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«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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IMPROVEMENT OF THE GRINDING PROCESS OF BULK MATERIALS IN AN IMPACT-CENTRIFUGAL MILL

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Abstract. *Relevance.* Obtaining powders with a uniform particle size distribution during the grinding of bulk materials in impact-centrifugal mills is one of the important tasks of modern industry. The need for such studies is associated with the desire to reduce the energy consumption of the grinding process and improve the quality of the final product, since the particle size distribution significantly affects the efficiency of subsequent technological operations in various industries. *Methods.* An analysis of existing designs of impact-centrifugal mills was carried out and the main directions for improving the grinding process were identified. A design of an impact-centrifugal mill equipped with a particle trajectory modification element installed on the rotor disk is proposed. The study was carried out using an experimental approach combined with analysis of particle motion in the working zone of the mill. A tracer method was used to determine particle trajectories along the surface of the accelerating blades, while the particle size distribution of the grinding products was determined by sieve analysis. *Results.* It was established that the use of the particle trajectory modification element makes it possible to distribute particles along the height of the accelerating blades depending on their size and to ensure their detachment from the blades at different heights. This improves the efficiency of particle destruction during impact interaction. Experimental studies were carried out during grinding of wheat, petroleum coke, and sylvinite in an impact-centrifugal mill equipped with a trajectory modification element with a height of 10–20 mm. It was shown that the proposed element provides finer grinding and a more uniform particle size distribution of the grinding product. *Conclusions.* The obtained results confirmed that the use of the particle trajectory modification element improves grinding quality and reduces the energy intensity of the process. The research results can be used in the design and modernization of equipment for grinding bulk materials.

Keywords: impact-centrifugal mill, rotor, grinding, particle size distribution, wheat, petroleum coke, sylvinite

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СОҚҚЫ-ОРТАДАН ТЕПКІШ ДИІРМЕНДЕ СУСЫМАЛЫ МАТЕРИАЛДАРДЫ ҰНТАҚТАУ ПРОЦЕСІН ЖЕТІЛДІРУ

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Аннотация. *Өзектілігі.* Сусымалы материалдарды соққы-орталықтан тепкіш диірмендерде ұнтақтау кезінде біркелкі гранулометриялық құрамдағы ұнтақтарды алу қазіргі өнеркәсіптің өзекті мәселелерінің бірі болып табылады. Мұндай зерттеулерді жүргізу қажеттілігі ұнтақтау процесінің энергия шығындарын төмендетуге және дайын өнімнің сапасын арттыруға ұмтылыспен байланысты, себебі бөлшектердің өлшемдік құрамы әртүрлі өнеркәсіп салаларындағы кейінгі технологиялық процестердің тиімділігіне елеулі әсер етеді. Әдістері. Жұмыста соққы-орталықтан тепкіш диірмендердің қолданыстағы конструкцияларына талдау жүргізіліп, ұнтақтау процесін жетілдірудің негізгі бағыттары анықталды. Ротор дискісіне орнатылған бөлшектер қозғалысының траекториясын өзгерту элементі бар соққы-орталықтан тепкіш диірменнің конструкциясы ұсынылды. Зерттеу бөлшектердің диірменнің жұмыс аймағындағы қозғалысын талдай отырып, эксперименттік әдіспен жүргізілді. Үдеткіш қалақшалар бетімен бөлшектердің қозғалыс траекторияларын анықтау үшін трассерлік әдіс қолданылды, ал ұнтақтау өнімдерінің гранулометриялық құрамы елеу (ситалық) талдау әдісімен анықталды. *Нәтижелері.* Бөлшектер қозғалысының траекториясын өзгерту элементін қолдану бөлшектерді олардың өлшеміне байланысты үдеткіш қалақшалардың биіктігі бойынша таратуға және олардың әртүрлі биіктіктен ажырауын қамтамасыз етуге мүмкіндік беретіні анықталды. Бұл соққы әсері кезінде бөлшектердің бұзылу тиімділігін арттырады. Эксперименттік зерттеулер бидай, мұнай коксы және сильвинитті ұнтақтау кезінде, траекторияны өзгерту элементінің биіктігі 10–20 мм болатын соққы-орталықтан тепкіш диірменде жүргізілді. Ұсынылған элементті қолдану ұнтақтау өнімінің неғұрлым ұсақ әрі біртекті гранулометриялық құрамын қамтамасыз ететіні көрсетілді. *Қорытынды.* Алынған нәтижелер бөлшектер қозғалысының траекториясын өзгерту элементін қолдану ұнтақтау сапасын арттыруға және процестің энергия сыйымдылығын төмендетуге мүмкіндік беретінін көрсетті. Зерттеу нәтижелері сусымалы материалдарды ұнтақтауға арналған жабдықтарды жобалау және жетілдіру кезінде қолданылуы мүмкін.

