https://doi.org/10.26898/0370-8799-2022-6-12 Тип статьи: оригинальная
УДК: 631.363.21 Type of article: original

ТЕОРЕТИЧЕСКОЕ ИССЛЕДОВАНИЕ ЭНЕРГОЭФФЕКТИВНОСТИ ИЗМЕЛЬЧИТЕЛЯ РОТОРНОГО ТИПА

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Изучены возможности энергосбережения при работе измельчителя зерна за счет повышения эффективности взаимодействия сырья с рабочими органами машины. Предложен измельчитель роторного типа, в котором частицы сырья разрушаются исключительно ударными воздействиями в процессе первичных ударов элементами вращающегося ротора и последующих вторичных ударов о неподвижные элементы камеры. При этом конструктивные параметры устройства обеспечивают частицам контакты с поверхностями ударных элементов под углами атаки, близкими к прямому углу, что обеспечивает высокую эффективность удара. Таким образом, каждая частица сырья в зоне удара испытывает только два, следующих друг за другом, контакта с ударными элементами, после чего частицы переработанного продукта выводятся из зоны удара. В такой схеме воздействия на сырье энергия ротора используется наиболее рационально. Эффективность работы предлагаемого устройства рассмотрена на основе потерь кинетической энергии, которые происходят при ударе частиц о поверхности рабочих органов. Взаимодействия сырья с элементами ротора и элементами камеры изучены как единый взаимосвязанный процесс, а совокупность ударных элементов ротора и камеры выделены в конструктивную единицу. Найдено аналитическое выражение, определяющее общие энергетические затраты, необходимые для реализации ударных воздействий в предлагаемом устройстве. Также введен критерий, характеризующий эффективность измельчителя в потреблении механической энергии для разрушения сырья ударными воздействиями. По введенному критерию выполнено сравнение эффективности работы предлагаемого устройства и центробежной дробилки, в которой измельчение сырья также осуществляется ударными воздействиями.

Ключевые слова: измельчитель зерна, удар, потери энергии, эффективность

THEORETICAL STUDY OF THE ENERGY EFFICIENCY OF A ROTARY GRINDER

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The possibilities of energy saving in the work of a grain grinder by increasing the efficiency of interaction of raw materials with the working bodies of the machine have been studied. A rotary grinder, in which the raw material particles are destroyed solely by impact actions in the process of primary impacts by the elements of the rotating rotor and the subsequent secondary impacts on the stationary elements of the chamber, is proposed. In this case, the design parameters of the device provide the particles with contacts with the surfaces of the impact elements at angles of attack close to the right angle, which ensures high impact efficiency. Thus, each raw material particle in the impact zone experiences only two successive contacts with the impact elements, after which the processed product particles are removed from the impact zone. In this scheme of action on the raw material the rotor energy is used most rationally. The effectiveness of the proposed device is considered on the basis of the loss of kinetic energy that occurs when the particles hit the surface of the working bodies. The interaction of the raw material with the rotor and chamber elements is studied as a single interrelated process, and the set of shock elements of the rotor and chamber are allocated as a structural unit. An analytical expression was found that determines the total energy cost required to implement the impact forces in the proposed device. A criterion that characterizes the efficiency of the grinder in the consumption of mechanical energy for the destruction of raw materials by impact forces is also introduced. A comparison of the efficiency of the proposed device and the centrifugal crusher, in which crushing of raw materials is also carried out by impact effects, is performed according to the introduced criterion.

Keywords: grain grinder, impact, energy loss, efficiency

Для цитирования: *Кукаев Х.С., Асманкин Е.М., Ушаков Ю.А., Абдюкаева А.Ф., Наумов Д.В.* Теоретическое исследование энергоэффективности измельчителя роторного типа // Сибирский вестник сельскохозяйственной науки. 2022. Т. 52. № 6. С. 103–110. https://doi.org/10.26898/0370-8799-2022-6-12

For citation: Kukaev Kh.S., Asmankin E.M., Ushakov Yu.A., Abdyukaeva A.F., Naumov D.V. Theoretical study of the energy efficiency of a rotary grinder. *Sibirskii vestnik sel'skokhozyaistvennoi nauki = Siberian Herald of Agricultural Science,* 2022, vol. 52, no. 6, pp. 103–110. https://doi.org/10.26898/0370-8799-2022-6-12

Конфликт интересов

Авторы заявляют об отсутствии конфликта интересов.

