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Research of the efficiency of the combined operation of dust collection and local ventilation systems during the operation of a heading machine

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Abstract. Intensive driving of mine workings is accompanied by the extraction of considerable quantities of dust of varying particle sizes. Coarse coal dust, when deposited upon the surfaces of workings and equipment, increases the risk of explosions and fires. Meanwhile, fine-dispersed dust is actively dispersed by ventilation

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airflows, worsening working conditions and contributing to the development of occupational respiratory diseases. The aim of this study was to provide a scientific justification for the effective parameters of the combined operation of local ventilation and dust collection systems for reducing dustiness of the mine atmosphere in blind mine workings. Analytical methods were employed to investigate the processes of mine atmosphere formation in the face area during heading machine operation. It was established that for the order to select optimal solutions that ensure the condition of the mine atmosphere in accordance with regulatory acts, it is necessary to take into account many different parameters (position of the air duct and dust collector relative to the face plane, physical properties of dust, location of the heading machine's cutting head and its operation mode, air velocity in the face area of the workings, etc.). The criteria for the effectiveness of the joint operation of local ventilation and dust collection systems during the operation of a heading machine are substantiated, which take into account the main parameters of the impact on the condition of the mine atmosphere in the face area and allow assessing its quality in order to select optimal solutions that ensure aerological safety and efficiency of the systems. The practical significance of the results is that the obtained efficiency criteria allow determining the optimal positions of dust collecting and ventilation equipment relative to the source of dust generation for their effective use, as well as the optimal aerodynamic parameters in order to improve the quality of the mine atmosphere in the face area of a blind workings

Keywords: dust formation; airflows; rock breaking; working conditions; fine dispersed dust

Introduction

Under conditions of intensive mechanised driving of mine workings, the problem of effectively purifying air withdrawn from the face area of blind workings becomes particularly acute. The increase in dust generation, caused by the high-speed destruction of rock, leads to elevated dust concentrations in the mine atmosphere, which in turn significantly complicates the maintenance of regulatory atmospheric indicators. In such circumstances, the purification of return ventilation air becomes a critical factor in ensuring safe working conditions, minimising occupational risks, and reducing the likelihood of dust-explosive situations. The issue of dust removal assumes special importance during mechanised driving with high-productivity heading machines. In such cases, coarse dust carried away from the face deposits upon the surfaces of workings and mining equipment, thereby worsening the conditions of explosion safety.

Over the past five years, numerous studies have addressed various aspects of this problem, including dust suppression methods, improvements in ventilation systems, and the development of new technologies for effective dust control. The work of H. Sun *et al*. (2023) summarised technologies of dust particle humidification through the use of water-based media. At the same time, as indicated by Q. Liu *et al*. (2025), the application of a transverse air curtain operating on the principle of negative fan pressure represents a promising dust control technology, combining the functions of ventilation and airflow barrier screening. In this context, the study by R. Huang *et al*. (2024), dedicated to modern dust control technologies in coal mines, established that high levels of dust control efficiency are achieved through the optimal integration of ventilation solutions with dust localisation systems, including the use of spray installations, barrier air curtains, and combined humidification methods.

P. Bhukya & K. Bhukya (2024) proposed a hybrid approach to assessing the performance of ventilation systems, combining computer modelling with experimental data in order to optimise airflow in underground coal mines, with particular emphasis on energy efficiency and uniform air distribution. Their study confirmed that the inefficiency of underground mine ventilation is largely attributable to the inadequate design of fans and airways. Such inefficiencies result in excessive energy losses, increased operating costs, and heightened risks to miners' safety. To address these shortcomings, A. Chatterjee *et al.* (2015) advanced an innovative method of regulating the speed of main ventilation fans through the use of variable frequency drives. This approach enables fan operation to be adapted to actual ventilation demand, thereby achieving not only enhanced energy efficiency but also optimised operating costs. The implementation of this technology has been shown to deliver an annual energy saving of approximately 2.54 million kWh.

In the study by J. Brodny & M. Tutak (2020), the level of dust concentration in a heading ventilated by auxiliary systems was analysed. The authors emphasised the importance of auxiliary ventilation in maintaining safe dust levels in underground mining environments. Their findings demonstrated that the ineffective organisation of auxiliary ventilation may lead to elevated dust concentrations, negatively affecting both working conditions and industrial safety. Consequently, it is considered expedient to pursue further research in this direction, particularly with regard to optimising air supply in headings and applying innovative ventilation solutions to reduce dust exposure for workers.

