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Increasing the efficiency of dust extraction at crusher feeding points

Abstract. The loading of crushers at mining and processing facilities is accompanied by intensive emissions of fine particulate dust, which deteriorates working conditions, increases the risk of occupational respiratory diseases, and causes additional abrasive wear of process equipment. The problem is particularly relevant where the use of water-based dust suppression methods is limited due to sludge formation, high water consumption, and difficulties in their application during the cold season. The aim of this study was to develop a design for a crusher feed hopper enclosure and to provide a scientific basis for a method of calculating the extraction parameters required to ensure uniform removal of contaminated air along the entire material loading zone. Mathematical modelling of air-flow dynamics was carried out using the static pressure method and the momentum equation. The model considered the air flow in a longitudinal extraction duct with a variable-width slot. It was established that respirable dust fractions with particle sizes of up to 10 μm predominate in the workplaces of crushing and screening plants, representing the greatest health hazard to workers. It was demonstrated that one of the causes of dust escaping from beneath the enclosure is the unevenness of extraction velocities along the duct. A mathematical model was developed to determine the variable width of the longitudinal extraction slot as a function of the distance from the extraction connection point. It was established that, to ensure a stable extraction velocity, the slot width should gradually decrease from the closed end of the duct towards the point where the extraction system is connected. Analytical relationships were obtained for calculating the geometrical parameters of triangular-section ducts that prevent dust deposition inside the system. A design for a mobile extraction enclosure for a crusher feed hopper was proposed, incorporating longitudinal slots of variable width and a hinged connection to the extraction duct. The practical significance of the results lies in the localisation of dust emissions and the reduction of dust

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concentrations in the workplace air by ensuring uniform extraction of contaminated air along the entire length of the crusher feed hopper

Keywords: dust aerosol; respirable fraction; emission localisation; slotted extractor; static pressure; air flow; enclosure

Introduction

Enterprises in the mining and processing industries are among those with the highest risk of dust pollution. One of the most significant sources of air pollution in the workplace is the loading of crushers, during which a considerable amount of fine dust is released as a result of free fall, impact and the crushing of mineral raw materials. Respirable particles measuring up to 10 μm pose a particular hazard, as they are capable of remaining suspended in the air for long periods and penetrating deep into the human respiratory system. Iron ore mining operations are characterised by the presence of significant amounts of free silicon dioxide in the dust, the effects of which are linked to the development of silicosis, chronic lung diseases and other occupational pathologies.

Water is the most common agent used for dust suppression, as it allows dust particles to agglomerate due to the capillary effect. The works of O. Lapshyn *et al.* (2023) and M. Beltran-Marquez *et al.* (2025) examined water spraying systems based on moistening the material to prevent the release of fine dust that pollutes the air in the workplace. This is one of the most common methods, implemented by installing nozzles directly above the feed hoppers of crushers. However, intensive water spraying leads to water wastage, over-moistening of the raw material and the formation of liquid slurry. Attempts to address this problem by optimising the chemical composition of spray solutions and introducing electrostatic fine-particle spraying technology were investigated in the work by Y.-H. Oh *et al.* (2026).

The use of surfactants improves the wettability of dust, making it heavier and easier to capture than with plain water (Xu *et al.*, 2023). The use of aqueous solutions of calcium chloride salts increases the surface tension of the water film between dust particles and slows down moisture evaporation, which ultimately allows for the efficient use of water resources in dust control (Zhao *et al.*, 2021). However, the main drawbacks of using water are the formation of sludge and the need to organise a water supply recycling cycle (settling tanks, transfer pumps, etc.), the formation of deposits on the internal surfaces of machinery, limited water use during the winter months, as well as the increased cost of dust collection, significant water consumption and energy expenditure, as confirmed by the study by Y. Li *et al.* (2026). This confirms that rational management of a company's water resources and high efficiency in the removal of respirable dust fractions cannot be achieved solely through wet methods.

Researchers M. Ji *et al.* (2022) proposed the use of air-mechanical foam to reduce dust load, as it requires less water and ensures the material's surface is covered, forming a continuous layer. However, this method can only be effective when the foam covers the surface of stationary material with a continuous layer. When feeding a crusher, the uniformly accelerated motion of the falling material and the resulting upward air currents will carry the foam away along with the dust, as the foam is a mixture of gas and liquid in the form of bubbles, which do not bind all the dust in the loose rock. Within the overall set of measures to control dust during the feeding of crushers, water spraying is regarded as an effective complement to the main measures. However, in many cases, the implementation of this method requires the reconstruction and re-equipping of crusher feeding points, which entails significant capital expenditure; furthermore, for coarse mineral feedstock in the initial stages of crushing, the proposed methods are ineffective. The methods mentioned above may, on the one hand, be effective under specific conditions, but on the other hand, their use is limited due to existing shortcomings.

The most effective way of containing dust emissions is considered to be enclosing the sources of dust emissions, in particular the loading zones of crushers (National Institute for Occupational Safety and Health, n.d.). Enclosing crushing equipment and loading zones prevents 80-90% of dust from entering the air at workstations. When combined with other dust suppression methods and measures, the greatest effectiveness is achieved in containing dust emissions and reducing dust concentrations in the workplace. An analysis of current methods indicates that the unloading of bulk materials without enclosures and extraction systems is, in all cases, accompanied by intense dust emissions. Fine dust generated as a result of the extraction and processing of minerals is characterised by high hydrophobicity, whilst the large droplet size of the irrigation liquid reduces the efficiency of its capture (Xu *et al.*, 2023). When comparing methods and means of dust suppression during crusher feeding, it can be concluded that the most effective solution is a combination of different methods, provided that crusher feeding points are equipped with enclosures fitted with local extractor pipes for connection to extraction systems. Thus, the aim of this study was to develop a design for a crusher feed hopper enclosure and to provide a scientific justification for the method of calculating aspiration parameters to ensure uniform extraction of contaminated air throughout the entire loading zone.

