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Study of the feasibility of classifying oversized lump material during conveyor transportation

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Abstract. In the modern mining and metallurgical industry, the operational stability of preparatory processing equipment, such as crushers and mixers, is significantly dependent on the uniformity of the granulometric structure distribution of the feed material. The presence of oversized lump material leads to dynamic overloads,

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accelerated wear of working components, and increased energy consumption. Conventional classification methods using scalping screens are economically inefficient at low contents of oversized lump material, which necessitates the development of cost-effective classification methods directly on conveyor lines. The aim of this study was to provide a scientific justification for the design of a machine for the mechanical removal of large-sized inclusions from a flow of bulk material in the unloading zone of a belt conveyor, based on a previously developed segregation heterogeneity model. The study employs methods of mathematical modeling, theoretical mechanics, and particle dynamics, which made it possible to substantiate the design of a classification device in the form of a rotating rod comb positioned above the conveyor discharge pulley. It has been established that the rational operating regime is achieved by matching the linear velocity of the belt with the kinematic parameters of the rod tip rotation, thereby minimising energy losses due to sliding. It has been mathematically proven that a rod profile in the form of a clothoid ensures its penetration into the material bulk along the normal path, significantly reducing impact loads. A comprehensive dynamic model has been developed, describing three stages of interaction: particle extraction from the layer, its relative motion along the rod surface, and free flight, which makes it possible to determine the geometric boundaries of the oversized lump material dispersion zone. This enables precise positioning of receiving hoppers and deflector plates for oversized lump material. The obtained mathematical models and geometric relationships allow for the design of efficient pre-classification units integrated into existing conveyor systems, ensuring protection of process equipment from overloads without the need for bulky and energy-intensive machinery

Keywords: belt conveyor; material segregation; mechanical classification; rotating rod comb; particle free-flight trajectory; size classification; discharge assembly

Introduction

Under current operating conditions of mining and metallurgical enterprises, ensuring the stable and reliable performance of equipment employed in material preparation processes is one of the key factors in improving production efficiency and reducing operating costs. The performance of crushing, mixing, and compaction equipment is strongly influenced by the granulometric composition of the feed material, particularly by the presence of isolated oversized lumps exceeding the permissible dimensions, as well as frozen or consolidated agglomerates formed due to moisture, temperature fluctuations, and prolonged storage. The entry of such inclusions into process equipment disrupts the prescribed operating conditions, increases dynamic loading, intensifies the wear of working components, and raises energy consumption, thereby adversely affecting the reliability of technological systems.

One of the most extensively investigated research directions concerns the influence of feed granulometric composition on the performance of crushing equipment. B. Rocha *et al*. (2024) conducted industrial-scale investigations of an HP500 cone crusher to determine the influence of feed characteristics on its operational performance. The authors analysed the effects of the maximum feed particle size, width of the relieve slot, and the physical and mechanical properties of the ore on crushing performance. Their results demonstrated that increasing the size of the largest feed particles decreases crusher throughput. Moreover, feed size, together with the width of the relieve slot and material properties, was identified as one of the principal factors governing crushing efficiency. These findings emphasise the necessity of limiting the entry of oversized lumps into the crusher to ensure stable equipment operation. Further development of this research direction was presented by M. Lindqvist & H. Li (2021), who developed a mathematical model of a cone crusher integrating a material breakage model with an energy-based description of the crushing process. Using numerical simulations, the authors investigated the influence of feed granulometric composition on crusher capacity, specific energy consumption, and the particle size distribution of the final product. It was found that increasing the upper feed size limit alters the material flow pattern within the crushing chamber, impedes particle movement through the compression zone, and causes a non-uniform distribution of loading over the crushing surfaces. As a consequence, fluctuations in power consumption occur, crushing efficiency decreases, and the wear rate of the working components increases.

An alternative approach to this problem was proposed by P. Itävuo & M. Vilkko (2021), who investigated the stabilisation of the crushing process through automatic control of a cone crusher operating under variable feed conditions. The developed control system maintained a predetermined reduction ratio regardless of fluctuations in feed granulometric composition. Industrial-scale tests demonstrated that the proposed control strategy substantially reduced process variability while increasing the average productivity of the crushing complex. Nevertheless, the need for sophisticated automatic control systems itself confirms that fluctuations in feed granulometric composition constitute one of the primary factors affecting cone crusher performance. The detrimental effect of oversized lumps is equally significant in hammer crushers, where material breakage is predominantly achieved through impact loading. T. Abilzhanuly *et al*. (2024) investigated the dynamics of material motion within the crushing chamber of a hammer crusher and demonstrated that feed granulometric composition, together with the design parameters of the working elements, significantly affects particle kinematics, process energy consumption, and the quality of the final product. The study showed that increasing particle size alters particle trajectories, modifies impact conditions, and reduces the uniformity of material breakage, ultimately resulting in deteriorated technological performance.

The practical consequences of hard oversized lumps inclusions entering industrial hammer crushers were examined by E. Kyekyere *et al*. (2024), who analysed the causes of premature failure of grate bars in a reversible hammer crusher used for secondary coal crushing. Based on macrostructural and microstructural analyses of damaged components, the authors concluded that one of the principal causes of intensive wear and failure was direct impact loading induced by hard oversized lumps entering the crushing chamber. Such particles were shown to intensify abrasive wear, promote fatigue crack initiation, and accelerate brittle fracture of working surfaces. The study concluded that maintaining uniform feed conditions and restricting the entry of oversized lumps are essential for increasing the service life of crusher components and ensuring stable equipment operation.

However, the above-mentioned studies are primarily focused on improving crusher design, developing mathematical models of the crushing process, or designing control systems capable of compensating for the adverse effects of fluctuating feed granulometric composition. In contrast, the problem of removing isolated oversized lumps directly from the bulk material stream on conveyor routes before the material enters the crushing equipment, thereby preventing overloads at an earlier stage of the technological process, has received very limited attention. The adverse effect of non-uniform granulometric composition is also observed in bulk material mixing processes, where particle size governs particle motion, the intensity of circulation flows, and the uniformity of mixture formation. Recent studies have demonstrated that variations in granulometric composition substantially affect the energy and kinematic characteristics of the mixing process, as well as the mechanical loads acting on the working elements of mixing equipment.

