the Foundation for modern hypotheses and assumptions. Particularly important attention was paid to the problems associated with specifying the grinding work, since this process itself is very energy-intensive. The first attempt to identify the energy costs of grinding was made by P. Rittinger. According to his hypothesis, it follows that the work spent on grinding is proportional to the size of the newly formed surface in the crushed material. A bit later, F. Kick and V. Kirpichev [6 – 8], independently from each other, put forward a hypothesis that the energy, required to obtain similar changes in the configuration of geometrically similar bodies of the same technological structure, change like the weight or volume of these bodies. P. A. Rebinder [6, 7] combined the hypotheses of Rittinger and Kick-Kirpichev, considering that the destruction occurs after the piece's deformation and the total work of crushing is the sum of the work of deformation and the work of new surfaces' formation.

The above researchers laid the foundations of fracture mechanics, established the laws for specifying the fracture work, however, in spite of this, currently there is no clear theory of this process. This is determined both by the complexity of the phenomena, observed in the material during destruction, and by the practically infinite variations in the properties of the materials themselves, such as hardness, density, plasticity and many others.

At the same time, many researchers note that for most materials, especially for fragile and fragile-flexible, the most acceptable in terms of energy efficiency are such methods of grinding as crushing and impact [9 – 15]. Upon impact, in the material there occur considerable short - term internal forces, which result in the appearance and development of cracks that destroy the integrity of the material. Therefore, impact mills are widely used in grinding of various materials [11,12, 15].

Basically, the working body of such mills is a rotating rotor, usually in the form of a disk with the accelerating blades, installed on it. When the rotor rotates, the crushed material, fed into its inner cavity, moves under the influence of inertial forces along the accelerating blades from the center of rotation to the periphery. Breaking off from the blades at a certain speed, the material's particles hit the fixed impact surface and break down into smaller parts [16 – 18].

The efficiency of impact grinding depends on the speed, at which the particle hits the impingement element, and the angle between the velocity vector and the normal to the impingement surface in the impact point of the particle. The greater the speed of the particle at the time of impact and the closer the impact angle in relation to the normal to the impact surface to zero, the more effective the grinding process. Therefore, we can assume that the grinding efficiency is affected by the profile and location of the blade. In addition, it should be noted that when the abrasive particles move along the blade, there is an intense abrasion of its surface. In this regard, the task is to select such parameters of the blade profile, at which the pressure on it will be minimal, which, in its turn, will reduce the friction force and increase the durability of the blade.

Typical designs of rotors in impact-throwing type mills in most cases are provided with radial accelerating blades (Fig.1, a) [16-18]. These blades are easy to manufacture and therefore they are widely used in rotary mills. The results of studies of the material's movement in mills with radial blades are presented in many works [16–20].

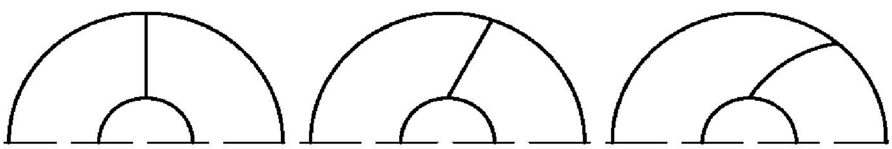


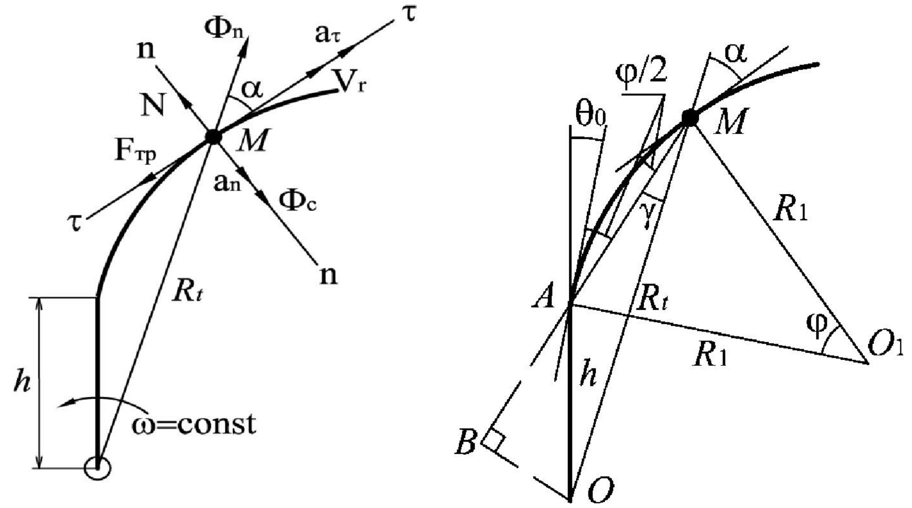
Figure 1 – The design schemes of impact-throwing type mills with different shape and location of accelerating blades