Conflict of interest

The authors declare no conflict of interest.

INTRODUCTION

Among the machines used for grinding of grain raw materials rotary grinders are widespread. Their popularity is due to the following advantages: simple design, reliability, versatility, ease of maintenance. Improvement of these machines is an urgent task, especially in the aspect of reducing energy consumption [1-5].

One of the ways to improve rotary grinders is to reduce energy consumption by increasing the efficiency of interaction of raw materials with the working bodies of the grinder[1] [6-8]. In the working chamber raw material grinding occurs as a result of blows of rotating rotor elements, as well as blows and abrasion of raw material particles on the working surfaces of the chamber elements. The peculiarity of work of the rotary grinders is that impact action of the rotor element not only loads the particle, but also simultaneously gives it or the formed fragments kinetic energy, which is then consumed in subsequent interaction with the chamber elements. The quality of interaction of the particle with the chamber element is determined by how fully the stock of its energy received from the rotor is used. In this aspect, a number of researchers note that the main reasons for increased energy consumption are irrational energy losses due to poor-quality impact on the raw material, as well as its friction against the chamber elements due to the circular motion. [9, 10].

The authors proposed a rotary grinder, in which the raw material particles, getting into the work chamber, are destroyed in the process of primary impacts by the elements of the rotating rotor (beater) and subsequent secondary impacts on the stationary elements of the

[1]Denisov V.A. Calculation of power consumption of centrifugal-impact crusher. Scientific Proceedings. Mechanization and automation of fodder preparation. MOSCOW: VIESH, 1986. vol. 66. pp. 106-122.

chamber (plates) at the angles of attack, close to 90°, which ensures high efficiency of impact effects (see Fig. 1). In this case the raw material is fed into the chamber perpendicular to the rotor rotation plane, and after the interaction with the plates the processed product particles are removed from the impact zone. Thus, the raw material particles in the impact zone experience only two contacts: with communication of kinetic energy (when the beater strikes) and with absorption of energy (when the particle hits the plate). In this grinding method, there is no friction of the raw material, and the particles are crushed exclusively by impact actions with high efficiency. Consequently, the rotor energy is used as rationally as possible. The impact of the beater completely determines the subsequent impact of the particle on the plate, which makes it possible to consider and mathematically formalize these impacts as a single process. In this case, the beaters and the plates corresponding to them function as a single organ, which can be called a shock-reflection pair [11].

The purpose of the research is a theoretical study of the energy efficiency of the proposed grinder and an analytical expression describing the energy consumption for the implementation of the grinding process.

MATERIAL AND METHODS

It is known that the total kinetic energy of the bodies after a collision is less than before it[2]. The loss of energy is associated with a number of physical processes occurring during the impact, including deformation of the bodies

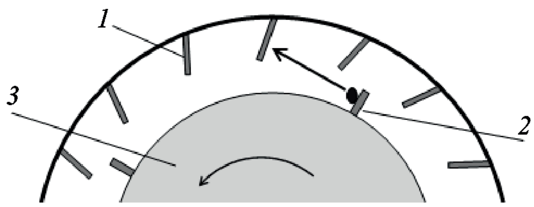

Рис. 1. Рабочие органы измельчителя (*1* – пластина, *2* – било, *3* – ротор)

Fig. 1. Working bodies of the grain grinder (*1* – plate, *2* – beater, *3* – rotor)

and development in their volumes of defects (cracks, etc.). If the aim of the collision is the destruction of one of the colliding bodies, the loss of kinetic energy indirectly shows the effectiveness of the collision. Then the ratio of losses of kinetic energy to the total energy expenditures for the implementation of the impact can be used as a criterion of the effectiveness of the device, which carries out grinding by an impact.