Түйін сөздер: соққы-орталықтан тепкіш диірмен, ротор, ұнтақтау, гранулометриялық құрам, бидай, мұнай коксы, сильвинит

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СОВЕРШЕНСТВОВАНИЕ ПРОЦЕССА ИЗМЕЛЬЧЕНИЯ СЫПУЧИХ МАТЕРИАЛОВ В УДАРНО-ЦЕНТРОБЕЖНОЙ МЕЛЬНИЦЕ

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Аннотация. *Актуальность.* Получение порошков с равномерным гранулометрическим составом при измельчении сыпучих материалов в ударно-центробежных мельницах является одной из актуальных задач современной промышленности. Необходимость таких исследований обусловлена стремлением снизить энергозатраты процесса измельчения и повысить качество готового продукта, поскольку размерный состав частиц оказывает существенное влияние на эффективность последующих технологических операций в различных отраслях промышленности. *Цель*. Совершенствовать процесс измельчения сыпучих материалов в ударно-центробежной мельнице за счет применения элемента изменения траектории движения частиц и оценить его влияние на гранулометрический состав готового продукта. *Методы*. В работе проведен анализ существующих конструкций ударно-центробежных мельниц и определены основные направления совершенствования процесса измельчения. Предложена конструкция ударно-центробежной мельницы с элементом изменения траектории движения частиц, установленным на диске ротора. Исследование проводилось экспериментальным методом с анализом движения частиц в рабочей зоне мельницы. Для определения траекторий движения частиц по поверхности разгонных лопастей применялся трассерный метод, а гранулометрический состав продуктов измельчения определялся методом ситового анализа. *Результаты и выводы*. Установлено, что использование элемента изменения траектории позволяет распределять частицы по высоте разгонных лопастей в зависимости от их размеров и обеспечивать их сход с различной высоты. Это способствует повышению эффективности разрушения частиц при ударном взаимодействии. Экспериментальные исследования проводились при измельчении пшеницы, нефтяного кокса и сильвинита на ударно-центробежной мельнице с элементом изменения траектории высотой от 10 до 20 мм. Показано, что применение данного элемента обеспечивает получение более тонкого и однородного по размерному составу продукта измельчения. Полученные результаты подтверждают эффективность использования элемента изменения траектории движения частиц для повышения качества измельчения и снижения энергоемкости процесса. Результаты исследования могут быть использованы при проектировании и модернизации оборудования для измельчения сыпучих материалов.

Ключевые слова: ударно-центробежная мельница, ротор, измельчение, гранулометрический состав, пшеница, нефтяной кокс, сильвинит

Introduction. The grinding process is widely used in industrial processing of materials and occupies an important place in the chemical, construction, engineering, mining and agricultural industries. During grinding, the sizes of various solid materials are reduced (Bogdanov, 2022; Afanasiev, 2025). Subsequent technological operations, the reactivity of materials, their transport characteristics and the quality of the final product largely depend on the efficiency of this process.

The destruction of the material during crushing can occur due to splitting, compression, impact, abrasion and other mechanical influences. In practice, in most industrial installations, several destruction mechanisms are implemented simultaneously. The choice of the most effective grinding method is determined primarily by the physical and mechanical properties of the processed material. For elastic and plastic materials, methods based on cutting and shearing are considered more effective, since impact in this case often causes only elastic deformation without destroying the material (Zhirov, 2019). At the same time, for brittle materials, the impact crushing method is the most effective, which ensures rapid particle destruction.