Therefore, the purpose of further research was to investigate the material's particle dynamics in impact type mills with arc blades of variable radius; to determine the influence of geometric characteristics of impact-centrifugal mills with different types of blades on the efficiency of impact grinding.

Study methods. To carry out the studies, there were used the numerical and analytical methods with the use of computers.

Studyresults. The material to be ground, before reaching the blade, is fed into the central part of the rotor, from where, under the influence of centrifugal forces, it moves to the inter-blade space. Despite the fact that the material is supplied as a continuous flow, it can be considered that the movement of particles along the blades occurs separately, since their speed in the radial direction is constantly increasing, so they move apart from each other. Also, in [21] it is pointed out that for mill sizes of grinded pieces of material of the order of 10 mm, mill loading cannot be considered a bulk medium, it is allowed to consider the motion of single particles.

Let's consider the general case of the material's particle movement along the accelerating arc blade, located in a horizontal plane (Fig. 2). Here we believe that the blade has a constant curvature radius R_1, and the particle is presented by a material point M.



h – a distance from the rotor center to the beginning of blades, R_t – the radius-vector module n

Figure 2 -Thedesignscheme

Let the particle be in any point of the blade surface. Here we assume that the rotor rotates at a constant angular velocity ω. In relative motion, the particle will be affected by the centrifugal inertial force Φ_n, the Coriolis inertial force Φ_c, the force of the particle's friction on the blade surface $F_{тр}$ and the reaction of the support surface N. The force of aerodynamic resistance will be neglected by us, since the centrifugal force of inertia is by an order of magnitude more than the force of aerodynamic resistance. The particle's motion along the blade in the axial direction of the rotor, i.e. across the blade, is not considered, since the value of gravity force at operating frequencies of the mill rotor rotation is by orders of magnitude less than the values of inertial forces.

The system of equations, describing the motion of a particle along the arc blade in a natural coordinate system (Fig. 2), will be written as:

$$m\ddot{s} = m\omega^2 R_t \cos\alpha - Nf,$$

$$m\frac{\dot{s}^2}{R_1} = -N - m\omega^2 R_t \sin\alpha + 2m\omega\dot{s}, \qquad (1)$$

where m – the mass of a particle, s – the arc coordinate, measured from the beginning of the blade, ω – the mill rotor angular velocity, f – the coefficient of sliding friction, N – the support's reaction.

The system of equations (1) completely describes the motion of particle M, if we know explicit expressions for the radius vector modulusR_t, cosα and sinα as a function of the generalized coordinate s. These expressions are easy to find with the help of Fig. 2. From the right triangle OBM we obtain

$$R_t^2 = \left(h\sin(\theta_0 + \frac{\varphi}{2})\right)^2 + \left(h\cos(\theta_0 + \frac{\varphi}{2}) + 2R_1\sin\frac{\varphi}{2}\right)^2. \qquad (2)$$

Angle θ_0 is the inclination angle of the tangent to the starting point of the blade. This angle specifies the orientation of the blade curvature radius R1 in the plane of the rotor.