In the interaction of raw materials with the impact-reflection pair, the total loss of kinetic energy can be represented as a sum of energy losses in the interaction with the beater and in the interaction with the plate. Let's assume that all contacts of the particles with the surfaces of the working bodies of the grinder occur at right angles. In this case the loss of kinetic energy ΔT can be found by the formula (see footnote 2)

$$\Delta T = (1 - k^2)\,\frac{m_1 m_2 (v_1 - v_2)^2}{2(m_1 + m_2)}, \qquad (1)$$

where m_1, m_2 – the masses of colliding bodies, kg; v_1, v_2 – velocities of the bodies before collision, m/s; k – recovery factor.

Let's consider the interaction of a beater and a particle. Let M be the mass of the beater in kg, m be the mass of the particle in kg, v be the beater's linear velocity, m/s. The initial velocity of the particle before the impact is much less than the velocity of the beater, so for simplicity let's take it as equal to zero. Let's apply (1) for the given case, then the kinetic energy loss expression at the impact of the beater $\Delta T_б$ will take the following form:

$$\Delta T_б = (1 - k^2)\,\frac{Mmv^2}{2(M + m)}. \qquad (2)$$

Since the beater is rigidly fixed to the rotor, most of the rotor mass is involved in the contact with the particle. Consequently, the mass of the particle is much less than the mass of the beater ($m << M$) and in the denominator of the expression (2) it can be neglected, and the mass of the beater can be reduced:

$$\Delta T_б = (1 - k^2)\,\frac{mv^2}{2}. \qquad (3)$$

[2]Yablonsky A.A. Course of theoretical mechanics: textbook for universities. A.A. Yablonsky, V.M. Nikiforova. Moscow: Integral-Press, 2006. 608 p.

After contact with the beater, the particle may survive or collapse into pieces. In the second case, the fragments of the destroyed particle fly away from the beater, forming a bursting cone. For simplification we will assume that the fragments after the impact have the same velocity and move in the direction of the plate along the central axis of the bursting cone. We will also assume that the interaction of all the fragments of the particle with the plate is equivalent to the corresponding interaction of the particle itself if it had survived.

The velocity u, which the particle acquires after the impact of the beater, can be found using a well-known expression (see footnote 2)

$$u = v_2 + (1 + k)\frac{m_1(v_1 - v_2)}{(m_1 + m_2)}, \tag{4}$$

which, taking into account $v_1 = v$, $v_2 = 0$, $m_1 = M$, $m_2 = m$, $m << M$ will look like this:

$$u = (1 + k)v. \tag{5}$$

Let's assume that the particle's velocity u is conserved up to the moment of its contact with a stationary plate of mass Mp. Let's apply the expression (1) to find the loss of the kinetic energy $\Delta T_п$ when the particle hits the plate

$$\Delta T_п = (1 - k^2)\frac{mM_п u^2}{2(m + M_п)}. \tag{6}$$

The plate is fixed to the body of the chamber, therefore $m << Mn$ and the mass of the particle in the denominator can be neglected:

$$\Delta T_п = (1 - k^2)\frac{mu^2}{2}. \tag{7}$$

It should be taken into account that the recovery factor in the general case depends on many factors, including the impact speed. On the basis of the experiments with different grain crops S.V. Zverev proposed the following functional dependence[3, 4]:

$$k = A - Bv - C\varphi, \tag{8}$$

where A, B, C – empirical coefficients, v – impact velocity, m/s; φ – grain moisture, %.

According to the formula (5) the speed of collision of a particle with a plate is greater than that of collision with a beater and, consequently, these contacts have different recovery coefficients. Let us assume that the empirical coefficients A, B, C are constant and the grain humidity φ is fixed.

Let's denote the coefficients of recovery at contacts with the beater k and plate k_2:

$$\begin{cases} k = A - Bv - C\varphi; \\ k_2 = A - Bu - C\varphi. \end{cases} \tag{9}$$

In the second equation of the system let us substitute formula (5) and the coefficient A expressed from the first equation. By performing the transformations, we obtain:

$$k_2 = k(1 - Bv). \tag{10}$$

Let's introduce the notation: $\delta = 1 - Bv$, then
$k_2 = \delta k$. (11)