Studies show that the specific energy consumption during impact grinding is significantly lower compared to compression or abrasion grinding. This is due to the fact that brittle materials break down faster and more efficiently during high-speed impact: cracks spread more intensively, and energy losses during particle destruction remain minimal (Levdansky, 2005). For this reason, impact technologies are widely considered as one of the most energy-efficient ways to produce fine and ultrathin powders from brittle materials.

Among the various types of impact equipment, special attention is paid to impact-centrifugal mills. This is due to their relatively simple design and high rotational speed of the working bodies. The basis of such a mill is a rotor with working elements located inside a cylindrical body with a reflective surface. As a rule, the rotor is made in the form of a disk with blades along the periphery. During operation, the material particles are accelerated by the blades, acquiring kinetic energy, and then collide with the impactors or the inner surface of the housing, where they are destroyed.

Compared with other types of crushing equipment, impact centrifugal mills have a number of advantages. They are characterized by lower specific energy consumption, relatively simple design and ease of operation. In addition, such mills are characterized by lower metal consumption, and the degree of grinding can be changed by adjusting the speed of rotation of the rotor (Khetagurov, 2018; Levdansky, 2008). In recent years, the development of high-speed rotary systems has mainly focused on improving the design and increasing the efficiency of energy transfer to the crushed material.

Despite these advantages, impact centrifugal mills still have a number of problems. One of the most serious is the rapid wear of the working elements of the equipment. Another important problem remains the significant variation in particle sizes in the finished product. If the issue of wear resistance can be partially solved by using high-strength steels and carbide surfacing materials, then increasing the uniformity of the product requires further improvement of the design of the working chamber and the organization of particle movement inside the mill.

Analysis of particle motion within the rotor of an impact-centrifugal mill shows that particle acceleration along the blade surfaces mainly occurs within a single geometric plane, regardless of particle size (Grebenchuk, 2013; Garkavi, 2016; Lipanov, 2015). As a result, larger particles may not hit the required number of impact events before leaving the grinding zone, while smaller particles may break apart too much. This causes uneven product distribution and wasteful energy use.

One of the modern approaches to increasing the uniformity of grinding is to control the movement of particles inside the rotary chamber, as well as improve the design of the blades and adjust the height of the material descent. When the trajectory of the particles along the accelerating blades changes, larger particles are separated at a higher height relative to the rotor disc, while smaller particles are separated closer to its lower part. This particle size distribution contributes to a more efficient interaction of the particles with the impact surfaces. As a result, a more uniform granulometric composition of the finished product is provided (Dhakate, 2023; Matveev, 2022).

Grinding and crushing processes are widely used in many industries such as mineral processing, chemical industry and materials science. At the same time, grinding accounts for a significant part of energy consumption, so improving the efficiency of grinding equipment remains one of the important scientific and practical tasks (Maregedze, 2024). Modern research shows that more efficient interaction of material particles with the working elements of the equipment allows not only to reduce energy consumption, but also to obtain a product with a more uniform granulometric composition.

Impact-centrifugal mills are high-speed grinding equipment in which material particles are accelerated by rotor blades and destroyed upon collision with impact surfaces. Research shows that the efficiency of the process and the properties of the finished product are significantly affected by parameters such as the number of blades, rotor diameter and impact velocity (Leudanski, 2020). Experimental data indicate that increasing the number of blades to a certain value increases the fineness of the grinding. However, after reaching the optimal value, a further increase in the number of blades has almost no noticeable effect (Fedarovich, 2024).

The improvement of impact mills is not only related to changing their size or the shape of the blades. Much attention is also paid to studying the behavior of various materials during grinding and analyzing the energy consumption of the process (Wills, 2016). Such studies help to determine under what conditions grinding is most effective and how the equipment parameters affect the quality of the finished product.