A relevant addition to the above-mentioned issues is the study by Q. Wang *et al*. (2022), in which modern methods of mathematical modelling and simulation were employed to substantiate the geometric parameters of mine ventilation installations. The study carried out a comprehensive analysis of airflow patterns and gas concentration distributions within the mine environment, taking into account diffusion processes that arise when the configurations of ventilation pipelines are altered. Particular attention was given to the influence of ventilation duct placement on the effectiveness of air exchange, and the dependence of ventilation performance on such parameters as airflow velocity, pipeline diameter, and spatial arrangement. The findings possess considerable practical significance, as they enable the optimisation of ventilation schemes in mine workings, thereby ensuring greater efficiency and safety in the operation of ventilation systems in coal mines.

As demonstrated by the results of numerical studies, dust generation processes in the face area are characterised by high complexity and multifactorial interactions. Mathematical and Computational Fluid Dynamics (CFD) modelling has shown that the efficiency of dust suppression systems depends substantially on airflow parameters as well as on the structural and operational characteristics of local dust collection devices (Wei *et al.*, 2020; Zheng *et al.*, 2024). In the study by Y. Li *et al.* (2024), numerical modelling of a two-phase gas-solid flow within the ANSYS Fluent environment was employed to characterise the parameters of ventilation duct positioning. It was established that placing the duct at a distance of 8 m from the face reduced dust concentration to approximately 39 mg/m^3, with an optimal suspension height of 1.5 m. Such a configuration ensured the effective removal of dust from the workers' breathing zone, reducing the likelihood of stagnant vortex zones forming. The numerical experiments further confirmed that excessive proximity of the duct (2-4 m) or increasing its height beyond 2 m resulted in elevated local dust concentrations owing to the secondary resuspension of particles.

The study by J. Liu *et al.* (2013) presented a comprehensive justification of ventilation system parameters based on the application of mathematical modelling methods. The authors emphasised that the rational selection of the cross-sectional area of ventilation roadways is a key factor in reducing both initial capital expenditures for construction and subsequent operating and energy costs of ventilation systems. The developed model, which incorporated capital, operational, and energy expenses, enabled the determination of optimal geometric parameters of mine workings. Application of the least-squares method, with consideration of time-dependent variations in costs, demonstrated that total expenses over a 35-year operational period could be reduced by almost four times compared with the traditional design approach, which relies solely on the limiting values of air velocity. At the same time, the study by B. Yu & L. Shao (2022) focused on energy conservation in the operation of ventilation systems, proposing an enhanced algorithm – Improved Equilibrium Optimiser – for minimising the energy consumption of ventilation networks. Its testing at the Wangjialing mine demonstrated a reduction in the power demand of the main fan by 333 kW (17.83%), thereby confirming the high economic efficiency of the proposed approach.

An analysis of the aforementioned studies indicates that the efficiency of dust collection in mine workings is determined not only by the hydrodynamic parameters of the airflow but also by rational engineering decisions concerning the organisation of ventilation. The integration of CFD-modelling for aerodynamic analysis with mathematical models provides a reliable basis for the development of comprehensive dust control systems that ensure both worker safety and the economic efficiency of mine ventilation. Thus, a scientific problem has emerged, namely the absence of scientifically substantiated solutions concerning the combined operation of dust collection and local ventilation systems during the operation of a heading machine. This necessitates research into the comprehensive study of aerodynamic interactions between ventilation systems, the optimisation of their structural and operational parameters in interrelation, and the adaptation of technical solutions to specific mining and geological conditions. Solving this problem is critically important for ensuring safe working conditions, reducing occupational risks, and achieving regulatory levels of dust concentration in stope faces and development headings.

Accordingly, the aim of this study was to substantiate the parameters of the combined operation of local ventilation and dust collection systems during the driving of development mine workings, taking into account the aerodynamic interaction between ventilation airflows and dust generation processes. Achieving this aim makes it possible to ensure a stable reduction of dust concentration in the mine atmosphere to regulatory levels, to minimise the risks of occupational diseases, and to create safe working conditions in the face areas of blind workings. The development of a scientific justification for effective systems of reducing mine air dustiness, considering the mutual influence of dust collection and local ventilation systems in their combined operation during mechanised driving of blind workings, as well as the adaptation of these systems to modern ventilation schemes and methods in line with dust dynamics, represents the central task of this research.