FromFig. 2 itfollowsthat

$$\cos\alpha = \frac{1}{R_t}\left(h\cos(\theta_0 + \varphi) + R_1\sin\varphi\right),$$

$$\sin\alpha = \frac{1}{R_t}\left(h\sin(\theta_0 + \varphi) + R_1(1 - \cos\varphi)\right). \qquad (3)$$

Taking into account that the angular coordinate $\varphi = s/R_1$ from system **Ошибка! Источник ссылки не найден.**, with taking into account **Ошибка! Источник ссылки не найден.**, we derive the equation of the particle motion as

$$\ddot{s} = \omega^2\left(h\cos(\theta_0 + \frac{s}{R_1}) + R_1\sin\frac{s}{R_1}\right) - f\frac{N}{m}, \tag{4}$$

where the support reaction

$$N = m\left(2\omega\dot{s} - \frac{\dot{s}^2}{R_1} - \omega^2(h\sin(\theta_0 + \frac{s}{R_1}) + R_1 - R_1\cos\frac{s}{R_1})\right).$$

From the nonlinear differential equation (4) it is possible to obtain special cases of the particle motion along the rectilinear inclined and radial blades. For this, it is needed to carry out the limiting transition $R_1 \to \infty$. As a result, we obtain a linear differential equation of the particle's motion along the rectilinear inclined blade:

$$\ddot{s} = \omega^2\left(h\cos\theta_0 + s\right) - f\,N/m,$$
$$N = m(2\omega\dot{s} - \omega^2 h\sin\theta_0). \tag{5}$$

If the blade is radial, i.e. $\theta_0 = 0$, then the equation of motion has the form:

$$\ddot{s} = \omega^2\left(h + s\right) - f\,N/m,$$
$$N = m\,2\omega\,\dot{s}. \tag{6}$$

The solution of equations (5) and (6) can be obtained in the analytical form, equation (4) is integrated numerically, but the determination of the particle's position on the blade as a function of time is of no interest, since for grinding efficiency analysis it is necessary to know the full speed of the particle at the time of its descent from the blade and the direction of this speed. The analysis of equation (4) shows that the friction force component is much smaller than the inertial component, hence it can be concluded that the friction force will not significantly affect the magnitude and direction of the total speed of the particle, so in further calculations it will be neglected. In this case, we can obtain the first integral of motion for equation **Ошибка! Источник ссылки не найден.** which makes it possible to determine the reaction of a support surface N as a function of the particle's position on the blade s.

$$\frac{\dot{s}^2}{2} = \omega^2\left(hR_1(\sin(\theta_0 + \frac{s}{R_1}) - \sin(\theta_0)) + R_1{}^2(1 - \cos\frac{s}{R_1})\right), \tag{7}$$

The integrals, similar to (7), are obtained for rectilinear inclined and radial blades by integrating equations (5) and (6) or by performing a limit transition $R_1 \to \infty$ for equation **Ошибка! Источник ссылки не найден.**.

$$\frac{\dot{s}^2}{2} = \omega^2\left(h\cos\theta_0 s + \frac{s^2}{2}\right), \tag{8}$$

$$\frac{\dot{s}^2}{2} = \omega^2\left(hs + \frac{s^2}{2}\right). \tag{9}$$

Equation **Ошибка! Источник ссылки не найден.** can be derived by writing the theorem of the particle kinetic energy change in the rotating coordinate system

$$\frac{m\dot{s}^2}{2} = \frac{m\omega^2 R_t^2}{2} - \frac{m\omega^2 h^2}{2}, \tag{10}$$

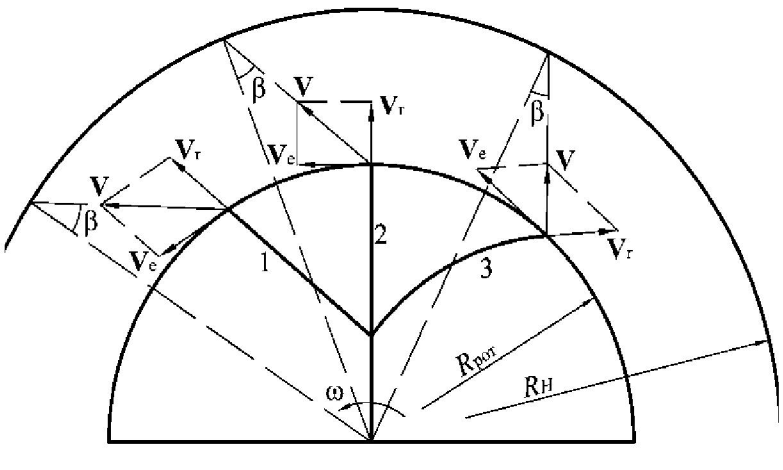
where in the right part there is recorded the work of the centrifugal inertial force during the particle's relocation from the initial position h to the current position R_t. Then from (10) we have

$$\dot{s}^2 = \omega^2 \left(R_t^2 - h^2 \right). \tag{11}$$

By putting expression (2) into equation (11), we obtain (7). Expression (11) leads to an important conclusion: the particle's relative velocity module during its departure from the rotor (when $R_t = R_{\text{рот}}$) does not depend on the profile and location of the accelerating blade.

$$\dot{s} \equiv V_r = \omega\sqrt{R_{\text{рот}}^2 - h^2} = \text{const}. \tag{12}$$

The direction of the relative velocity vector, of course, will depend on the shape and location of the blade (Fig.3).