Let us determine the loss of kinetic energy ΔTп in contact with the plate, for which we transform the expression (7), taking into account formulas (5) and (11):

$$\Delta T_п = (1 - k_2^2)\frac{mu^2}{2} = (1 - \delta^2 k^2)\frac{mu^2}{2} =$$

$$= (1 - \delta^2 k^2)\frac{m}{2}(1 + k)^2 v^2 =$$

$$= \frac{mv^2}{2}(1 - \delta^2 k^2)(1 + 2k + k^2); \tag{12}$$

$$\Delta T_п = \frac{mv^2}{2}(1 + 2k + (1 - \delta^2)k^2 - 2\delta^2 k^3 - \delta^2 k^4). \tag{13}$$

Now let's find the total loss of kinetic energy ΔT during interaction of the particle with the impact -reflection pair. For this purpose, let's add expressions (3) and (13) and after transformation we obtain:

$$\Delta T = mv^2\left(1 + k - \frac{\delta^2 k^2}{2} - \delta^2 k^3 - \frac{\delta^2 k^4}{2}\right). \tag{14}$$

Energy expenditures, necessary for the realization of contacts of the particle with the working bodies of the impact-reflection pair,

[3]Zverev S.V. Zvereva N.S. Physical properties of grain and products of its processing: a textbook for students of higher educational institutions studying for a speciality 260601 (170600) "Machines and devices of food manufactures" of a direction of preparation of the certified specialist 260600 (655800) "Food engineering". DeLi Print, 2007. 175 p.

[4]Glebov L.A. et al. Enhancement of the process of grinding components of mixed fodders. Moscow: Central Scientific and Research Institute of the Ministry of Bread and Groceries of the USSR, 1988. 51 p.

are equal to the expenditures of the mechanical energy of the rotor during the interaction of the beater and the particle. After the impact the rotor energy is reduced by the value W, equal to the sum of losses of the kinetic energy at impact of the beater ΔT_b and changes in the kinetic energy ΔE of the particle:

$$W = \Delta T_б + \Delta E. \quad (15)$$

Prior to the contact with the beater the velocity of the particle is insignificant, let us assume that it is zero. Then the change of the kinetic energy is equal to the kinetic energy acquired by the particle immediately after the impact:

$$\Delta E = \frac{mu^2}{2}. \quad (16)$$

Taking into account expression (5), the following formula will look like:

$$\Delta E = \frac{mv^2}{2}(1 + k)^2. \quad (17)$$

Let's substitute expressions (3) and (17) in the formula (15) and, having performed the necessary transformations, we obtain the final expression determining energy costs associated with the process of implementation of raw material grinding in the shock-reflective pair:

$$W = mv^2(1 + k). \quad (18)$$

Let's introduce the notion of energy absorption coefficient (EAC) as a value equal to the ratio of total losses of kinetic energy in impacts to the energy input for their realization, and denote by γ. The EAC value shows the share of the mechanical energy spent, which was transformed into other types of energy, including those related to the destruction of particles. Accordingly, for a impact-reflection pair, γ is found as the ratio of ΔT to W:

$$\gamma = \frac{\Delta T}{W}. \quad (19)$$

Taking into account formulas (14) and (18), the expression γ for the impact-reflection pair will be:

$$\gamma = \frac{\left(1 + k - \frac{\delta^2 k^2}{2} - \delta^2 k^3 - \frac{\delta^2 k^4}{2}\right)}{(1 + k)}. \quad (20)$$

RESULTS AND DISCUSSION

Ratio (14) allows us to analyze the dependence of total losses of kinetic energy on the recovery coefficient during interaction of raw materials with the impact-reflection pair *ΔT(k)*. Fig. 2 shows theoretical diagrams of *ΔT(k),* built at different values of the beater's speed (30, 40, 50 m/s) per unit mass of raw material (m = 1 kg). The presence of extremums indicates that at certain values of the recovery factor k, the total loss of kinetic energy will be maximum for a given beater speed. However, the recovery factor is a function of speed [see expression (8)], so for a given speed corresponds to a certain recovery factor, which determines the value of total energy losses (marked by dots in the graphs), and it does not correspond to the maximum of the curve *ΔT(k).*

Expression (18) allows us to determine the energy costs associated with the process of grinding raw materials, and the EAC [see expression (19)] shows how effectively the energy is used in this process. The notion of EAC can be used as a criterion for comparing the efficiency of devices that grind by impact method.