Materials and Methods

The study analysed research into the particle size distribution of dust at crushing and screening plants and the aerodynamic mechanisms of dust emission during the loading of crushers; a mathematical model of airflow in a slotted air duct was developed, and a design for a mobile extraction enclosure was proposed to localise dust emissions during the loading of crushers. The analysis included scientific studies published predominantly between 2021 and 2026 in international peer-reviewed journals, containing research findings on dust particle-size distribution, the processes governing its dispersion in workplace air, the effectiveness of dust suppression, and the aerodynamics of extraction systems.

The object of the study was the process of localising dust emissions during the loading of crushers with mineral raw materials using an extraction enclosure with slotted extraction. The subject of the study was the aerodynamic behaviour of air flows in an extraction air duct with a slot of variable width, which determines the uniformity of contaminated-air removal along the crusher feed hopper. The theoretical basis of the study is the classical static-pressure aerodynamic method combined with the momentum equation. This approach made it possible to account for changes in static pressure along the air duct resulting from the entrainment of additional air masses through the extraction slot and pressure losses due to friction. Unlike simplified empirical calculation methods, the use of the momentum equation provides a physically justified description of the processes governing the formation of air flows in slotted extraction devices.

The main research method was mathematical modelling of the air-flow movement in the collecting air duct of the extraction enclosure. The object of calculation in the developed mathematical model was the continuous volume of air flow moving inside the collecting longitudinal air duct of the extraction enclosure through an extraction slot of variable width. The air duct was considered as a continuous-extraction collector with a transit outlet for the dust-air mixture to the ventilation unit. The following assumptions were made when developing the mathematical model: the air-flow coefficient through the slot μ and the aerodynamic friction resistance coefficient λ were assumed to be constant along the entire length of the extraction slot and air duct, respectively; the velocity distribution across the cross-sections of the air duct was assumed to be uniform; the momentum of the air entering through the slot, projected onto the axis of the duct, was assumed to be zero. These assumptions made it possible to use the momentum equation to determine the excess static pressure ΔP at any point in the system.

The initial parameters of the mathematical model were: the length of the air duct (the geometric length of the localisation zone of the crusher's feed hopper) l, m; the cross-sectional area of the air duct F, m^2; the suction velocity of the air flow in the slit, which ensures the capture (extraction) of respirable dust particles ϑ_x, m/s; the air density ρ, kg/m^3. In accordance with the developed mathematical model and the aerodynamic method of static pressures, the calculation determines the width of the longitudinal slot δ_x in an arbitrary cross-section. Calculating this value enabled precise geometric adjustment of the opening to compensate for the drop in static pressure and maintain a stable suction velocity along the entire length. The rationale for the method of calculating air ducts with a longitudinal slot, based on the static pressure method, is set out below.

A key drawback of many standard aspiration systems is uneven suction: the flow is stronger closer to the fan, whilst in more distant sections it is insufficient for dust collection. The proposed method has resolved this problem through the geometric adaptation of the air duct's suction slot. In suction air ducts with a slot, the average air velocity inside the duct is determined by the formula:

$$\vartheta = \mu \cdot \sqrt{2 \cdot (P_a - P)/\rho} = \mu \cdot \sqrt{-2 \cdot \Delta P/\rho}, \quad (1)$$

where μ – the flow coefficient; P – the static pressure inside the air duct; P_a – the static pressure outside the air duct; $\Delta P = P - P_a$ – the excess static pressure; ρ – the density of air. Taking formula (1) into account, the air flow rate Q at a suction slot of width δ is described by the relationship:

$$Q = \mu \cdot \delta \sqrt{2 \cdot (\pm \Delta P)/\rho}. \quad (2)$$

It can be seen from equation (2) that, for uniform air intake, the width of the slot must vary along the entire length of the air duct. To ensure uniform air intake through a slot in an air duct of constant cross-sectional area F and length l, the width of the longitudinal slot at any cross-section x is determined by the following equation:

$$\delta_x = \frac{F \cdot \vartheta}{l \cdot \vartheta_x} = \frac{Q}{l \cdot \vartheta_x}. \quad (3)$$

The air intake velocity at the slot in an arbitrary cross-section x is described by the relationship:

$$\vartheta_x = \mu \cdot \sqrt{(2/\rho) \cdot (P_a - P_x)}. \quad (4)$$

To determine the excess pressure ΔP in aspiration air ducts, the equation of momentum is used. In this case, pressure losses due to flow are not taken into account, and the projection of the volume of air drawn in through the slot onto the axis of the duct is equal to zero. For the volume of air inside a suction air duct with a longitudinal slit, the momentum equation, projected onto the axis of the air duct, takes the form:

$$P_0 \cdot F - P_x \cdot F - \int_0^x \tau_x \cdot P dx = \rho F \, \vartheta_x^2, \quad (5)$$

where $x = 0$ – the cross-section at the start of the air duct on the closed end; x – the cross-section at the opposite end near the air outlet at a distance corresponding to the length of the air duct, meaning $x = l$; τ_x – the friction stress, $\tau_x = \lambda/4 \cdot \rho\vartheta_x^2/2$; λ – coefficient of aerodynamic friction drag. If the value of the frictional shear stress τ_x, into equation (5) and all terms of the equation are then divided by F, the following equation is obtained

$$P_0 - P_x - \int_0^x \frac{\lambda}{d_0} \cdot \frac{\rho\vartheta_x^2}{2} dx = \rho \, \vartheta_x^2. \quad (6)$$