Several new mill designs have been proposed in recent years. For example, Guryanov and coauthors (2025) developed a modified impact mill with a different operating principle. Research results have shown that the new design provides more efficient particle destruction and at the same time reduces energy consumption (Guryanov, 2025). This confirms the researchers' desire to improve traditional grinding equipment, make the process more efficient and increase the fineness of grinding.

Currently, computer simulation methods are widely used to study grinding processes. CFD-DEM modeling is one of the most common research methods today. This method allows for a more detailed analysis of particle motion, air flows, and collision processes inside the mill (Shen, 2024). Such models help to better understand the effect of rotor speed, airflow, and other parameters on grinding efficiency. Although many studies are devoted to other types of mills, the results obtained can also be useful for improving impact-centrifugal mills.

Special attention is paid to studying the movement of particles inside the working chamber and their interaction during the operation of the equipment (Dmytrak, 2025). Such studies make it possible to explain the grinding mechanism in more detail and determine the conditions under which particle destruction occurs most effectively.

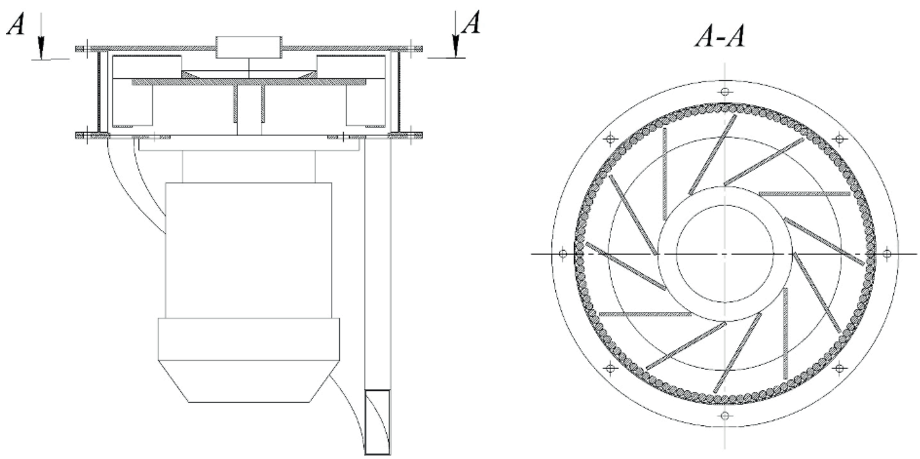
At the same time, the issues of controlling the movement of particles inside impact-centrifugal mills are still insufficiently studied. This is especially true for the use of special elements capable of changing the trajectory of particles along the rotor blades. The use of such elements can increase the efficiency of particle collisions and improve the uniformity of the final product.

Thus, the conducted research has significantly expanded the understanding of grinding processes and the operation of impact-centrifugal mills. However, the problem of controlling the trajectories of the particles still remains unresolved.

Therefore, research aimed at improving the rotor design in order to improve grinding quality and reduce energy consumption continues to be relevant.

Despite the considerable number of studies devoted to impact grinding and the improvement of impact-centrifugal mills, the problem of controlling particle trajectories inside the rotor zone remains insufficiently investigated. In particular, limited attention has been paid to the use of structural elements capable of modifying particle motion along the accelerating blades. Therefore, the aim of this study is to investigate the influence of a particle trajectory modification element mounted on the rotor disk on particle motion behavior and the granulometric composition of grinding products.

Materials and methods. Experimental investigations of the grinding process of bulk materials were carried out on the impact-centrifugal mill developed by us (Figure 1).



1 – housing; 2 – upper flange; 3 – lower flange; 4 – cover; 5 – bottom plate;
6 – feed inlet; 7 – reflective surface; 8 – electric motor;
9 – rotor disk; 10 – accelerating blades; 11 – impact blades; 12, 13 – stiffening rings;
14 – particle trajectory modification element (PTME); 15 – discharge outlet.
Figure 1. Impact-centrifugal mill.