Materials and Methods

To model the movement of airflows in the face area, modern CAD-software was employed, and the influence of a free turbulent jet issuing from the air duct was analysed. The methodology for determining the parameters of this jet was based on the approach described by O. Mukha *et al.* (2019), subject to the following assumptions: the jet is considered to originate from a pole located at a distance of $X_0 = 0{,}29R_0/a$ from the edge of the supply air duct; the potential core of the jet extends to a length of $X_p = 0{,}96R_0/a$.

The jet boundary was defined according to the formula:

$$Rp = 3{,}4aX. \tag{1}$$

where $X = X_0 + X_c$ – the distance of the jet cross-sections from the "pole". Within this boundary, integration was carried out for the dependencies describing the distribution across the jet cross-section of momentum and energy of the elementary masses of the dust-air mixture:

$$2\pi\int_0^{Rp}\rho V^2 y\,dy. \tag{2}$$

In accordance with the scheme and the stated assumptions (constant pressure across the cross-sections, linearity of the jet boundary, etc.), the equations of momentum conservation and excess enthalpy retention of the jet were applied for all cross-sections, taking into account the entrainment of ambient air mass. According to the theory of turbulent jets impinging upon a blind end, for $V = V_m[1 - (Y/R_p)^{3/2}]^2$ in a cold jet, the relationship between dimensionless velocity and dimensionless distance along the jet axis was applied, which demonstrates a linear decay of velocity V_m with distance $V_m/V_0 = 0{,}96R_0/aX$ (Tkachenko & Stepanova, 2012). The turbulence constant a, which defines the rate of velocity decay of V_m with distance, was taken as 0.07, corresponding to subsonic airflow conditions. Figure 1 presents a schematic diagram indicating the parameters used in calculating the airflow rate in the face area of a blind working.

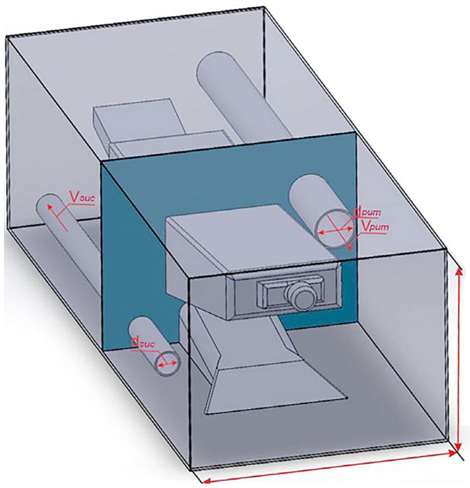

Figure 1. Scheme for determining parameters that affect the quality of the mine atmosphere in the face area of a blind working

Source: developed by the authors

Since the ratio of the quantity of fresh air Q_{pum}, supplied through the pressure pipeline of diameter d_{pum}, to the quantity of air Q_{suc}, extracted by the dust collection system through the suction duct of diameter d_{suc}, has a significant impact on the aerodynamics of ventilation flows in the face area during the combined operation of dust collection and ventilation systems, thereby ultimately determining their efficiency, this ratio was adopted as the efficiency criterion (ventilation criterion), denoted by the letter B:

$$B = \frac{Q_{pum}}{Q_{suc}}. \tag{3}$$

In the absence of recirculation and under conditions of maximum possible extraction of the dust-laden atmosphere, the ventilation criterion B can be defined as follows:

$$B = \frac{Q_{pum}}{Q_{suc}+Q_{p.min}}, \tag{4}$$

where $Q_{p.min.}$ – the minimum air quantity required for ventilation of the working, m^3/s;

$$Q_{pum} = \upsilon_{pum}S_{pum} = \upsilon_{pum}\frac{\pi d_{pum}^2}{4}, \tag{5}$$

where υ_{pum} – is the average air velocity in the pressure duct, m/s; S_{pum} – the cross-sectional area of the pressure duct, m^2; Q_{suc} – the quantity of air extracted by the dust collection system, m^3/s;

$$Q_{suc} = \upsilon_{suc}S_{suc} = \upsilon_{suc}\frac{\pi d_{suc}^2}{4}, \tag{6}$$

where υ_{suc} – the average air velocity at the suction inlet of the dust collector, m/s; S_{suc} – the cross-sectional area of the suction duct of the dust collector, m^2; d_{suc} – the diameter of the suction duct of the dust collector, m.