G. Chandratilleke *et al*. (2021) employed the Discrete Element Method (DEM) to investigate the mixing of bulk materials in a ribbon mixer, aiming to determine the influence of the physic and mechanical properties and granulometric composition of the material on process performance. The authors analysed circulation flow patterns, mixing kinetics, and variations in the torque acting on the mixer drive shaft. The results revealed that an increase in particle size significantly alters material circulation, prolongs the time required to achieve a homogeneous mixture, and increases the torque required for mixing. These findings clearly indicate that the granulometric composition of the feed material directly affects the energy performance of mixing equipment. Similar conclusions were reported by Z. Zuo *et al*. (2023) in their investigation of bulk material mixing in a paddle mixer. Based on experimental studies combined with DEM simulations, the authors analysed the influence of the design parameters of the mixing blades, rotational speed, and material properties on particle motion. It was established that increasing particle size modifies particle trajectories, circulation velocity, and the intensity of interparticle interactions, leading to reduced mixture homogeneity and lower mixing efficiency. These findings further confirm that a stable granulometric composition of the feed material is one of the key prerequisites for the efficient operation of mixing equipment.

The problem of increased mechanical loading on mixer components was investigated by D. Han *et al*. (2022), who analysed the wear mechanisms of intensive mixer rotors operating under prolonged service conditions. Based on an investigation of the contact interactions between material particles and working surfaces, the authors demonstrated that increasing contact loads intensifies abrasive and fatigue wear, alters the geometry of the working elements, and consequently deteriorates mixing quality. These results confirm that elevated mechanical loading is one of the principal factors limiting the service life of mixing equipment. Therefore, contemporary studies consistently demonstrate that the granulometric composition of bulk materials significantly influences particle kinematics, process energy consumption, and the durability of mixer components. At the same time, the available literature indicates that most studies focus on optimising mixer design or operating conditions, whereas the preliminary removal of isolated oversized lumps from the material stream as a means of reducing mechanical loading on mixing equipment has received virtually no attention.

Similar relationships are observed in the compaction of bulk materials using High Pressure Grinding Rolls (HPGR), whose operational efficiency largely depends on the formation of a compressed particle bed between the rolls. The particle size distribution of the feed plays a decisive role in ensuring a uniform distribution of contact stresses among particles and determines the efficiency of interparticle breakage. A. Aminalroaya & P. Pourghahramani (2021) experimentally investigated the influence of feed characteristics on material breakage in HPGR. Their study demonstrated that both the mechanical properties and granulometric composition of the feed material determine the formation of the compressed particle bed, the distribution of energy among particles, and the efficiency of interparticle breakage. Feed heterogeneity was shown to deteriorate compaction conditions, thereby adversely affecting the technological performance of HPGR.

Thus, regardless of the type of process equipment, contemporary studies consistently indicate that the presence of oversized lumps in a bulk material stream leads to deteriorated process performance, increased energy consumption, higher mechanical loading of working components, and accelerated wear. However, the overwhelming majority of published studies are devoted to improving equipment design, optimising operating conditions, or developing automatic control systems that compensate for the adverse effects of oversized lumps only after they have entered the working zone of the machine. In contrast, the prevention of oversized lumps entry through their preliminary removal from the conveyor stream remains insufficiently investigated. One of the most widely adopted engineering solutions for preventing oversized lumps from entering process equipment is their preliminary removal using scalping screens. Such machines separate oversized lumps by transporting the material over a screening surface with relatively large apertures, thereby effectively protecting downstream process equipment against overloads. However, the application of scalping screens is economically justified primarily when the feed contains a considerable proportion of oversized lumps. When their content does not exceed 5%, the use of a dedicated screening machine results in high capital investment, substantial energy consumption, and additional maintenance costs, significantly reducing the economic efficiency of this approach.

Accordingly, the development of alternative methods for the preliminary removal of isolated oversized lumps without employing dedicated classification equipment represents an important research direction. A promising basis for implementing such an approach is the utilisation of the natural segregation phenomena occurring during the transportation of bulk materials on belt conveyors. Contrary to the traditional perception of a conveyor as merely a transportation device, recent studies have demonstrated that bulk materials continuously undergo particle size segregation during conveying. As a result, coarse particles tend to concentrate in the upper layers of the material stream, whereas finer particles migrate toward their lower part. Z. Liu *et al*. (2022) conducted experimental investigations and numerical simulations of bulk material segregation on belt conveyors. The authors demonstrated that the intensity of stratified segregation depends on the particle size ratio, conveying velocity, and the geometry of the material stream. It was shown that a stable particle size stratification is formed already in the initial conveying section and remains preserved until the material is discharged.

Further development of this research direction was presented by Y. Duan *et al*. (2025), who employed DEM simulations to investigate the mechanisms governing the formation of a segregated bulk material structure during conveying and discharge. The authors demonstrated that the resulting segregation pattern determines the spatial distribution of particles of different sizes within the discharge zone and can be utilised for the selective separation of specific size fractions without additional classification operations. These findings suggest that the conveying process should be regarded not only as a transportation operation but also as an important stage of material preconditioning before subsequent processing. Therefore, the analysis of the available literature indicates the absence of engineering solutions utilising the natural segregation of bulk materials on belt conveyors for the mechanical removal of isolated oversized lumps directly within the conveyor discharge zone. This unresolved scientific problem defines the relevance and novelty of the present study. The objective of this study was to establish the fundamental interaction mechanisms between the working element and the segregated bulk material stream within the discharge zone of a belt conveyor and to substantiate the design and kinematic parameters of a device capable of selectively removing isolated oversized lumps without the use of dedicated classification equipment.

Materials and Methods

The investigation of the mechanical separate process of isolated oversized lumps from segregated bulk material was carried out on the basis of a conceptually developed device design (Fig. 1).