The mill consists of a vertical cylindrical housing (1), which is attached by means of the upper (2) and lower (3) flanges to the cover (4) and the bottom plate (5), respectively. A feed inlet (6) is provided in the cover for supplying the initial material. Inside, the housing is lined with impact reflective rods (7). An electric motor (8) is mounted to the bottom plate of the mill. The rotor is installed on the motor shaft and consists of a disk (9), on which accelerating blades (10) are rigidly fixed in the upper part along the periphery, and impact blades (11) are installed in the lower part. The accelerating blades are interconnected by a stiffening ring (12), and the impact blades are similarly connected by a ring (13). A particle trajectory modification element (14) (TME) is located in the central region of the rotor disk at the entrance to the inter-blade space of the accelerating blades. For the discharge of the ground products, a semicircular channel is provided in the bottom plate (5), to which a spiral-shaped discharge outlet (15) is attached (Levdansky, 2004).

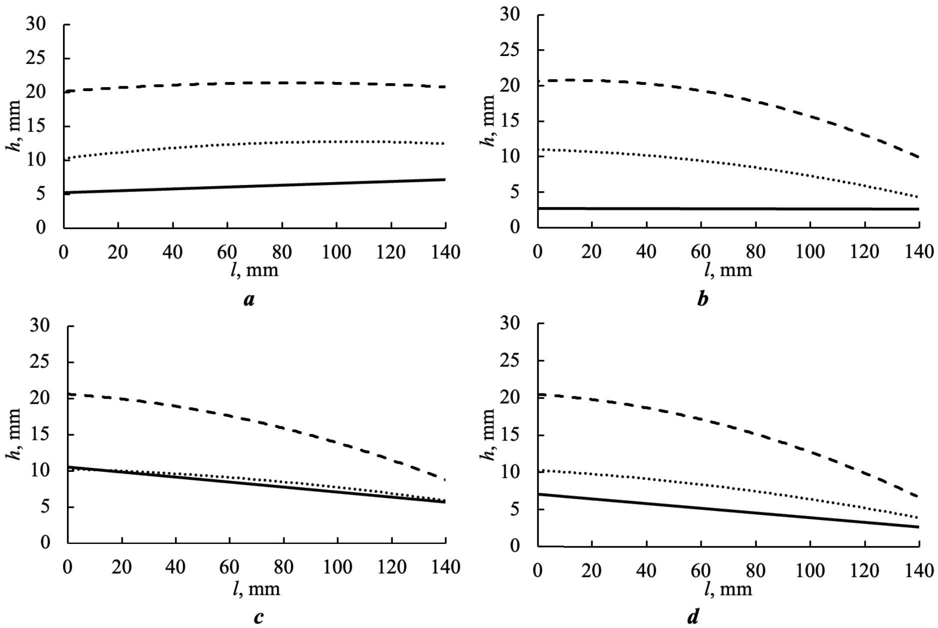
The developed mill operates as follows. The electric motor (8) drives the rotor of the mill, which consists of the disk (9), the accelerating (10) and impact (11) blades, the TME (14), and the fixing rings (12, 13). During rotor rotation, a rarefaction zone is formed in the center of the disk (9), due to which air enters the mill through the feed inlet (6). The air acts as a transporting medium for the ground material toward the discharge outlet (15) (Levdansky, 2004).

The initial material supplied for grinding through the feed inlet (6), depending on its initial particle size, may fall onto the surface of the disk (9), be influenced by the airflow and directed to the surface of the TME (14), or immediately enter the accelerating blades (10). Large particles that fall onto the surface of the disk (9) or the TME (14), under the action of centrifugal inertial force, move from the center of the disk (9) toward the periphery, are lifted by the TME (14), and then enter the upper part of the accelerating blades (10). Moving through the inter-blade space formed by the accelerating blades (10), the material is accelerated to velocities regulated by the rotor rotational speed, and upon detachment from the blades, it collides with the reflective rods (7). During impact of the particles against the impact rods (7), grinding occurs.