For uniform air intake $\vartheta_x = \vartheta x/l$. Substituting ϑ_x into formula (6) and integrating gives:

$$P_x = P_0 - \frac{x^2}{l^2}\left(2 + \frac{\lambda x}{3d_0}\right)\frac{\rho\vartheta^2}{2}, \quad (7)$$

where d_0 – the equivalent diameter of the air duct. If ϑ_x, calculated using formula (4), and P_x, calculated using formula (7), are substituted into formula (3), the slot width at an arbitrary cross-section x is calculated using the following formula:

$$\delta_x = \frac{1}{\sqrt{\frac{1}{\delta_0} + \frac{\mu^2 x^2}{F^2}\left(2 + \frac{\lambda \cdot x}{d_0}\right)}}, \quad (8)$$

where δ_0 – the slit width at the start of the air duct on the closed end, meaning at $x = 0$. It is evident from equation (8) that the slit width will be at its greatest at $x = 0$, which is at the start of the air duct on the closed end. As x increases to $x = l$, the slit width will be at its smallest. Consequently, the maximum slot width must be such that the dust suction velocity along the entire length of the slot is not less than the permissible value. To this end, the maximum slot width δ_0 must be calculated using the formula:

$$\delta_0 = \frac{Q}{l \cdot \vartheta_x}. \quad (9)$$

For an air duct with a cross-section in the form of an isosceles triangle, the equivalent diameter d_0 is calculated using the formula:

$$d_0 = \frac{2ah}{a + 2b}, \quad (10)$$

and the cross-sectional area F is calculated using the formula:

$$F = \frac{1}{2} ah, \quad (11)$$

where a – the base of the isosceles triangle; b – the side of the isosceles triangle; h – the height of the isosceles triangle. Consequently, the change in static pressure P_x along the air duct from its closed end at $x = 0$ to the outlet at $x = l$ is described by equation (7). This equation takes into account both the dynamic component of the flow and friction losses, where d_0 – the equivalent diameter of the air duct.

To ensure a stable dust extraction rate, the slot width δ_0 must be at its maximum at the closed end of the air duct and gradually decrease to its minimum value near the extraction unit. Formula (8) was used to calculate the slot width at an arbitrary cross-section x. The proposed method is universal and allows the calculation to be adapted to the specific shape of the air duct. For example, for extraction systems with an air duct cross-section in the shape of an isosceles triangle (which is often used to prevent dust from settling on the walls), the area F and the equivalent diameter d_0 are determined in terms of the geometric parameters of the base a, the side b and the height h. Thus, the proposed method for calculating the variable slot width δ_x is modern and scientifically sound, enabling high extraction efficiency to be achieved at the feeding points of crushers throughout the entire feeding zone by equalising the suction velocity distribution. This minimises dust ejection zones and prevents energy wastage due to excessive ventilation at specific points in the system.

Results and Discussion

Particle size distribution of dust and its hazard to workers

Mineral raw materials and bulk materials unloaded into the crusher contain fine dust formed as a result of rock fragmentation by blasting in a quarry or mine, as well as from friction between pieces of material or impacts of pieces against various surfaces during transport and transhipment. Fine dust is characterised by high hydrophobicity; it is capable of remaining suspended for long periods and contaminating the air. An analysis of recent studies on the particle size distribution of dust in crushing and screening plant areas has shown a predominance of respirable dust fractions up to 10 μm. The study by Z. Liu *et al*. (2023) established that over 84% of the dust in the air of a crushing plant consists of particles up to 2.5 μm in size, which remain suspended for a long time and are characterised by high mobility. Research by A. Penchala *et al.* (2025) found that the ratio between dust fractions of 1 μm, 2.5 μm and 10 μm remains virtually unchanged even at a height of 30 m above the dust emission source, indicating their high resistance to settling and their ability to remain in the atmosphere of industrial facilities for extended periods.

The research findings presented in the work by V. Shapovalov (2019) indicated that airborne dust levels at workplaces in the crushing and screening plants of Kryvyi Rih generally exceed health standards. Furthermore, most of the dust in the air at these workplaces contains free SiO_2 in the form of quartz and has a particle size of up to 5 μm. It is precisely the fine dust fractions measuring up to 5 μm that pose the greatest risk to workers' health, as confirmed by the study by K. Vanka *et al*. (2022), as well as in the study by O. Chencheva *et al*. (2023) on the pathogenesis of occupational lung diseases. Silicon dioxide, also known as silica, is a chemical compound commonly found in quartz, the grains of which have sharp edges. As iron ore components are more difficult to grind than quartz, the relative content of silicon dioxide in airborne dust may be higher than in rock. Inhaling dust containing silicon dioxide is harmful to human health, as it can become trapped in the lungs, causing inflammation and scarring of the lung tissue. This condition is known as silicosis and can lead to permanent lung damage or even the death of the patient (Vanka *et al.*, 2022).

Dust particles larger than 50 μm are trapped in the nose, nasopharynx, trachea and large bronchi when inhaled. Although these particles do not reach the lungs, they cause mechanical irritation of the mucous membrane, leading to chronic rhinitis and laryngitis. According to the findings of G. Liu *et al.* (2026), this dust also contributes to secondary contamination of the work area through resuspension caused by air currents and the operation of equipment. Dust particles measuring 15-10 μm are trapped in the upper respiratory tract and small bronchi. It is this fraction that is responsible for the development of occupational bronchitis. Dust particles measuring up to 10 μm reach the alveoli of the lungs, although they are mainly trapped in the upper respiratory tract. Modern medicine, notably K. Vanka *et al.* (2022), classifies this fraction as "thoracic". It is critical because particles of this size are capable of absorbing toxic substances and microorganisms onto their surface, transporting them deeper into the respiratory system.