It is known that destruction of raw materials by impact is also carried out in centrifugal grinders, but in comparison with rotary grind-

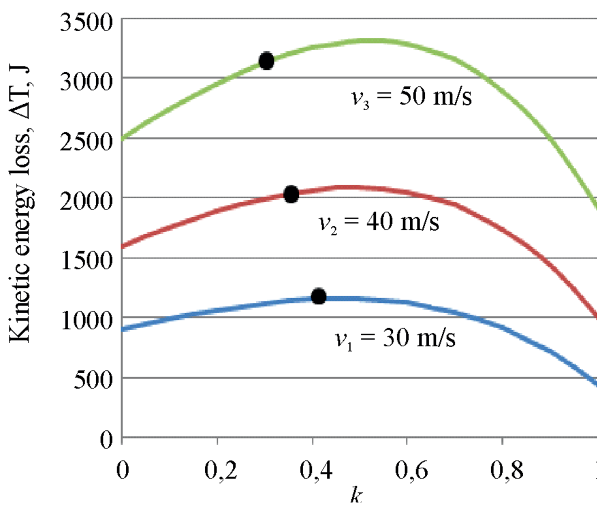

Рис. 2. Графики зависимостей общих потерь кинетической энергии Δ*T(k)* при взаимодействии сырья с ударно-отражательной парой

Fig. 2. Graphs of dependences of the total losses of kinetic energy ΔT(k) during the interaction of raw materials with an impact-reflective pair

ers, they are characterized by low energy consumption[5] [12]. Let's define EAC for the centrifugal grinder and compare it with the EAC of the impact-reflection pair. In a centrifugal grinder, raw material particles are accelerated by an accelerating disc and thrown onto stationary baffle elements, where they are destroyed by impact. Let the contact of the particles with the surfaces of the baffle elements occur at right angles. Then the loss of kinetic energy is defined by the expression

$$\Delta T_{цд} = (1 - k^2)\,\frac{mv^2}{2}, \qquad (21)$$

where m – respectively, the mass, kg; v – particle velocity (m/s), accelerated by the disk.

The energy input for the impact in a centrifugal grinder consists of the kinetic energy imparted to the particle and the work done to overcome the friction of the particle on the blade of the accelerating disk:

$$W_{цд} = \frac{mv^2}{2} + A. \qquad (22)$$

If friction on the blade is disregarded, the work to overcome friction is zero ($A = 0$) and the EAC expression for the centrifugal grinder will be:

$$\gamma_{цд} = \frac{\Delta T_{цб}}{W_{цд}} = 1 - k^2. \qquad (23)$$

Analysis of expressions (20) and (23) showed that for all possible values of the recovery factor $k \in [0,1]$ the inequality is true

$$\gamma \geq \gamma_{цд}. \qquad (24)$$

Consequently, the impact-reflection pair consumes mechanical energy more efficiently than the centrifugal grinder even without taking into account friction in the latter. Dependence graphs of EAC of the impact-reflection pair at different beating speeds (curves *1, 2, 3*) are close to each other (see Fig. 3). It means that the efficiency of impact-reflection pair does not depend on the mode of operation. At $k = 0$ (inelastic impacts), the EAC of the impact-reflection pair and the centrifugal grinder without friction on the blades (curve *4*) are equal to the maximum possible value - unity. As k increases from 0 to 1, the EAC of both the centrifugal grinder and the impact-reflection pair monotonically decrease. The EAC of the centrifugal grinder, in which friction costs are taken into account, will obviously be less than that of the grinder without friction at any value of k (curve *5*).