The fine particles formed during grinding are captured by the downward air stream and, together with it, while rotating, descend to the discharge outlet (15). Larger (insufficiently ground) particles rebound from the impact rods (7) and, due to gravitational force and the influence of the downward air flow, fall under the impact of the impact blades (11) (Levdansky, 2004). When colliding with the impact blades (11), the particles undergo partial fragmentation and then, moving along them, are accelerated and thrown back to the impact rods (7) for repeated grinding. Repeated impact destruction occurs many times until the particles reach the required degree of fineness. Due to their small size, after rebounding from the impact rods (7), they either cannot reach the impact blades (11) or descend below them, and together with the air flow are removed from the mill through the discharge outlet (15) (Levdansky, 2004).

The determination of particle motion trajectories was carried out as follows. White sheets of paper were attached over the entire surface of the accelerating blades. During mill operation, colored particles were fed through the feed inlet. As the particles moved along the accelerating blades, marks of their trajectories remained on the surface of the white sheets. Silica gel particles with size fractions of 0.5–1 mm, 1–2 mm, and 4–5 mm were used as the colored particles. The use of silica gel particles was justified by their spherical shape. After completion of the experimental investigations, the sheets were removed, and the positions of the traces left by the colored silica gel particles were recorded. Further, based on the obtained coordinates along the blade height (h, mm) and length (l, mm), trajectory graphs were constructed depending on particle size, rotor rotational speed, and the height of the trajectory modification element.

Results and Discussion. The trajectories of particles with different size fractions moving along the surface of the accelerating blades at various rotor rotational speeds (n, rpm) are presented in Figure 2.



——— - without the use of the trajectory modification element (TME);

---------- - with a trajectory modification element (TME) height of 10 mm;

— — — - with a trajectory modification element (TME) height of 20 mm.

Figure 2. Experimentally obtained particle motion trajectories for silica gel fractions under different operating conditions: (a) 4–5 mm, n = 3000 rpm; (b) 4–5 mm, n = 1800 rpm; (c) 1–2 mm, n = 3000 rpm; (d) 1–2 mm, n = 1800 rpm.

The experimental results demonstrated that the installation of the trajectory modification element (TME) on the rotor disk significantly influences particle trajectories and their detachment height from the accelerating blade surface. It was established that larger silica gel particles (4–5 mm) at a rotor speed of 3000 rpm are lifted by the TME and detach from the blade surface at a height comparable to the height of the TME. Under the same rotational speed, smaller particles (1–2 mm) detach at a considerably lower height. When a TME with a height of 20 mm was installed, the detachment height of these particles was approximately 10–12 mm.

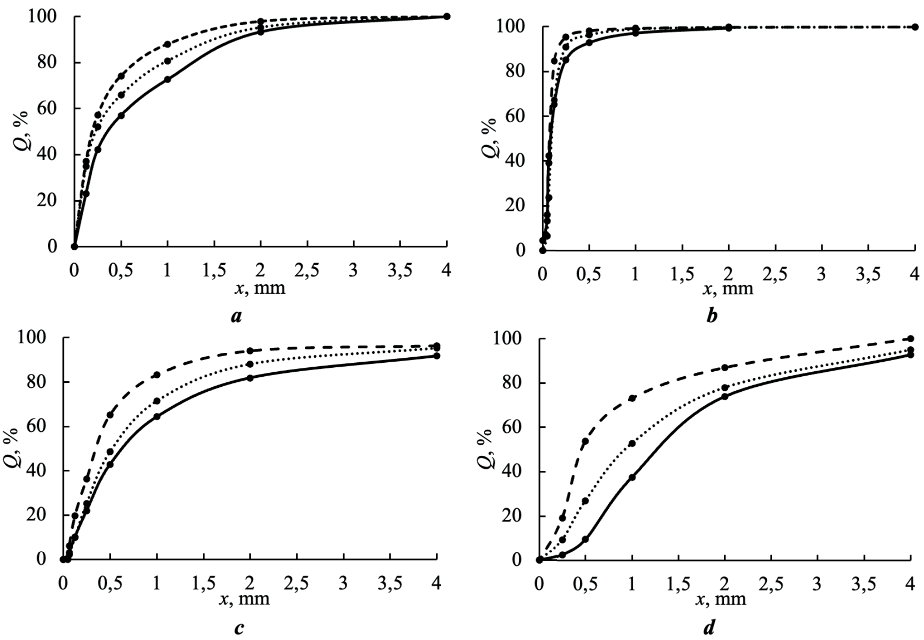
The reduction in detachment height for smaller particles is associated with the influence of the airflow. The smaller the particle size, the lower its inertial resistance and the greater the aerodynamic effect acting upon it. In the impact-centrifugal mill, where the air stream moves from the feed inlet toward the discharge outlet, the main air mass in the inter-blade space flows near the rotor disk surface, pressing particles toward it (Levdansky, 2004). Larger particles are less affected by the airflow; therefore, after being redirected by the TME, they move predominantly within a single plane due to centrifugal forces.