$R_{\text{рот}}$ – the rotor radius; R_H –the impingement surface radius.

Figure 3 - The direction of the particle's total velocity at various blade positions

Let's decompose the particle's total velocity at the moment of its descent from the blade to the radial component v_n and the tangent component v_τ:

$$v_n = V_r \cos\alpha_c,\; v_\tau = \omega R_{\text{рот}} - V_r \sin\alpha_c., \tag{13}$$

where α_c – the angle value α at the time of descent of the particle from the blade (the angle of descent) is determined by formulas (3). Then the square of the particle's total velocity, with taking into account (12), will be

$$v^2 = v_n^2 + v_\tau^2 = 2\omega^2 R_{\text{рот}}^2\left(1-\sqrt{1-\left(h/R_{\text{рот}}\right)^2}\sin\alpha_{\text{c}}\right) - \omega^2 h^2. \quad (14)$$

The formula shows that for the blade, at the end of which $\sin\alpha_c = 0$ (for example, a radial blade), the square of the particle's total velocity at the moment of its descent from the blade will be

$$v_{\text{п}}^{\;2} = 2\omega^2 R_{\text{рот}}^2 - \omega^2 h^2.$$

The rate of descent of a particle from a rectilinear inclined blade will depend on the direction of the slope of this blade (in the direction of the angular velocity ω or opposite to it, Fig. 3). The limit transition $R_1 \to \infty$ for such a blade, according to (3), gives $\sin\alpha_c = h/R_{\text{рот}}\sin\theta_0$ and, in accordance with formula (14), the total speed of the particle with the passing blade inclination $v > v_{\text{п}}$ (since the blade inclination angle θ_0 in this case is negative) and $v < v_{\text{п}}$ with the blade inclination in the direction, opposite to the angular velocity ω. Similar conclusions can be made for the arc blade.

The value of the particle's total velocity says nothing about the grinding process efficiency, since the impact impulse accounts for only part of this velocity. The impact impulse can be determined by the formula

$$p = mv\cos\beta, \quad (15)$$

whereβ – the angle between the vector of total velocity and the normal to the surface in the point of impact of the particle (Fig.4).

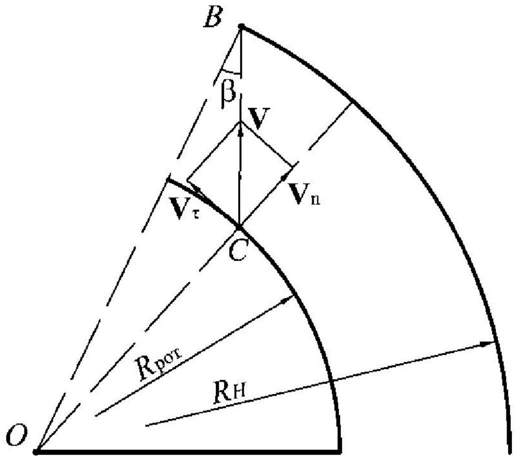


Figure 4- Determination of the particle's impact impulse.

Using the sine theorem for triangle *OBC* (Fig. 9), we derive

$$\cos\beta = \sqrt{1-\left(\frac{R_{\text{рот}}}{R_H}\right)^2\left(\frac{v_\tau}{v}\right)^2}, \quad (16)$$

whereR_H – the radius of the mill's impingement surface.