The greatest danger is posed by ultrafine dust particles measuring up to 2 μm (the respirable fraction), as they remain in the lungs for a prolonged period and damage lung tissue (Liu *et al.*, 2026). This is fully confirmed by the results of pathogenesis studies (Vanka *et al.*, 2022). Such dust is ingested by alveolar macrophages, triggering a cascade of inflammatory reactions, leading to fibrosis of the lung tissue (silicosis, anthracosis) and the potential entry of nanoparticles into the systemic circulation. Irritation of the upper respiratory tract in the early stages is accompanied by a tickling sensation in the throat, coughing and the expectoration of contaminated sputum. This is due to the body's defensive reflexes – sneezing, coughing and bronchial activity. Prolonged exposure to dust causes inflammation of the upper respiratory tract, the symptoms of which include dryness of the mucous membranes, reduced sputum production, a dry cough and hoarseness.

The greatest danger to human health arises when dust penetrates deep into the lungs, where it comes into contact with lung tissue, bronchioles and alveoli. When dust enters the lungs, its harmful components are absorbed in large quantities due to the extensive surface area of contact, causing irritation to the lungs and systemic toxicity. Dust that enters the lungs and accumulates over a long period of time causes the growth of connective tissue (fibrotic nodules) around each alveolus; this tissue is unable to react with oxygen in the air, oxygenate the blood or remove carbon dioxide during exhalation. Prolonged accumulation of dust contributes to the growth of hardened lung tissue, as a result of which part of the lungs loses the ability to perform its function – to absorb oxygen and release carbon dioxide. A lack of oxygen causes shortness of breath whilst walking or performing physical work, weakens the body's immune system and reduces work capacity, and contributes to the development of diseases of the heart and other organs. Such symptoms are characteristic of fibrogenic dust, which contains silicon dioxide, iron oxides and other substances (Chencheva *et al.,* 2023). Prolonged exposure to such dust is the main cause of occupational respiratory diseases among workers.

Aerodynamic mechanisms of dust emission during the loading of crushers

The amount of contaminated air entering production premises during the feeding of crushers depends primarily on the type of crushing equipment, as well as on the physical and mechanical properties of the raw material – for example, the material's hardness, moisture content, particle size distribution and other factors. During unloading, the bulk material draws air down to the bottom of the crusher's feed hopper, creating excess pressure. At the lowest points of the material's fall, as it strikes the surface with dynamic impact, there is intense dust emission and air pollution, which is carried by air currents to the workstations.

Furthermore, the process of the material's vertical fall is also accompanied by dust emission, which is carried into the workspace by transverse air currents. According to the findings of G. Liu *et al.* (2026), the air entrained during the handling of bulk materials is the primary factor in dust emission. The researchers demonstrate that during industrial processes, such as the feeding of crushers, the velocity of air flows at the boundary of the falling material creates turbulence that carries dust beyond the confines of the enclosure, and the volume of air entrained by the bulk material is directly proportional to the drop height. On the other hand, the operation of crushers is accompanied by the formation of airflows inside the crusher housing, which carry dust into the air at workstations. The mechanism by which updrafts are formed and the amount of dust generated are determined by the specific operating characteristics of the crushers. In their study, A. Saramak & Z. Naziemiec (2019) confirmed that the intensity of dust emission depends not only on the hardness of the ore but also on the aerodynamic characteristics of the crushers. In the study by I. Petrenko *et al.* (2024), researchers analysing dust sources at mining and processing plants concluded that cone and jaw crushers have different levels of dust emissions due to differences in the aerodynamics of their housings. During the operation of jaw crushers, compressed air is periodically expelled at a frequency equal to the number of jaw oscillations.

In this process, dust-laden air is carried by airflows from the crusher chamber to the feed opening and onwards to the work areas. The formation of upward flows within the cavity of a cone crusher is caused by the interaction of the working parts and the oscillation of the cone within the volume of air confined by the machine's housing. In this case, the velocity of the updrafts inside the crusher's feed hopper reaches 0.5 m/s, and 0.2 m/s during idle operation. During the loading of the cone crusher, the flow of rock mass is further crushed upon impact with the surface of the cone, and the resulting fine dust is carried by the upward air currents into the workshop air. In their study, K. Vanka *et al.* (2022) demonstrate that the most hazardous respirable dust (up to 5 μm) is released precisely at the moment of dynamic impact of the material against the surface. Figure 1 illustrates dust emission during the unloading of a dump truck into the feed hopper of a cone crusher.

***Figure 1.** Dust generation during the unloading of a dump truck into the feed hopper of a cone crusher*
***Source:** compiled by the authors*

The highest levels of dust emission are observed during the operation of a hammer crusher, in the housing of which an excess pressure of 20-30 N/m^2 builds up. During the operation of hammer crushers, the rotating rotor creates excess pressure inside the housing and directs airflows that carry dust from the feed opening into the working chamber. However, researchers A. Saramak & Z. Naziemiec (2019) concluded that a jaw crusher generates less fine dust per tonne of product compared to other machines, in particular a cone crusher, where constant friction creates a stable dust cloud.