However, reducing the rotor speed to 1800 rpm changes the particle motion trajectories. For 4–5 mm particles with a 20 mm TME, detachment occurs at a height of 10–15 mm relative to the rotor disk. When the TME height is 10 mm, the detachment height increases by 2–3 mm compared to operation without the TME. These results are consistent with physical expectations, since decreasing rotor speed reduces the centrifugal force acting on the particles. Consequently, particles are pressed less strongly against the accelerating blades and, under gravity, move closer to the rotor disk surface.

Comparable results were obtained for 1–2 mm particles at n = 3000 rpm. However, comparison of data obtained at 1800 and 3000 rpm shows that the detachment height for 1–2 mm particles changes only slightly, in contrast to the more pronounced changes observed for 4–5 mm particles. This behavior of the particles is associated with a more intense effect of the air flow at a rotational speed of 3000 rpm on particles 1-2 mm in size. Under the action of the flow, they are pressed harder against the rotor disc. When the speed decreases to 1800 rpm, the centrifugal force decreases, so the holding effect on the surface of the blades becomes less pronounced (Fedarovich, 2024).

Trajectory analysis of 0.5–1 mm silica gel particles showed that the TME has a negligible influence on their motion. When these particles are introduced into the mill, they are captured by the airflow and transported directly into the inter-blade space of the accelerating blades, with minimal contact with the rotor disk and the TME.

To evaluate the influence of the TME on the granulometric composition of the grinding products, experimental comminution tests were conducted using different materials in the developed impact-centrifugal mill. The rotor diameter at the outer blade edges was 0.45 m. The number of accelerating and impact blades was 12, installed at an angle of 15° to the radial direction opposite to the direction of rotation. Wheat grains, petroleum coke, and sylvinite were used as the processed materials. The initial particle size distribution of petroleum coke and sylvinite was 10–8 mm, 5–4 mm, 4–2 mm, and 2–1 mm. The rotor rotational speed during wheat and petroleum coke grinding ranged from 600 to 3000 rpm, while for sylvinite it ranged from 600 to 1200 rpm. The particle size distribution of the grinding products was determined by mechanical sieve analysis. Each experimental test was carried out three times, and the average values were used for the analysis. The deviation between repeated measurements did not exceed 5%. The mass retained on each sieve was recorded, and cumulative particle size distribution curves (Q, %) versus sieve size (x, mm) were constructed. The results are presented in Figure 3.



——— - without the use of the trajectory modification element (TME);
--------- - with a trajectory modification element (TME) height of 10 mm;
— — — - with a trajectory modification element (TME) height of 20 mm.

Figure 3. Particle size distribution of the grinding products: (a) wheat grains at n = 2400 rpm; (b) petroleum coke at n = 2400 rpm; (c) petroleum coke at n = 600 rpm; (d) sylvinite at n = 600 rpm.