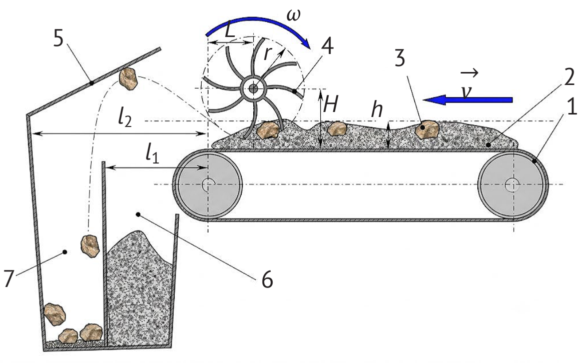


Figure 1. Basic diagram of the device for removal of isolated oversized lumps from segregated bulk material

Source: developed by the authors

In the initial problem formulation, the process of transporting segregated bulk material 2 by a horizontal belt conveyor 1 moving at a constant linear velocity *v* was considered. As a result of segregation within the material flow, a particle size heterogeneous structure was formed in which isolated oversized lumps 3 with an average size *d* became localized within the near-surface layer at a depth comparable to their characteristic size. To implement the process of their removal, a rotating working element in the form of a rod comb 4 was installed in the conveyor discharge zone. Structurally, the comb was designed with an axial spacing between the rods not exceeding *d*. During rotation, the comb 4 interacts with the upper layer of the material 2, captures the isolated oversized lumps 3, and imparts additional kinetic energy to them, causing their separation from the main material stream and subsequent motion along a free-flight trajectory inclined to the horizontal in the direction of material movement. To limit the particle dispersion zone, a deflector surface 5 was incorporated into the design. Fine material fractions 2 that do not interact with the comb 4 freely discharge into the receiving hopper 6, whereas the isolated oversized lumps 3 that receive an additional impulse are transported over a greater distance and discharged into the remote receiving hopper 7.

The rational operating regime of the rotating working element is determined by the condition of minimising energy losses caused by the sliding of isolated oversized lumps relative to finer particles at the moment of their removal from the material layer. To satisfy this condition, according to the computational scheme used for determining the geometric and kinematic parameters of the rotating working element shown in Figure 2, point *A* corresponding to the material detachment from the upper surface of the layer of thickness *h* must coincide with the point at which the rod exits the material bulk. In this case, the projection of the linear velocity of the rod tip at the specified point must be equal to the linear velocity of the conveyor belt *v*.

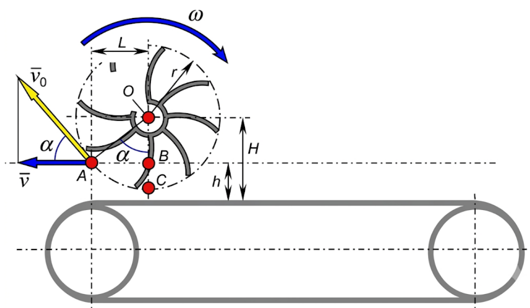
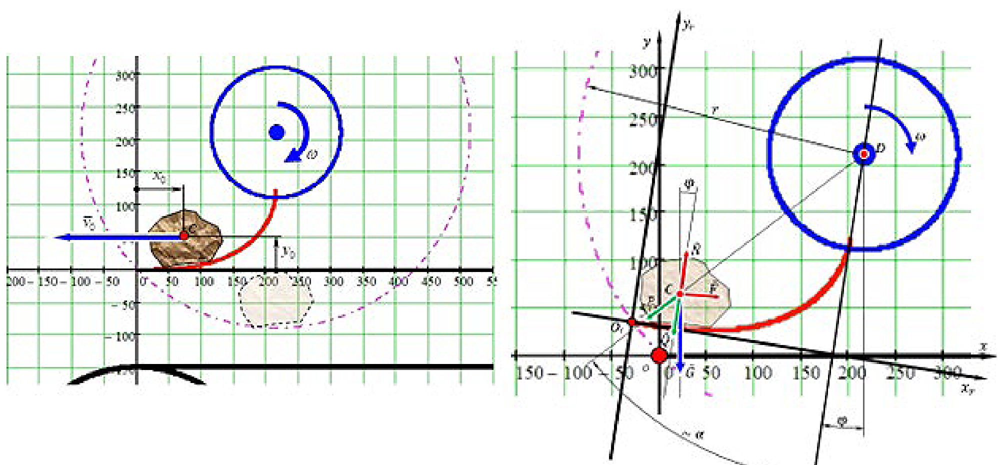


Figure 2. Computational scheme for determining the geometric and kinematic parameters of the rotating working element
Source: developed by the authors

For the justified selection of the installation position of the receiving hopper for oversized lump fractions or the positioning of the deflector plate intended to direct them into the hopper, the law of motion of a single oversized lump particle was investigated. At the first stage, the relative motion of the particle along the surface of the rotating rod was studied. The analysis is based on the following representation of the process: the interaction of the isolated oversized lumps with the rod, while it remains within the material bulk, occurs exclusively in the vertical direction, corresponding to its detachment from the material layer. After exiting the bulk material, the particle enters a sliding regime along the rod surface during its rotation. In this case, the initial sliding velocity is equal to the conveyor belt velocity, and the initial coordinate is comparable to the characteristic particle size (Fig. 3a). The force diagram acting on the particle captured by the rod during its relative motion is shown in Figure 3b.



a b

Figure 3. Computational scheme of particle relative motion on the surface of a rotating rod
Notes: a – initial motion parameters of the particle; b – force diagram acting on the particle during its relative motion
Source: developed by the authors

For describing the motion, two coordinate systems are introduced: a fixed system *xOy* associated with the axis of the conveyor discharge pulley, and a moving system $x_r\ O_r\ y_r$ rigidly attached to the rod and rotating together with it. The dynamics of the particle's relative motion are described by the fundamental law of dynamics for a material point, taking into account the action of gravity, constraint reactions, as well as inertial components induced by the rotational motion of the reference system, in particular the Coriolis and centrifugal forces.

The rotation angle of the rod is defined as a function of time:

$$\varphi(t) = \omega \cdot t \text{ rad}. \quad (1)$$

To simplify the mathematical description, it is assumed that the particle position along the rod coincides with its geometric profile, while its initial position is defined taking into account the characteristic particle size and the system geometry. Under these conditions, the relative velocity during the particle transition onto the gentle section of the rod is assumed to be determined solely by the variation of the x_r coordinates. Under these assumptions, the forces acting on the particle are projected onto the axes of the moving coordinate system, which makes it possible to formulate the equations of motion in the form of a system of differential equations expressed in projections onto the corresponding axes:

$$\begin{cases} G \cdot \sin\varphi + F - P \cdot \sin\alpha = m \cdot a_{rx} \\ -G \cdot \cos\varphi - P \cdot \cos\alpha + N - Q = m \cdot a_{ry} \end{cases}, \quad (2)$$

where G – the gravitational force, N; F – the sliding friction force, N; P – the centrifugal force, N; N – the normal reaction force, N; and Q – the inertial force associated with Coriolis acceleration, N.