Then the particle's impact impulse (15), with taking into account (14) and (16), will be

$$p = m\sqrt{v_n^2 + v_\tau^2\left(1-\left(R_{рот}/R_H\right)^2\right)}\,. \qquad (17)$$

In formula (17) the first summand under the root determines the contribution of the radial component of the total velocity; the second summand - the contribution of the tangential component. If to solve the problem for extremum of the impact impulse function (17), then the particle's descent angle, at which the maximum impact impulse will be reached, at a specified $R_{рот}/R_H$ ratio, is determined by the formula

$$\sin\alpha_c^{max} = \frac{1-(R_H/R_{рот})^2}{\sqrt{1-(h/R_{рот})^2}}\,. \qquad (18)$$

The maximum impact impulse here will be

$$p_{max} = m\omega\sqrt{R_H^2 - h^2}\,. \qquad (19)$$

The analysis of formula (17) showed that with increasing the radius of the impingement surface, the impact impulse maximum is shifted towards the negative values of angles of the particle's descent from the blade (for example, if the blade is inclined in the direction of the angular velocity). The dependence of the impact impulse on the angle of the particle's descent from the blade for different values of$k = R_H/R_{рот}$ is shown in Fig. 5.

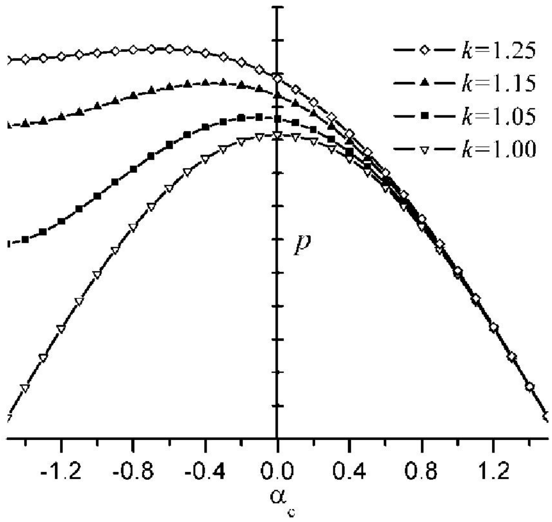


Figure 5 - Dependence of the particle's impact impulse on the angle of the particle's descent

From the figure it is seen that the impact impulse increases with increasing radius of the impingement surface, but in practice to achieve an increase in the impact impulse in this way is difficult, since during the particle's movement in the space between the rotor and the impingement surface there are appearing the air flows that greatly slow down the speed of the particle, so the gap between the rotor and the impingement surface is usually made minimum, so that $k = R_H/R_{рот}$ does not exceed 1.05. If to assume $R_{рот}/R_H = 1$, then formula (17), with taking into account (12), can be approximately written as

$$p = mV_r\cos\alpha_c = m\omega\sqrt{R_{рот}^2 - h^2}\cos\alpha_c\,. \qquad (20)$$

From formula (20) (and from Fig. 4) it is seen that at $R_{рот}/R_H \approx 1$ the maximum impact impulse is achieved during the particle's descent from the blade, having $\alpha_c = 0$. This value α_c can be achieved either on the radial blade or on the arc blade, at the end of which the tangent to this blade τ will coincide with the radius vector R_t. Thearcblade,providing$\alpha_c = 0$, isshowninFig. 6.

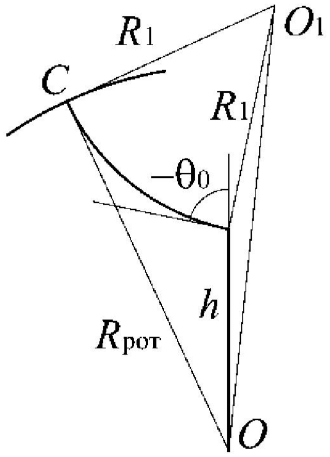


Figure 6 - Determination of the arc blade's optimal angle of inclination θ_0

From the right triangle OO_1C in Fig. 6 we can determine the dependence of the arc blade's angle of inclination θ_0 from the radius of its curvature, which will provide $\alpha_c = 0$.

$$\sin\theta_0 = -\frac{R_{\text{рот}}^2 - h^2}{2h}\frac{1}{R_1}. \quad (21)$$

The sign "–" in formula (21) shows that to ensure the condition $\alpha_c = 0$, the blade must be tilted in the direction of the angular velocity ω. From formula (21), we obtain the possible range of variation of the curvature radius

$$\frac{R_{\text{рот}}^2 - h^2}{2h} \le R_1 < \infty, \quad (22)$$

with the angle θ_0 changing from $-\pi/2$ to 0.