An analysis of current methods and means of controlling dust emissions during the loading and operation of crushers allows to identify the most effective approaches to addressing this issue. The most effective way to localise dust emissions remains the installation of enclosures at crusher loading points, fitted with local extraction ducts for connection to extraction systems. According to NPAOP 0.00-1.82-18 (2018), fitting crusher loading points with extraction enclosures is a mandatory legal requirement. The geometric shape of the enclosure must be suited to the aerodynamics of the airflows for the relevant dust emission sources and have an optimal internal volume. If the internal volume of the enclosure is too large, it hinders the formation of the necessary directed airflows and requires the extraction of a greater volume of contaminated air. If the internal volume of the enclosure is too small, the airflows carry dust into the workspace, thereby reducing the efficiency of the extraction system. To direct the flow towards the extraction zone, the enclosure's outlet pipe, connected to the extraction system's air duct, must ensure uniform extraction of the entire volume of dust-laden air. At the points where the enclosure meets the process equipment, a tight seal must be ensured to prevent dust from being carried into the working area of the production premises. The design of the enclosure should be simple, convenient during operation and/or during repairs, and should not obstruct access to the working parts of the crushers. Consequently, enclosing the crusher feeding points is crucial for localising dust emissions and reducing dust concentrations at workstations.

An analysis of dust emission sources during crusher feeding indicates that the main cause of air pollution is not only the crushing process itself, but also the aerodynamics of the interaction between the material and the air. To neutralise dust emission sources, the extraction system must not only extract air but also compensate for the excess pressure created by the ejective effect. Modern science confirms that static pressure is a key factor in ensuring a uniform flow during extraction. Thus, the static pressure method is used to design an extraction duct with a slot. In their study, W. Nie *et al.* (2024) demonstrated that standard extraction systems create areas of uneven pressure. The study confirms that optimising the geometry of air ducts and equalising flow velocities reduces dust concentration by 84% by eliminating recirculation zones. In the study by Y. Song *et al.* (2022), which focuses on edge and slot extractors, the authors mathematically demonstrate that the system's energy efficiency (energy savings of up to 96%) is achieved precisely through the precise regulation of the suction opening width to compensate for the drop in static pressure along the length of the device.

The study by Y. Gao *et al.* (2024) examined in detail how a change in slot size radically alters the static pressure profile. The study confirms Equation (8), indicating that as the distance from the suction source increases, the aperture must be geometrically adjusted to maintain aerodynamic performance. An analysis of current methods for calculating aspiration systems allows the following conclusions to be drawn in favour of the proposed method. Studies by W. Nie *et al.* (2024) and Y. Song *et al.* (2022) confirmed formula (7) in the context that the static pressure P_x is not linear along the air duct due to friction losses λ and the "attachment" of new air masses. This makes the proposed calculation method, based on the momentum equation, significantly more accurate than simplified methods. All the analysed models show that, for a constant slot width, the suction velocity decreases geometrically with distance from the fan. Formula (8) for determining the variable width δ_x at an arbitrary cross-section x is the mathematical solution to this physical problem and an essential tool for overcoming pressure non-uniformity.

The transition from traditional systems with a constant cross-section to the proposed method for calculating the variable slot width makes it possible to overcome the main problem of aspiration at crusher feed points – aerodynamic non-uniformity. The achieved accuracy in velocity stabilisation is a compelling argument in favour of the energy efficiency of the developed system. Optimisation prevents air from being "drawn in" at points near the fan, which, according to the work of Y. Song *et al.* (2022), reduces the system's overall energy consumption by 15-20% whilst maintaining dust capture efficiency. Recent research in the field of industrial extraction and aerodynamics confirms that the static pressure method is the most appropriate for slotted air ducts for the following reasons.

Unlike empirical methods, the use of the momentum equation in projections onto the axis ensures mathematical accuracy and allows for the physical nature of the air flow to be taken into account when it is drawn in at an angle of 90° (where the velocity projection onto the axis is zero). Equation (7) takes into account the aerodynamic drag coefficient λ and the equivalent diameter d_0. The proposed method allows the calculation of parameters for specific air duct shapes, such as an isosceles triangle, which is a practical solution for preventing dust accumulation inside the air duct itself due to its sloping walls.

Justification and design of the extraction probe for the crusher feed hopper

The efficiency of dust extraction at crusher feed points depends entirely on the design of the enclosure, which may not always be airtight. Taking into account the structure of the airflows that carry dust into the air at workstations during the unloading of loose mineral raw materials makes it possible to propose a design for the crusher feed hopper enclosure that effectively localises dust emissions and ensures uniform extraction of contaminated air along the feed hopper.

The enclosure is designed in the form of an inverted trough, the sides of which are fitted with rubber strips. The enclosure is positioned above the crusher's feed hopper and can be moved across it, depending on which side the dump trucks are unloading from. The cover's mobility allows for effective localisation of dust emissions when the crusher is fed alternately from different sides of the feed hopper, thereby resolving the issue of "dead zones" in the extraction process. Figure 2 shows the design of the feed hopper enclosure for a cone crusher, whilst Figure 3 shows the layout of the crusher feed hopper enclosure (top view).

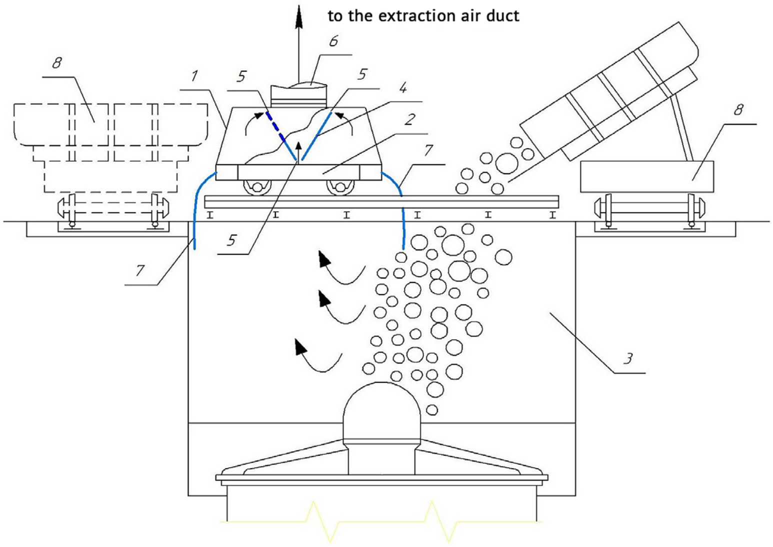

Figure 2. *Enclosure of the feed hopper of a cone crusher*

Notes: *1 – enclosure body, 2 – frame, 3 – feed hopper of the cone crusher, 4 – V-shaped hood, 5 – longitudinal extraction slots, 6 – outlet connection, 7 – flexible material skirts, 8 – dump trucks*