The mass of the isolated oversized lumps was expressed in terms of its density ρ and average characteristic particle size d:

$$m \approx \rho \cdot \frac{4}{3}\pi\left(\frac{d}{2}\right)^3 \approx 0.524 \cdot \rho \cdot d^3 \text{ kg}. \quad (3)$$

Taking into account the physical nature of the process, the forces included in the right-hand sides of the equations can be represented in the following form:

$$G = m \cdot g = 0.524 \cdot \rho \cdot d^3 \cdot g \approx 5.137 \cdot \rho \cdot d^3 \ N, \quad (4)$$

where g – the acceleration due to gravity, m/s²;

$$F = k \cdot N, \quad (5)$$

where k – the coefficient of sliding friction between the isolated oversized lumps and the rod surface;

$$P = m \cdot \omega^2 \cdot r = 0.524 \cdot \rho \cdot d^3 \cdot \omega^2 \cdot r, \quad (6)$$

where ω – the angular velocity of rotation, rad/s;

$$Q = m \cdot 2 \cdot \omega \cdot v_r = 1.047 \cdot \rho \cdot d^3 \cdot \omega \cdot \cdot \sqrt{(x_r')^2 + (y_r')^2} \approx 1.047\rho \cdot d^3 \cdot \omega \cdot x_r'. \quad (7)$$

Substituting expressions (1-6) into the original system of equations (7) and expressing the accelerations in differential form, the transformed system of equations is obtained:

$$\begin{cases} 5.137 \cdot \rho \cdot d^3 \cdot \sin(\omega \cdot t) + k \cdot N - \\ -0.524 \cdot \rho \cdot d^3 \cdot \omega^2 \cdot r \cdot \sqrt{1-(\cos\alpha)^2} = \\ = 0.524 \cdot \rho \cdot d^3 \cdot x_r'' \\ -5.137 \cdot \rho \cdot d^3 \cdot \cos(\omega \cdot t) - \\ -0.524 \cdot \rho \cdot d^3 \cdot \omega^2 \cdot r \cdot \cos\alpha + N - 1.047 \cdot \rho \times \\ \times d^3 \cdot \omega \cdot x_r' = 0.524 \cdot \rho \cdot d^3 \cdot y_r'' \end{cases} \cdot \quad (8)$$

Considering the negligible acceleration along the $O_r\ y_r$ axis at the moment the isolated oversized lumps leaves the rod, the normal reaction force is, in the first approximation, determined from the condition of quasi-static equilibrium of force projections onto this axis:

$$N = 5.137 \cdot \rho \cdot d^3 \cdot \cos(\omega \cdot t) + 0.524 \cdot \rho \cdot d^3 \cdot \omega^2 \cdot r \cdot \cdot \cos\alpha + 1.047 \cdot \rho \cdot d^3 \cdot \omega \cdot x_r'. \quad (9)$$

To solve the relative motion of the isolated oversized lumps along the surface of the rod of the specified structural design, initial conditions for the relative velocity and coordinate were used:

$$\begin{cases} v_{r0} = -v \\ x_{r0} = d \end{cases}. \quad (10)$$

The time of motion of the isolated oversized lumps along the rod surface is determined from the equation of motion, solved with consideration of the initial conditions (16), when the particle reaches the specified coordinate value $x_r = 0$. The obtained law of motion makes it possible to determine the trajectory of the isolated oversized lumps after ejection, which in turn enables the substantiation of the positioning of the receiving hopper or the deflector plate used to direct the particle flow.

Results and Discussion

The following geometric (1-3) and kinematic (4) relationships are established, linking the parameters of conveyor motion and the rotation of the working element.

$$BC = d \text{ m}; \quad (11)$$

$$r = H - h + d \text{ m}; \quad (12)$$

$$L = \sqrt{2 \cdot \frac{H-h}{d} + 1} \text{ m}; \quad (13)$$

$$n = \frac{30 \cdot v}{\pi \cdot (H-h)} \text{ rpm}. \quad (14)$$

To minimise impact loads during the penetration of the working element into the bulk material layer, the rod profile was designed as a clothoid, thereby ensuring that the rod enters the material along the normal to the free surface and providing a smooth change in its direction of motion. The selection of a clothoid profile is justified by its fundamental geometric property, namely, the linear variation of curvature with arc length (Meek *et al.*, 2004; Levien, 2008). In contrast to a circular arc, which has constant curvature, or profiles characterised by abrupt curvature discontinuities, a clothoid provides a continuous increase in curvature from zero. Consequently, the normal acceleration and the contact forces between the rod and the bulk material increase gradually, thereby eliminating impact-type interaction. Owing to these characteristics, clothoid curves are widely employed in the design of motion trajectories for engineering systems requiring a smooth variation in curvature, reduced jerk, lower dynamic loading, and improved motion stability. These advantages have been confirmed by recent studies in vehicle control and trajectory planning, demonstrating that clothoid-based trajectories provide smoother curvature transitions and lower dynamic loads than trajectories containing curvature discontinuities (Li *et al.*, 2023).

For the analytical description of the rod profile, a computational scheme is introduced (Fig. 4), in which a Cartesian coordinate system rigidly fixed to the surface of the material layer is used. The origin is located at the point where the material leaves the upper surface of the layer, the abscissa axis is tangent to this surface, while the ordinate axis is directed along the normal to it.