$$Q_{p.min} = \upsilon_{p.min}\cdot Sp. = \upsilon_{p.min}\cdot(b\cdot h), \tag{7}$$

where $\upsilon_{p.min}$ – the minimum permissible air velocity, m/s; b and h – the width and height of the mine working, m. Thus, the most effective solution is the one that takes into account the ventilation criterion, expressed in the following form:

$$B = \left\{\frac{Q_{pum}}{Q_{suc}+Q_{p.min}}\right\}, \tag{8}$$

or, in an expanded form suitable for use in computer modelling:

$$B = \left\{\frac{\upsilon_{pum}\pi d_{pum}^2}{4\left[\upsilon_{suc}\frac{\pi d_{suc}^2}{4}+\upsilon(b\cdot h)_{p.min}[]\right]}\right\}. \tag{9}$$

The ventilation efficiency criterion for the combined operation of the systems (B) is indirectly dependent on the velocity of the air supplied to the face and on the velocity of the air generated at the suction inlet of the dust collector. The lower the air velocity supplied to the face and the higher the suction velocity of the dust collector, the greater the number of dust fractions captured by the dust collection system. In addition, the mass and diameter of dust particles indirectly influence the efficiency of the dust collector. The greater the particle mass and diameter, the stronger the gravitational force, and consequently, the smaller the proportion of dust particles entering the dust collection system. For the dust collection system installed in the face zone to operate effectively, it is necessary to determine such values of the influencing parameters for which the dust removal efficiency criterion (η_ε) approaches unity and satisfies the requirements of NPAOP 10.0-7.08-93 (1993):

$$\eta_\varepsilon \geq \left(1 - \frac{1}{\varepsilon}\frac{N_p}{N_{da}}\right), \tag{10}$$

where ε – the suction multiplicity, usually taken as $\varepsilon = 0.8$; Np – the permissible dust concentration in the face, mg/m^3; N_{da} – the dust concentration in the face when foam is applied, mg/m^3.

The value of the ventilation criterion (B) must exceed unity by a margin sufficient to satisfy the safety regulations regarding the minimum airflow velocity in the working. The parameters of the initial data influencing the quality of the mine atmosphere, as well as their permissible ranges of variation, are presented in Table 1. The parameters and their ranges of variation were determined in accordance with the requirements established in NPAOP 10.0-1.01-10 (2010).

Table 1. Initial data for airflow modelling

Parameters influencing the quality of the mine atmosphere, the variation of which is possible within the range defined by the designer, and which have little or no impact on the mining technology employed	Distance from the air duct to the face plane	l, m	2.5…8	according to safety regulations, the maximum distance is 8 m
	Diameter of the air duct	d_{pum}, m	0.6	from 0.4 to 1.0 m (standard diameters of air ducts used in mines)
	Diameter of the suction duct of the dust collector	d_{suc}, m	0.5	may be adjusted independently or specified by the manufacturer
	Average air velocity at the suction inlet of the dust collector	υ_{suc}, m/s	11	from 8 to 22
	Average air velocity at the outlet of the air duct	υ_{pum}, m/s	12	from 10 to 12, ranging from the calculated value based on the gas factor to the maximum values defined by the auxiliary ventilation fan
	Density of a single dust particle	ρ_n, kg/m^3	1,400	taken as equal to the density of coal (may be replaced by the density of rocks excavated during driving)
	Number of dust particles of identical shape and substance	N_{ex}	100	number of dust particles tracked during calculation (assumed as 100, based on the design velocity)
	Radius of a dust particle	r_n, μm	10 μm	taken from field measurements (or from the actual distribution)
	Molar mass	M_c, kg/kmol	12	standard value for coal
	Initial velocity of dust particle ejection	υ_n, m/s	2	determined by the rotation speed of the cutting unit
	Dust mass flow rate	m_n, kg/s	50	determined according to the established methodology
Fixed parameters	Width of the mine working	b, m	4	parameters of the development heading in accordance with the project
	Height of the mine working	h, m	3.5	parameters of the development heading in accordance with the project
	Minimum permissible airflow velocity in the working	$\upsilon_{p\ min}$, m/s	0.25	according to safety regulations
	Height of the heading machine cutting unit position	Z, m	from 0 to 3.5	from 0 to h
	Minimum permissible airflow velocity in the face area of the working	$\upsilon_{в\ min}$, m/s	0.5	according to safety regulations

Source: developed by the authors based on NPAOP 10.0-1.01-10 (2010)

The efficiency of dust collection in the zone of the heading machine cutting unit is practically zero; therefore, in order to reduce dust concentration in this area, it is necessary to employ an auxiliary dust suppression measure such as foam.