Source: *developed by the authors*

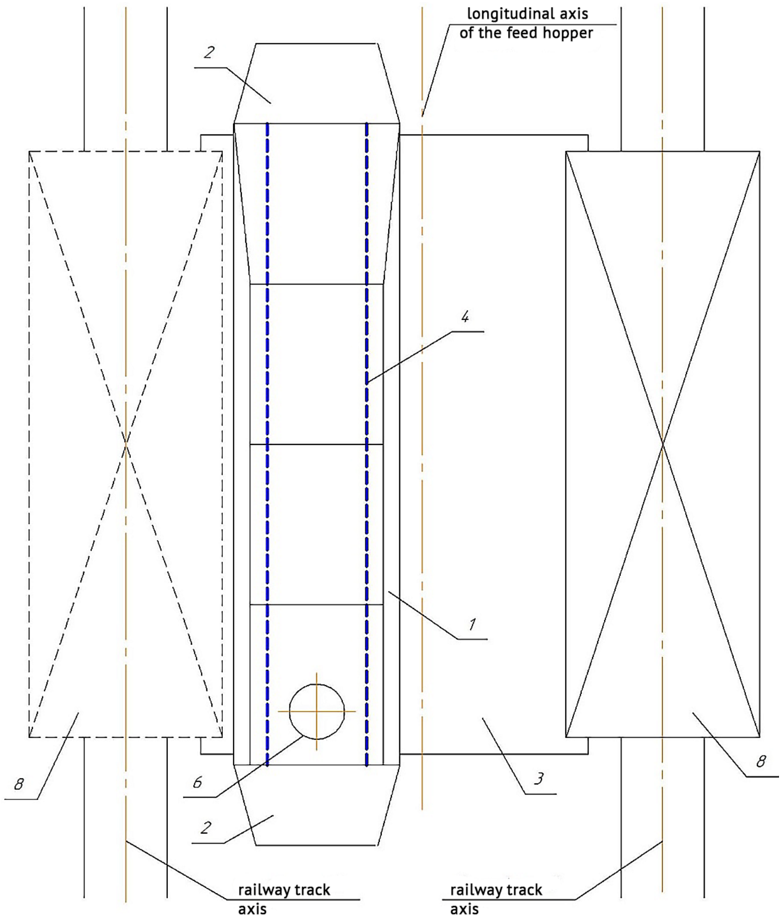

Figure 3. *Layout of the feed hopper enclosure (top view)*

Notes: *1 – enclosure body, 2 – frame, 3 – feed hopper of the cone crusher, 4 – V-shaped hood, 6 – outlet connection, 8 – dump trucks*

Source: *developed by the authors*

The enclosure of the feed hopper of the cone crusher consists of a body 1, which has a trapezoidal cross-section (Figure 2). The body 1 is mounted on a frame 2, which moves on wheels in a direction perpendicular to the longitudinal axis of the feed hopper 3 (Figure 3). Along both sides of the frame 2, skirts 7 made of an elastic material (used conveyor belt) are attached to prevent dust from being carried by air flows beyond the enclosure of the feed hopper. The entire enclosure structure is positioned above the feed hopper 3 between the railway tracks along which dump trucks 8 are delivered, preventing damage to the enclosure during material unloading. Thus, the enclosure covers part of the top of the cone crusher feed hopper, depending on which side the dump trucks are unloaded from. To stop the enclosure frame at the required position, KU-121 limit switches (Volianiuk & Mishchuk, 2020) or switches of another design (Dwyer Omega, n.d.) are installed. Limit switches are safety devices that automatically stop the enclosure when it reaches its extreme positions.

A V-shaped hood 4 with longitudinal suction slots 5 at the mouth and in the upper parts of the side walls is located in the cavity of the enclosure of housing 1 (Fig. 2). The V-shaped hood ensures the extraction of contaminated air, which is contained by the enclosure during unloading. As extraction takes place on one side of the enclosure (Fig. 3), the intake slots 5 have a variable width to ensure uniform air extraction along the entire length of the V-shaped hood 4, with the narrower width of the slots located on the side of the outlet pipe 6, which is connected to the air duct of the extraction system. The maximum slot width δ_0 will be on the opposite, closed end of the V-shaped hood 4 relative to the outlet pipe 6, where $x = 0$. Thus, as one approaches the inlet pipe 6, that is, as x increases to $x = l$, the slit width will decrease. The slit width at cross-section x is calculated using formula (8). The V-shaped hood 4 with longitudinal suction slots 5 acts as a suction air duct with a cross-section in the form of an isosceles triangle with base a, side b and height h, reduced to the base.

The dust removal device for receiving hoppers operates as follows. Before unloading the dump car 8, the housing 1 on the frame 2 is moved to the opposite side of the receiving hopper 3. The material unloaded from the dump car 8 draws air into the receiving hopper 3, creating excess pressure in its lower part, which causes dust to be carried into the air at the workstations. The upward flow of dust-laden air enters the cavity of housing 1 and, through the suction slots 5 of the V-shaped hood 4 and the outlet pipe 6, enters the aspiration system pipework. During the unloading of material from the dump truck 8, the aprons 7 prevent dust-contaminated air from escaping beyond the boundaries of the receiving hopper enclosure. Thus, the proposed enclosure design localises dust emissions during the unloading of bulk material and improves the efficiency of extraction at the crusher feeding points by ensuring uniform extraction of contaminated air along the receiving hopper.