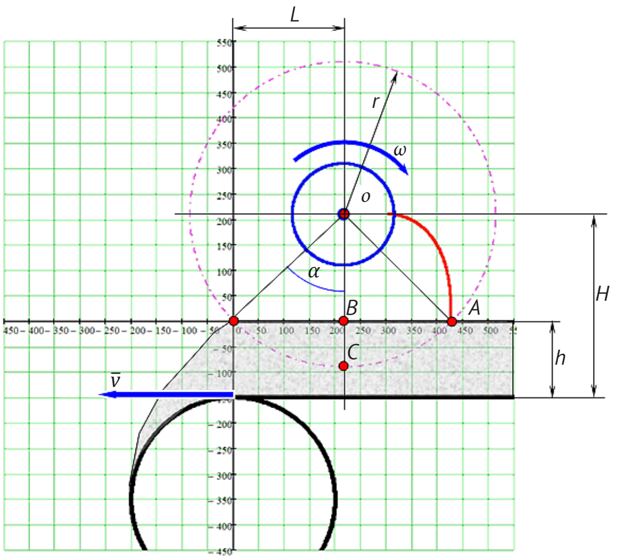


Figure 4. Computational scheme of the rod profile of the rotating working element
Source: developed by the authors

On the basis of the developed computational scheme, the rod profile is described by the parametric equations:

$$\begin{cases} x(t) = a\sqrt{\pi} \cdot \int_0^{\tau} cos\left(\frac{\pi\xi^2}{2}\right) d\xi \\ y(t) = a\sqrt{\pi} \cdot \int_0^{\tau} sin\left(\frac{\pi\xi^2}{2}\right) d\xi \end{cases}, \qquad (15)$$

where t – a dimensionless parameter, with $0 \leqslant t \leqslant 1$; a – is a scale factor defining the dimensions of the rod profile.

Substituting the obtained function of the normal reaction force (14) into the first differential equation of the system (13), it is transformed into its canonical form:

$$x_r'' - 2 \cdot k \cdot \omega \cdot x_r' = k \cdot \omega^2 \cdot r \cdot cos\alpha - \omega^2 \cdot r \cdot \sqrt{(1 - (cos\alpha)^2)} + g \cdot sin(\omega \cdot t) + g \cdot k \cdot cos(\omega \cdot t). \qquad (16)$$

The resulting differential equation (15) describes the relative motion of the isolated oversized lumps along the surface of the rod of the specified structural design.

The relative velocity of the isolated oversized lumps is defined as the first-time derivative of the obtained law of motion:

$$v_r(t) = \frac{dx_r(t)}{dt} \text{ m/s.} \qquad (17)$$

At the moment of detachment of the isolated oversized lumps from the rod, this velocity takes the value $v_r(T)$.

In the second stage, the absolute velocity of the isolated oversized lumps ejection was determined. In this case, the rod rotation angle at the moment of ejection was calculated using expression (6):

$$\varphi(T) = \omega \cdot T \text{ rad,} \qquad (18)$$

where T – the moment of ejection of the isolated oversized lumps from the rod surface.

The translational linear velocity of particle ejection is determined by the uniform rotational motion of the rod comb at a radius r (Fig. 5):

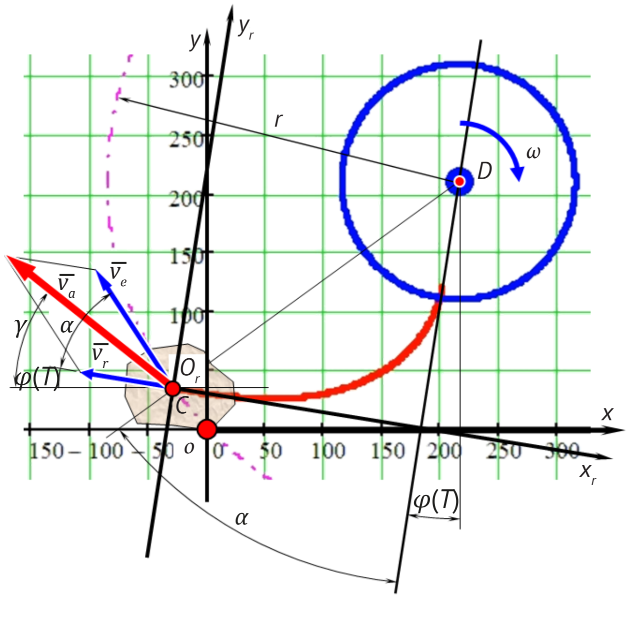


Figure 5. Computational scheme of oversized lump particle ejection velocities
Source: developed by the authors

$$v_e = \omega \cdot r \text{ m/s.} \qquad (19)$$

The relative velocity v_r of the particle was determined from the solution of differential equation (17) under the initial conditions (16). The particle ejection angle relative to the horizontal corresponds to the inclination angle of the absolute velocity vector with respect to the horizontal axis. The projections of this vector in the selected inertial coordinate system (see Fig. 4) are expressed as follows:

$$\begin{cases} v_{ax}(T) = -v_e \cdot cos[\alpha + \varphi(T)] - v_r \cdot cos[\varphi(T)] \\ v_{ay}(T) = v_e \cdot sin[\alpha + \varphi(T)] + v_r \cdot sin[\varphi(T)] \end{cases}, \quad (20)$$

The magnitude of the particle absolute velocity vector at the moment of ejection is given by:

$$v_a(T) = \sqrt{[v_{ax}(T)]^2 + [v_{ay}(T)]^2} \text{ m/s}, \quad (21)$$

The trigonometric components of the ejection angle were determined from the relationships between the magnitude of the absolute velocity vector and its projections:

$$cos\,\gamma = \frac{v_{ax}}{v_a}; \quad (22)$$

$$sin\,\gamma = \frac{v_{ay}}{v_a}. \quad (23)$$

Thus, the absolute ejection velocity of the isolated oversized lumps, its projections, and the inclination angle relative to the horizontal were determined, which made it possible to proceed to the third stage of the study – the analysis of its free-flight. The general solution of the problem of motion of a free material point projected at an angle to the horizontal in the selected inertial coordinate system (Fig. 6) is expressed as follows:

$$\begin{aligned} x(t) &= v_{ax} \cdot t + C_1 \\ y(t) &= -0.5\ g \cdot t^2 + v_{ay} \cdot t + C_2. \end{aligned} \quad (24)$$