Substituting formula (8) into the expressions (20) and (23), the corresponding EAC dependences on speed can be obtained: for the impact-reflection pair $\gamma(v)$ and for the centrifugal crusher $\gamma cg\ (v)$ without friction. Expressions of functions $\gamma(v)$ and $\gamma cg\ (v)$ are not given here due to their magnitude, but their theoretical graphs are presented (see Fig. 4). They show the correctness of the relation

$$\gamma(v) \geq \gamma_{цд}(v) \qquad (25)$$

for any values of the velocities realized in practice. For example, calculations performed at a beating speed v = 50 m/s show that the difference between $\gamma(v)$ and $\gamma cg\ (v)$ is about 0.07 (7%). But taking into account friction, the curve $\gamma cg\ (v)$ will be much lower than $\gamma(v)$, and the difference between $\gamma(v)$ and $\gamma cg\ (v)$ will become significant. It should be noted that the shock-reflective pair is opposed to such a centrifugal grinder, in which the speed of collision of particles with the baffling elements is equal to the speed of the beater of the shock-reflective

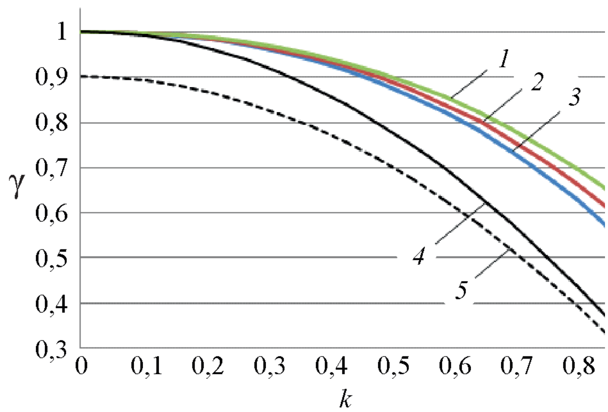

Рис. 3. Графики зависимостей $\gamma(k)$ ударно-отражательной пары (*1* – 30 м/с, *2* – 40 м/с, *3* – 50 м/с) и центробежной дробилки $\gamma_{цд}(k)$ (*4, 5*)

Fig. 3. Graphs of dependences γ(k) of an impact-reflective pair (*1* – 30 m/s, *2* – 40 m/s, *3* – 50 m/s) and a centrifugal crusher $\gamma_{цд}$(k) (*4, 5*)

[5] *Золотарев С.В.* Ударно-центробежные измельчители фуражного зерна (основы теории и расчета). Барнаул: ГИПП «Алтай», 2001. 200 с.

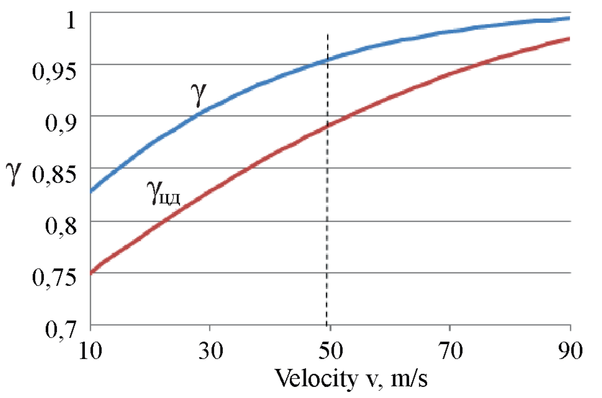

Рис. 4. Графики зависимостей КПЭ для ударно-отражательной пары $\gamma(v)$ и для центробежной дробилки $\gamma_{цд}(v)$ без учета трения

Fig. 4. Graphs of dependences of the energy absorption coefficient for the impact-reflective pair $\gamma(v)$ and for the centrifugal crusher $\gamma_{цд}(v)$ without friction

pair. In calculations and graphs (see Fig. 2-4) empirical coefficients are used (see footnote 3): A = 0,66; B = 0,0043; C = 0,009 for barley at humidity φ = 13%.

CONCLUSION

The analytical expression for determining the energy costs associated with the grinding of raw materials in the working area of the impact-reflection pair of the proposed grinder is found. The criterion characterizing the efficiency of the device in energy expenditures for the destruction of raw materials by impact actions is introduced. The advantage of the proposed grinder in energy efficiency in comparison with centrifugal grinders, which, as a rule, are characterized by low values of energy consumption, is shown on the basis of this criterion.

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Дата поступления статьи / Received by the editors 25.05.2022
Дата принятия к публикации / Accepted for publication 08.09.2022
Дата публикации / Published 27.12.2022