Results and Discussion

On the basis of the results of the calculations performed according to the above methodology, ventilated zones were constructed (zones filled with clean air are shown in green). If the quantity of air supplied to the face (Fig. 2) is significantly greater than the quantity of air extracted by the dust collection system ($Q_{pum}/Q_{suc} > 1$), part of the dust-laden mine air is not captured by the dust collector but is carried further along the mine working by the active airflow.

Clean air supplied through the pressure duct, as well as purified air entering the working after passing through the dust collector and subsequently mixing with the dust-laden stream (shown in yellow) not captured by the dust collector and carried further along the working by the ventilation jet, are shown in green. In this case, ventilation flows are formed that ensure the required air velocity (not less than 0.15 m/s), as prescribed by safety regulations (NPAOP 10.0-1.01-10, 2010). Therefore, this configuration of the combined operation of the ventilation and dust collection systems is positive from the standpoint of occupational hygiene and safety (since such negative factors as airflow recirculation and stagnant zones with zero air velocity are absent). However, in this case, a certain amount of fine dust is dispersed along the entire length of the blind working. The dynamics of ventilation flows in the face zone, which determine the condition of the mine atmosphere both in the face zone and along the entire length of the blind working, depend on the value of the ventilation criterion *B*.

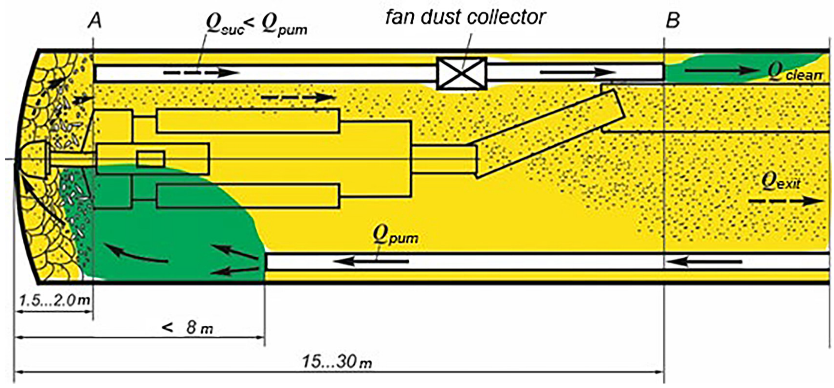

Figure 2. Formation of air movement in the bottomhole space under the condition $Q_{pum} > Q_{suc}$
Source: developed by the authors

If the criterion $B = 1$ (Fig. 3), then all the air supplied to the face is extracted by the dust collection system, and under these conditions the state of the mine atmosphere is determined exclusively by the dust removal efficiency criterion η_{ε}. The efficiency of dust collection systems lies in the range of 0.7-0.93. If $\eta_{\varepsilon} = 0.93$, is assumed, then along the entire length of the blind working (starting from the exhaust outlet of the dust collector), the outgoing ventilation stream will be cleaned of fine dust fractions. However, in the section of the face zone from the suction duct of the dust collector to its exhaust outlet, the airflow velocity will be close to zero, meaning that this part of the working is essentially unventilated. As a result, in this space, where electrical equipment is present and no methane monitoring by stationary sensors of the automatic gas control system is provided, a stagnant zone (shown in red) is formed, in which there is a high probability of an increase in methane concentration (local stratified accumulations). This factor is particularly critical for gaseous mines. For non-gaseous mines, this part of the face zone represents discomfort in terms of climatic conditions (Fig. 3).