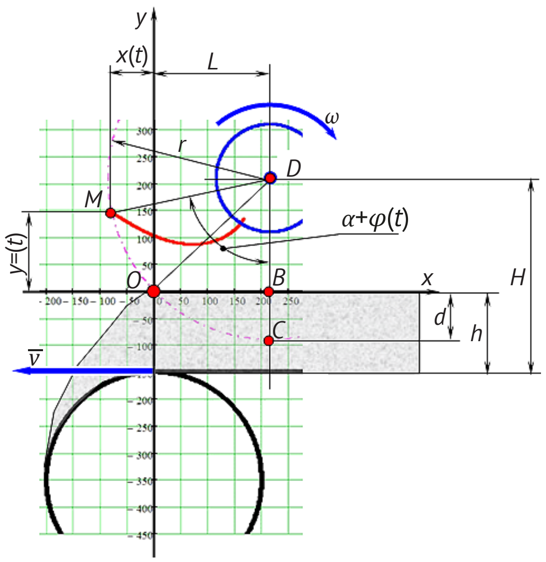


Figure 6. Computational scheme of oversized lump particle free-flight

Source: developed by the authors

The integration constants were determined from the initial conditions, namely the coordinates and velocity of the isolated oversized lumps at the moment of its ejection. According to the computational scheme (see Fig. 6), the absolute coordinates of the isolated oversized lumps during its sliding motion along the surface of the rotating rod are given by:

$$\begin{cases} x(t) = -r \cdot sin[\alpha + \varphi(t)] + L \\ y(t) = H - h - r \cdot cos[\alpha + \varphi(t)] \end{cases}. \quad (25)$$

According to the obtained results of solving equation (15) under conditions (16), the particle motion time from the beginning of sliding to the moment of ejection is equal to *T*. Therefore, the absolute coordinates of the ejection point are expressed as follows:

$$\begin{cases} x(T) = -r \cdot sin[\alpha + \varphi(T)] + L \\ y(T) = H - h - r \cdot cos[\alpha + \varphi(T)] \end{cases}. \quad (26)$$

These coordinates serve as the initial conditions for the subsequent motion of the isolated oversized lumps as a material point during the free-flight stage. The particular solution of the equations of motion was obtained from the general solution (24) by substituting the initial coordinates (26) and the initial velocity (21). As a result, the law of motion of the isolated oversized lumps during free flight after solving the Cauchy problem is expressed as follows:

$$\begin{aligned} x(t) &= v_{ax}(T) \cdot t + x(T) \\ y(t) &= -0.5g \cdot t^2 + v_{ay}(T) \cdot t + y(T) \end{aligned}. \quad (27)$$

Using the developed mathematical model, a numerical analysis of the selective removal of an isolated oversized lump was performed to investigate its interaction with the rotating rod of the working element under typical belt conveyor operating conditions. In the first stage, the evolution of the particle's dynamic characteristics during its motion along the clothoid profile of the rod was investigated (Fig. 7).

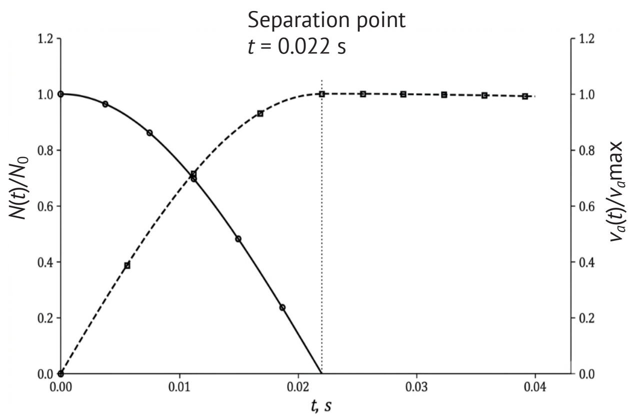


Figure 7. Dynamics of the interaction between an isolated oversized lump and the rod

Source: developed by the authors

The results showed that the relative contact reaction $N(t)/N_0$ (where $N(t)$ is the instantaneous normal contact force between the particle and the rod surface, N; N_0 is the normal contact force at the initial point of contact, N), decreases monotonically from 1 to 0, reaching zero after 0.022 s, which corresponds to the instant when contact with the rod is lost. Simultaneously, the relative particle velocity $v_a(t)/v_{a_{\max}}$ (where $v_a(t)$ is the instantaneous absolute particle velocity, m/s; $v_{a_{\max}}$ is its maximum value, m/s), increases continuously and reaches its maximum immediately before particle detachment. This indicates that the maximum kinetic energy of the particle is attained precisely at the transition from constrained motion along the rod to free flight, which is essential for achieving the maximum particle throw distance. These results demonstrate that the clothoid profile provides a gradual reduction in contact loading without abrupt changes in the contact reaction, while the maximum particle velocity is attained immediately before detachment. Such a variation in the kinematic characteristics confirms the suitability of the clothoid profile for establishing stable initial conditions for the subsequent free-flight phase. In the second stage, the influence of the kinematic parameters of the working element, specifically its rotational speed ($n_{r.c}$), on the particle separation velocity (v_a), and the particle-rod contact time (t_{rod}), was investigated (Fig. 8).

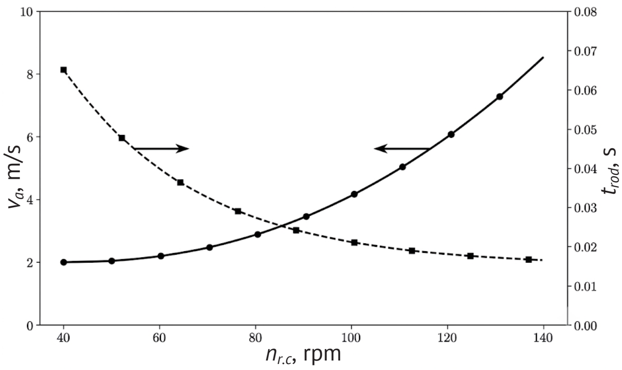


Figure 8. Effect of rotor rotational speed on separation velocity and contact time
Source: developed by the authors

The results indicate that increasing the rotational speed from 40 to 140 rpm increases the particle separation velocity by fourfold. At the same time, the particle-rod contact time decreases by 30%. These findings demonstrate a substantial increase in the intensity of mechanical energy transfer to the particle with increasing rotor speed. Figure 9 presents the results of the analysis of the influence of the coefficient of friction between the isolated oversized lump and the rod surface. The results show that increasing the coefficient of friction by 0.4 reduces the particle separation velocity by 55%. A similar trend is observed for the particle throw distance. This behavior is attributed to increased mechanical energy dissipation due to frictional forces, resulting in a corresponding reduction in the energy converted into the particle's translational kinetic energy. Therefore, the coefficient of friction represents one of the key parameters governing the efficiency of selective particle separation.