For wheat grinding, the use of the TME at rotor speeds from 600 to 3000 rpm led to a reduction in the amount of under-ground material in the product (Figure 3a). Specifically, installation of a 20 mm high TME reduced the 4–2 mm fraction by 9.01% at n = 3000 rpm, by 15.4% at n = 2400 rpm, and by 20.21% at n = 1200 rpm. Simultaneously, the proportion of fine fractions (0.125–0.25 mm) increased by 16.53% at n = 3000 rpm, 13.97% at n = 2400 rpm, and 11.59% at n = 1200 rpm. Thus, the TME increased the fineness of the obtained powder across the entire studied rotational speed range. This effect is primarily attributed to the narrow initial size distribution of wheat grains, which results in uniform exposure to additional impact loads due to trajectory modification.

In petroleum coke grinding, changes in the particle size distribution strongly depended on rotor speed (Figures 3b, c). At n = 3000 rpm, the 2–4 mm fraction decreased by only 0.42% with a 20 mm TME, whereas at 1800 rpm and 600 rpm the reductions were 2.91% and 12.2%, respectively. The minimal effect at high rotational speed is explained by the high brittleness and low mechanical strength of petroleum coke particles. At high peripheral velocities, sufficient kinetic energy is transferred to the material, leading to fracture upon the first impact. Because of this, the effect of the separation height becomes less pronounced. At low rotational speeds, the destruction of particles occurs gradually, as a result of successive multiple impacts. In such conditions, increasing the separation height can increase the grinding efficiency. The proportion of fine fractions (<0.25 mm) increased within the range of 9.51–13.44% across the studied rotational speeds.

Sylvinite is characterized by low mechanical strength, with a Mohs hardness not exceeding 2. Similar to petroleum coke, the installation of the TME at higher rotor speeds (1200 rpm) did not significantly affect the content of coarse fractions. However, at n = 600 rpm, the effect was substantial. The presence of a 20 mm TME reduced the 2–4 mm fraction by 12.91%. The proportion of particles larger than 4 mm decreased from 7.17% (without TME) to 5.03% with a 10 mm TME and to less than 0.5% with a 20 mm TME. Meanwhile, the 0.25–0.5 mm fraction increased by 16.59% at the same rotational speed with a 20 mm TME.

These results confirm that the installation of the trajectory modification element enables the production of a narrower particle size distribution for sylvinite grinding. Selective impact comminution with the TME allows the material to be ground to particle sizes below 0.8 mm, which is required for the liberation of potassium chloride crystals (Pechkovskiy, 1978). At the same time, it is necessary to minimize particles smaller than 0.05 mm, which are difficult to recover during flotation and may be discarded. The use of the TME enables achievement of the required granulometric parameters at lower rotor speeds, thereby reducing the specific energy consumption of the grinding process. Similar tendencies associated with improved grinding efficiency due to controlled particle motion were also reported in studies devoted to high-speed impact grinding systems (Shen, 2024; Guryanov, 2025).

Conclusion. Previously used rotor designs of impact-centrifugal mills intended for fine grinding do not provide sufficiently high efficiency. The achievement of fine particle size reduction was mainly ensured by increasing the rotor rotational speed and enlarging its diameter. In this case, the selection of these parameters was determined by the largest particles present in the feed material. Such an approach led to significant overgrinding of smaller particles, resulting in additional energy consumption. Moreover, extra energy was required to increase the rotor speed of the impact-centrifugal mill.

The use of a rotor equipped with a trajectory modification element (TME) enables more rational utilization of the entire working volume of the mill. When selecting the nominal rotor rotational speed, larger particles of the feed material are directed toward the upper regions of the reflective surface, thereby increasing the number of impact interactions they experience. As a result, the required fineness of grinding is achieved through controlled redistribution of particle trajectories rather than solely through increased rotational speed.

At the same time, overgrinding is minimized, which, together with the reduction in rotor rotational speed, decreases the specific energy consumption of the grinding process. The proposed design improves the uniformity of the particle size distribution and enhances the energy efficiency of the comminution process without requiring an increase in rotor diameter or excessive operational speed.

The obtained results confirm the effectiveness of trajectory-controlled impact grinding and demonstrate the technical feasibility of implementing the proposed modification in industrial-scale impact-centrifugal mills.

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