It would be impossible to move the enclosure over the crusher's receiving hopper if the extraction duct were rigidly attached to housing 1 without the possibility of rotation. To solve this problem, a hinged connection must be provided between housing 1, outlet pipe 6 and the extraction duct. Figure 4 shows a diagram of the hinged connection between the extraction duct and the housing, whilst Figure 5 shows a diagram of the hinged connection between the extraction duct and the housing (top view).

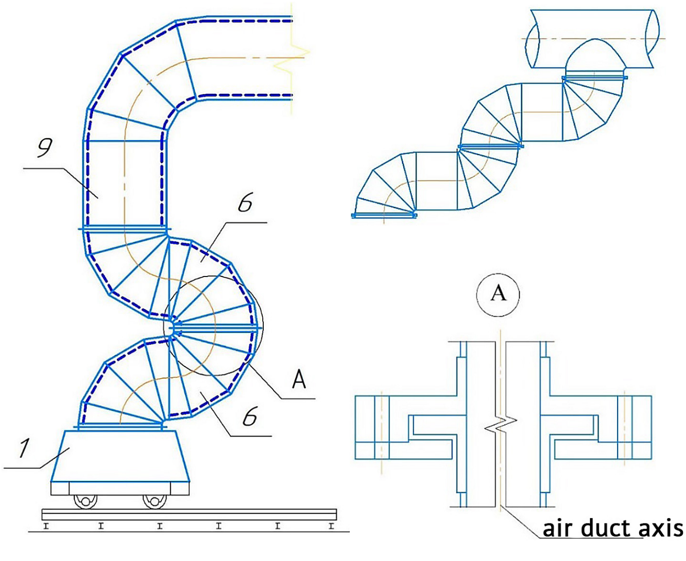

Figure 4. *Schematic of the hinged connection between the extraction air duct and the enclosure body*
Notes: *1 – enclosure body, 6 – outlet connection, 9 – extraction air duct*
Source: *developed by the authors*

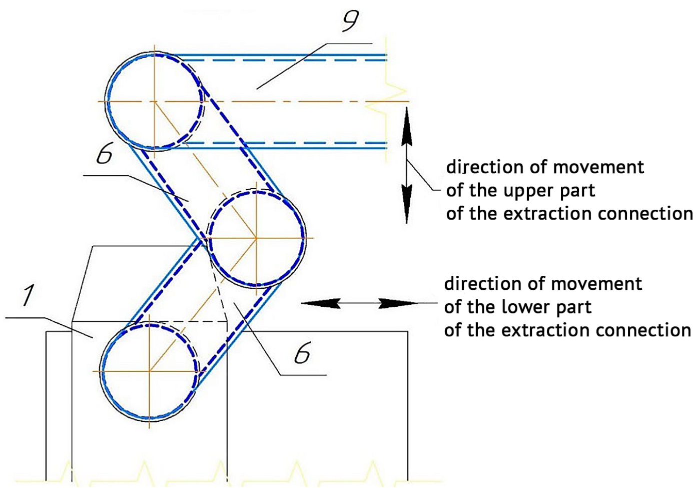

Figure 5. *Schematic of the hinged connection between the extraction air duct and the enclosure body (top view)*
Notes: *1 – enclosure body, 6 – outlet connection, 9 – extraction air duct*
Source: *developed by the authors*

To allow rotation, the outlet connection 6 consists of at least two parts, which are connected by hinges to each other, to the enclosure 1 and to the extraction air duct 9 (Figures 4 and 5), thereby eliminating air ingress from outside in extraction systems of different capacities. The three hinged connections allow the position of the outlet connection 6 to be changed simultaneously in two directions when the enclosure 1 is moved. As the enclosure 1 moves, the outlet connection 6 changes its position simultaneously in two directions due to the three hinged connections (Figure 5). At the same time, the position of the extraction air duct 9 remains unchanged. When the enclosure 1 is moved in the opposite direction, the kinematics of the outlet connection 6 occur in the reverse direction. Thus, the three hinged connections of the outlet connection prevent air ingress during operation of the extraction system and allow the enclosure to be moved over the crusher feed hopper, thereby eliminating the problem of "dead zones" in the extraction system.

A comparison of the proposed design with contemporary international developments shows that it is consistent with current trends in the improvement of local dust extraction systems. For example, a study by B. Tian *et al.* (2023) established that the efficiency of slotted extractors is largely determined by the relationship between the geometric parameters of the slot and the uniformity of extraction velocity distribution along its length. The proposed design also utilises longitudinal extraction slots; however, unlike the study cited, it features a variable slot width along the V-shaped hood, which ensures a more uniform air flow and more even extraction of contaminated air along the entire length of the intake hopper. In the study by T. Wu *et al.* (2023), a dust-suppression enclosure is proposed for an open-cast quarry crushing plant, the effectiveness of which is achieved by creating a closed circulation flow inside the enclosure. A common feature with the proposed design is the use of the principle of localising dust directly in the area where it is emitted. At the same time, the proposed design is distinguished by the presence of a mobile enclosure capable of moving over the feed hopper depending on the unloading point of the dump trucks, which eliminates "dead zones" in the suction process and improves the efficiency of the extraction system.