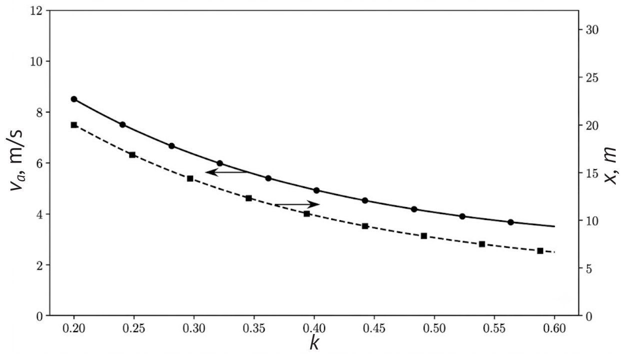


Figure 9. Effect of friction coefficient on particle kinematics and trajectory
Source: developed by the authors

The practical implications of the developed mathematical model are illustrated in (Fig. 10), which presents a family of trajectories of isolated oversized lumps corresponding to rotor rotational speeds ranging from 40 to 140 rpm, together with the trajectory of the fine fraction for comparison.

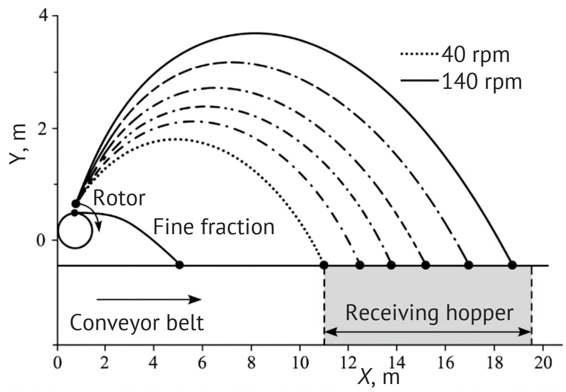


Figure 10. Isolated oversized lump trajectories at different rotational speeds of the working element and the recommended position of the receiving hopper
Source: developed by the authors

A quantitative analysis of the obtained trajectories revealed that increasing the rotor rotational speed predictably extends the flight distance of isolated oversized lumps in the X. At the minimum rotational speed of 40 rpm, the particle landing distance is $X \approx 11$ m. Increasing the rotational speed to 140 rpm shifts the landing point to $X \approx 18.8$ m, while simultaneously increasing the maximum trajectory height to $Y \approx 3.7$ m. Consequently, a well-defined landing zone for isolated oversized lumps is formed within the range of $X = 11...19.5$ m. In contrast, the fine fraction exhibits a fundamentally different motion pattern. Rather than being entrained into the ascending flow, fine particles follow a considerably shorter trajectory and land at X≈5 m. The resulting stable spatial separation, characterised by a minimum gap of more than 5…6 m between the landing zones of the oversized lumps and fine fractions, provides a scientific basis for determining the geometric parameters of the discharge unit.

The obtained results demonstrate that the proposed approach to the mechanical separation of isolated oversized lumps is feasible, provided that the design and kinematic parameters of the rotating working element are properly coordinated with the material conveying conditions on the belt conveyor. The developed mathematical model made it possible to establish the fundamental interaction mechanisms between an isolated oversized lump and the rod, determine the conditions governing particle detachment, and predict its subsequent flight trajectory. In contrast to the majority of recent studies (Hastie *et al.*, 2010; Fei *et al.*, 2026), which primarily focus on minimising particle segregation or improving conveyor system design to preserve material flow homogeneity, the present study is the first to exploit natural segregation as the basis for the mechanical separation of isolated oversized lumps without the use of dedicated heavy-duty classification equipment. One of the principal findings of the present study is that the use of a rod with a clothoid profile ensures a gradual reduction in the contact reaction between the working element and the oversized lump, thereby eliminating abrupt impact loading. At the same time, the particle reaches its maximum velocity immediately before detachment from the rod. This result is consistent with the findings reported by K. Ran *et al.* (2024), who demonstrated, in the context of robotic systems, that incorporating clothoid curves into trajectory planning enables the generation of geometrically smooth paths, minimises kinematic jerk, and significantly reduces dynamic loads acting on robotic actuators under stringent kinematic constraints. However, their study focused on obstacle avoidance algorithms and path planning for mobile robots, whereas the present work is the first to a pply the same geometric principle of continuous curvature variation to the design of the working element of a mechanical device intended for the selective removal of isolated oversized lumps. This finding demonstrates that the advantages of clothoid curves are not limited to autonomous motion control and navigation applications but can also be effectively exploited in the design of heavy-duty process equipment for the conveying and selective separation of bulk materials.

Another important finding of this study is the fourfold increase in the particle separation velocity as the rotational speed of the working element increases from 40 to 140 rpm, accompanied by an approximately 30% reduction in the particle-rod contact time. These results indicate that the kinematic parameters of the working element directly govern the efficiency of mechanical energy transfer to the particle. This conclusion is fully consistent with the findings of previous studies based on the DEM. In particular, DEM simulations of copper ore flow through conveyor transfer stations (Walker *et al.*, 2020), as well as investigations of the discharge trajectory and flow dynamics of cohesive materials from a belt conveyor onto an inclined impact plate (Scheffler & Coetzee, 2023), have clearly demonstrated that the interaction characteristics, velocity conditions, and the evolution of normal and tangential contact forces directly determine the efficiency of mechanical energy transfer to individual particles.