Conclusions. In the course of research there were obtained the laws of motion of the material's particles in an impact -centrifugal mill with blades of an arc profile of variable radius, there were established the basic mechanisms that allow to determine the impact impulse and, accordingly, the efficiency of grinding, depending on the profile of the blade.

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СОҚҚЫЛЫ-ОРТАДАН ТЕПКІШ ДИІРМЕНДЕРДЕГІ БӨЛШЕКТЕРДІҢ ДИНАМИКАСЫН ЗЕРТТЕУ

Аннотация. Аса энергия шығынды болып келетін соққылы-ортадан тепкіш диірмендердің жұмысына талдау негізінде, осы шығындарды азайтатын көздерді іздестіру ерекше қызығушылық тудырады. Құрылымдық элементтер мен түйіндермен қатар, технологиялық сервиспен қатар, бөлшектердің динамикасының әсері маңызды рөл атқарады. Өз кезегінде, ұсақталған бөлшектердің қозғалыс жылдамдығының сипаты айналдыру элементтерінің конструкциясы, әсер ету бағыты, бөлшектердің конфигурациясы және оған тиесілі материал, сондай-ақ бірқатар басқа факторлар сияқты айнымалылардың функциясы болып табылады.

Жұмыста әртүрлі пішіндегі соққылы-лақтырылған типтегі диірмендердің есептік сұлбаларына және жылдамдатқыш пышақтардың орналасуына талдау жүргізілді. Горизонталь жазықтығында орналасқан доғалық жылдамдатқыш жүзі бойындағы материалдың бөлшектерінің қозғалысы қарастырылды және есептеу сұлбасы берілді. Бөлшектердің әртүрлі орналасуы бар бөлшектердің жалпы жылдамдық бағыты графикалық түрде қарастырылды және бөлшектің әсер ету серпінін бөлшектердің кету бұрышына тәуелділігі ұсынылды. Бөлшектердің әртүрлі орналасуы бар бөлшектердің жалпы жылдамдық бағыты графикалық түрде қарастырылады және бөлшектің әсер ету серпінін бөлшектердің кету бұрышына тәуелділігі ұсынылады. Айнымалы радиустардың доғалы профилінің пышақтарымен соққы-ортадан тепкіш диірмендегі материалдық бөлшектердің қозғалысы туралы заңдар алынып, пышақтың бейініне байланысты әсер ету импульсін және, тиісінше, тегістеу тиімділігін анықтауға мүмкіндік беретін негізгі заңдылықтар орнатылды.

Түйін сөздер:соққылы-ортадан тепкіш диірмендер, есептік сұлба, бөлшек, жылдамдық, қозғалыс, жұмыс органы, айналмалы ротор, соққылы импульс, профиль, тиімділік.

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ИССЛЕДОВАНИЕ ДИНАМИКИ ЧАСТИЦ В УДАРНО-ЦЕНТРОБЕЖНЫХ МЕЛЬНИЦАХ

Аннотация. Исходя из анализа работы ударно-центробежных мельниц, являющихся энергозатратными, особый интерес представляет поиск источников, позволяющих свести к минимуму эти затраты. Наряду с конструктивными элементами и узлами, а также технологическим сервисом, большую роль при этом играет влияние динамики частиц, движущихся в роторах мельниц. В свою очередь, скоростной характер движения измельченных частиц является функцией от таких переменных, как конструкция отбойных элементов, направление удара, конфигурация частицы и материал, к которому она принадлежит, а также ряда других факторов.

В работе выполнен анализ расчетных схем мельниц ударно-метательного типа с различными формами и расположением разгонных лопаток. Рассмотрен общий случай движения частицы материала по дуговой разгонной лопатке расположенной в горизонтальной плоскости и приведена расчетная схема. Графически рассмотрено направление полной скорости частицы при различном расположении лопаток и предложена зависимость ударного импульса частицы от угла схода частицы. Получены законы движения частиц материала в ударно-центробежной мельнице с лопатками дугового профиля переменного радиуса, установлены основные закономерности, позволяющие определить ударный импульс и, соответственно, эффективность измельчения в зависимости от профиля лопатки.

Ключевые слова: ударно-центробежные мельницы, расчетная схема, частица, скорость, движение, рабочий орган, вращающийся ротор, ударный импульс, профиль, эффективность.

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