Experimental studies by Q. Feng *et al.* (2025) demonstrated that the efficiency of partially enclosed extraction systems during the transfer of bulk materials depends significantly on the area, location and extraction velocity through the ventilation openings. In contrast to these designs, the proposed enclosure utilises a V-shaped hood with a system of longitudinal slits of variable width, ensuring an even distribution of air flow throughout the entire dust emission zone. Furthermore, the use of flexible aprons and a hinged air duct connection makes it possible to simultaneously improve the enclosure's airtightness and maintain its mobility. Thus, the main advantages of the proposed design compared with known modern solutions are the enclosure's mobility, the elimination of "dead zones" in the extraction process, the uniform extraction of contaminated air along the feed hopper due to the variable-width slits, and the ability to operate effectively during the sequential unloading of material from different sides of the crusher.

Conclusions

The processes of feeding a crusher via conveyors, dump trucks or tippers into an open hopper or receiving funnel generate a huge amount of dust, which pollutes the air in the workplace. Mineral raw materials and bulk materials unloaded into the crusher contain fine dust capable of remaining suspended in the air for long periods and polluting the air. At the same time, airborne dust levels at workplaces exceed health standards, and most of the dust in the air contains free SiO_2 in the form of quartz and has a particle size of up to 5 μm. It has been established that fine dust (particles up to 5 μm) poses the greatest risk to workers' health, as it is capable of penetrating deep into the lungs and causing occupational diseases. Inhaling dust containing silicon dioxide is harmful to human health and can lead to permanent lung damage and silicosis.

The amount of contaminated air entering production premises during the loading of crushers depends mainly on the physical and mechanical properties of the raw materials and the type of crushing machinery, the operation of which is accompanied by the formation of upward air currents. The most effective solution for localising dust emissions and reducing dust concentrations at workstations is a combination of various methods for controlling dust emissions during the loading of crushers, provided that the crusher loading areas are equipped with covers fitted with local extractor ducts for connection to extraction systems. A key factor in improving the efficiency of extraction at crusher loading points is ensuring uniform air intake along the entire length of the loading hopper. The method proposed in this sduty for calculating air ducts with a longitudinal slot of variable width, based on the static pressure method, allows the suction velocity profile to be levelled out. This minimises dust escape zones and prevents energy wastage due to excessive ventilation, ensuring high efficiency of the extraction system regardless of the distance of the section from the fan.

Taking into account the structure of the air flows that carry dust into the air at workstations during crusher loading, a design is proposed for a cover over the crusher's feed hopper, which effectively localises dust emissions and improves the efficiency of dust extraction at the crusher loading points by ensuring uniform extraction of contaminated air along the feed hopper. The cover is positioned above the crusher's feed hopper and can be moved over it, depending on which side the dump truck is to be unloaded from. To enable the enclosure to be moved over the crusher feed hopper, its outlet connection consists of at least two parts and has three hinged connections, which prevent air ingress during operation of the extraction system and allow the enclosure to be moved over the crusher feed hopper, thereby solving the problem of "dead zones" in the extraction system. In the future, it is planned to extend the scope of research into the dynamics of air flows inside the hood, taking into account the turbulence that arises when large volumes of material fall. Investigating the influence of the internal volume and shape of the hood housing on the aerodynamics of updrafts for various types of crushers, to ensure maximum extraction efficiency. Identifying the optimal parameters for for combining extraction with spray irrigation or foam-generating systems for hydrophobic dust, in order to avoid excessive wetting and a reduction in ventilation efficiency.

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Conflict of Interest

None.

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Підвищення ефективності аспірації місць завантаження дробарок

Анотація. Процеси завантаження дробарок на підприємствах гірничодобувної та переробної промисловості супроводжуються інтенсивним виділенням дрібнодисперсного пилу, що погіршує умови праці, підвищує ризик розвитку професійних захворювань органів дихання та спричиняє додатковий абразивний знос технологічного обладнання. Особливої актуальності проблема набуває в умовах обмеженого використання водних методів пилопригнічення через утворення шламу, значні витрати води та складність їх застосування в холодний період року. Метою даної роботи було розроблення конструкції укриття приймальної воронки дробарки та наукове обґрунтування методу розрахунку параметрів аспірації для забезпечення рівномірного відсмоктування забрудненого повітря вздовж усієї зони завантаження матеріалу. У роботі було застосовано математичне моделювання динаміки повітряних потоків на основі методу статичних тисків і рівняння кількості руху. Об'єктом моделювання був повітряний потік у повздовжньому всмоктувальному повітропроводі зі щілиною змінної ширини. Установлено, що на робочих місцях дробильно-сортувальних фабрик переважають респірабельні фракції пилу з розмірами часток до 10 мкм, які становлять найбільшу небезпеку для здоров'я працівників. Показано, що однією з причин виносу пилу з-під укриття є нерівномірність швидкостей всмоктування вздовж повітропроводу. Розроблено математичну модель для визначення змінної ширини повздовжньої всмоктувальної щілини залежно від відстані до витяжного вузла. Встановлено, що для забезпечення стабільної швидкості всмоктування ширина щілини повинна поступово зменшуватися від заглушеного кінця повітропроводу до місця підключення витяжної мережі. Отримано аналітичні залежності для розрахунку геометричних параметрів повітропроводів трикутного перерізу, що запобігають осіданню пилу в середині системи. Запропоновано конструкцію мобільного аспіраційного укриття приймальної воронки дробарки з повздовжніми щілинами змінної ширини та шарнірним приєднанням до витяжного повітропроводу. Практичне значення отриманих результатів полягає у локалізації виділення пилу і зниженні концентрації пилу в повітрі робочої зони за рахунок забезпечення рівномірного відсмоктування забрудненого повітря по всій довжині приймальної воронки дробарки

Ключові слова: пиловий аерозоль; респірабельна фракція; локалізація викидів; щілинний відсмоктувач; статичний тиск; повітряний потік; укриття