The obtained results also demonstrated the decisive influence of the rod surface condition on the particle separation process. Specifically, increasing the coefficient of friction between the rod surface and the isolated oversized lumps by 0.4 was found to reduce both the particle separation velocity and the corresponding flight distance by approximately 55%. This behavior is attributed to increased mechanical energy dissipation caused by frictional forces, resulting in a smaller proportion of the available energy being converted into the particle's translational kinetic energy. The identified mechanism is fully consistent with the fundamental findings of S. Laudari *et al.* (2023), who, through DEM simulations of binary granular mixtures, demonstrated that contact friction, both between particles and at the particle-equipment interface, has a critical influence on velocity profiles, energy dissipation, and the overall kinematics of double-faction flows. These findings emphasise the necessity of maintaining strict control over the condition and wear of the rotating rod surfaces to preserve the designed particle throw distance and, consequently, the efficiency of isolated oversized lump separation.

The simulations further demonstrated that an appropriate combination of the device's kinematic and geometric parameters makes it possible to achieve a spatial separation of up to 6 m between the landing zones of the fine fractions and isolated oversized lumps material. This result is fully consistent with the fundamental principles of bulk material separation based on aerodynamic and inertial properties (Rhodes, 2008). According to the fundamental laws of dynamics, the flight distance of a body moving through air depends on its initial momentum, mass, and the aerodynamic drag force. In conventional gravity-based conveyor discharge systems, the natural separation between the trajectories of particles of different masses is minimal because all particles leave the belt with nearly identical initial velocities, making efficient classification impossible without dedicated receiving hoppers or classification devices. In contrast, the present study demonstrates that the application of an additional mechanical impulse generated by the rotating working element can deliberately amplify this natural trajectory separation.

By imparting additional kinetic energy to isolated oversized lumps at the moment of contact, the proposed device ensures their stable displacement beyond the landing zone of the main fine-material stream. As a result, reliable industrial-scale separation is achieved without remixing of the isolated oversized lumps and fine material flows.

Conclusions

This study theoretically substantiated a novel approach for the separation of isolated oversized lumps from a bulk material stream directly within the discharge zone of a belt conveyor. The proposed approach was based on the natural segregation of the conveyed material and its selective interaction with a rotating working element. Unlike conventional solutions, the proposed method does not require dedicated energy-intensive classification equipment, thereby providing the basis for improving the efficiency of existing material handling and processing systems. The developed mathematical model describes the complete process of isolated oversized lumps separation, including its extraction from the segregated material layer, relative motion along the rod surface, and subsequent free flight. The derived analytical relationships make it possible to determine the particle separation velocity, the coordinates of the detachment point, the trajectory parameters, and the predicted landing zone, thereby providing a sound basis for the design and optimisation of the geometric parameters of the conveyor discharge unit.

It was established that the use of a rod with a clothoid profile ensures a gradual reduction in the contact reaction between the working element and the isolated oversized lumps without generating abrupt dynamic loads. The oversized lu mps reaches its maximum velocity immediately before detachment from the rod, creating the most favorable conditions for the efficient mechanical separation of it from the bulk material stream. The numerical analysis demonstrated that increasing the rotational speed of the working element from 40 to 140 rpm results in a fourfold increase in the particle separation velocity while simultaneously reducing the particle-rod contact time by 30%. These findings indicate that the kinematic parameters of the working element constitute one of the key factors governing the efficiency of mechanical energy transfer to the material particles.

A significant influence of the coefficient of friction between the rod surface and the isolated oversized lump on the separation efficiency was demonstrated. An increase in the coefficient of friction by 0.4 results in an approximately 55% reduction in both the particle separation velocity and the particle throw distance. This finding should be taken into account when selecting materials for the working elements and when assessing their wear under operating conditions. It was established that the proposed technical solution provides stable spatial separation of the trajectories of isolated oversized lumps and fine particles, with the corresponding landing zones separated by more than 5...6 m. This enables the efficient mechanical separation of isolated oversized lumps from the conveyed material stream and provides a sound basis for the optimal positioning of receiving hoppers or deflector elements without the need for additional classification equipment. Future research should focus on the experimental validation of the proposed mathematical model using a laboratory-scale test rig, investigating the influence of the physics and mechanical properties of bulk materials and the degree of particle segregation on separation efficiency, as well as optimising the design parameters of the working element for different operating conditions and materials conveying regimes.

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Conflict of Interest

None.

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Дослідження можливості сортування крупнокускового матеріалу на конвеєрному тракті підчас його транспортування

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Анотація. У гірничо-металургійній галузі надійність роботи підготовчого обладнання значною мірою визначається однорідністю гранулометричного складу сировини, при цьому наявність поодиноких великокускових включень спричиняє динамічні перевантаження, інтенсивний знос робочих органів і зростання енерговитрат, що обґрунтовує необхідність розробки маловитратних методів їх видалення безпосередньо на транспортних магістралях. Метою роботи було наукове обґрунтування конструкції машини для механічного вилучення великокускових включень з потоку сипкого матеріалу в зоні розвантаження стрічкового конвеєра на основі попередньо розробленої сегрегаційної неоднорідності. У роботі були використані методи математичного моделювання, теоретичної механіки та динаміки матеріальної точки, які дозволили науково обґрунтувати конструкцію сепаруючого пристрою у вигляді обертової стрижневої гребінки, розташованої над розвантажувальним барабаном конвеєра. Було встановлено, що раціональний режим роботи забезпечувався узгодженням лінійної швидкості стрічки та кінематичних параметрів обертання кінців стрижнів, що мінімізувало енергетичні втрати на ковзання. Математично доведено, що профіль стрижня у формі клотоїди забезпечує його занурення в масив матеріалу по нормалі, суттєво знижуючи ударні навантаження. Розроблено комплексну динамічну модель, яка описує три стадії взаємодії: виокремлення частинки з шару, її відносний рух по поверхні стрижня та вільний політ, що дозволило визначити геометричні межі зони розльоту великокускового матеріалу. Це забезпечило точне позиціонування приймальних бункерів та відбійних пластин-дефлекторів для великокускових фракцій. Отримані математичні моделі та геометричні співвідношення дозволяють проектувати ефективні вузли попередньої класифікації на базі існуючих конвеєрних ліній, що забезпечує захист технологічного обладнання від перевантажень без встановлення громіздкого енергоємного обладнання

Ключові слова: стрічковий конвеєр; сегрегація матеріалу; механічне відокремлення; стрижнева гребінка; траєкторія вільного польоту; класифікація фракцій; розвантажувальний вузол