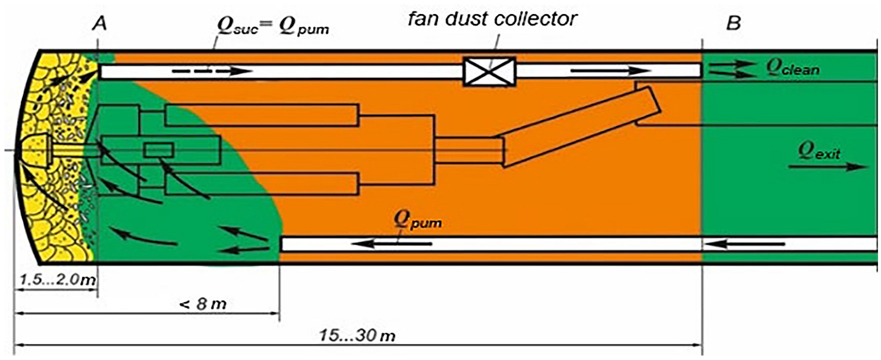

Figure 3. Formation of air movement in the bottomhole space
Notes: provided that $Q_{pum} = Q_{suc}$
Source: developed by the authors

If $B < 1$ (i.e., the dust collector's flow rate exceeds the volume of air entering the working face) (Fig. 4), the dust extraction system will draw not only the air from the immediate face area but also a portion of the air exiting the dust collector's discharge, thereby causing air recirculation.

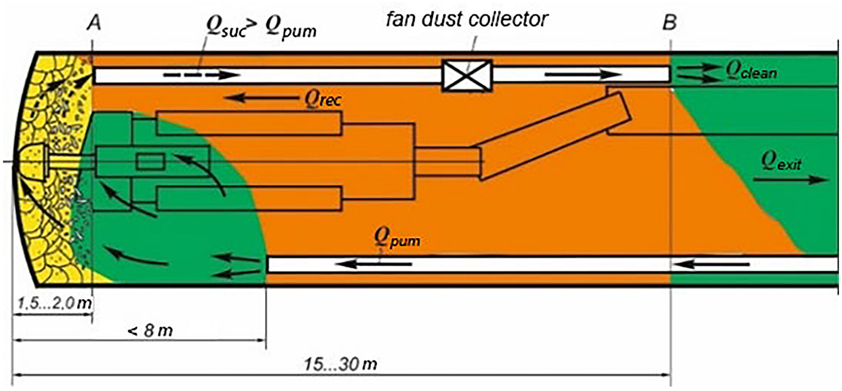

Figure 4. Formation of air movement in the bottomhole space
Notes: provided that $Q_{pum} < Q_{suc}$
Source: developed by the authors

In this case, as in the previous one, air dust removal will be virtually 100 %. However, due to the phenomenon of recirculation, methane concentrations in the space between sections *A* and *B* may be elevated. To enhance the efficiency of the combined operation of dust extraction and ventilation systems, an air supply scheme in the immediate face area may be employed. Provided that $B > 1$, the formation of mine air flow in the immediate face area under this scheme is illustrated in Figure 5.

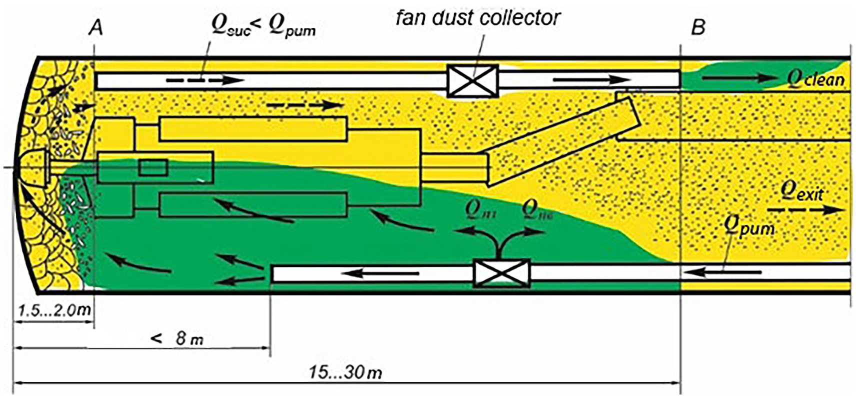

Figure 5. Formation of air movement in the bottomhole space when using a scheme with air refreshment
Notes: provided that $B > 1$
Source: developed by the authors

The introduction of fresh air into the working face through a lateral inlet in the supply duct results in a substantial expansion of the ventilated zone in the immediate face area, thereby improving the atmospheric conditions at the workplace. When employing this fresh air distribution scheme under conditions where $B \approx 1$, the stagnant zone (depicted in red) (Fig. 6) and the recirculation zone (Fig. 7) are significantly reduced.

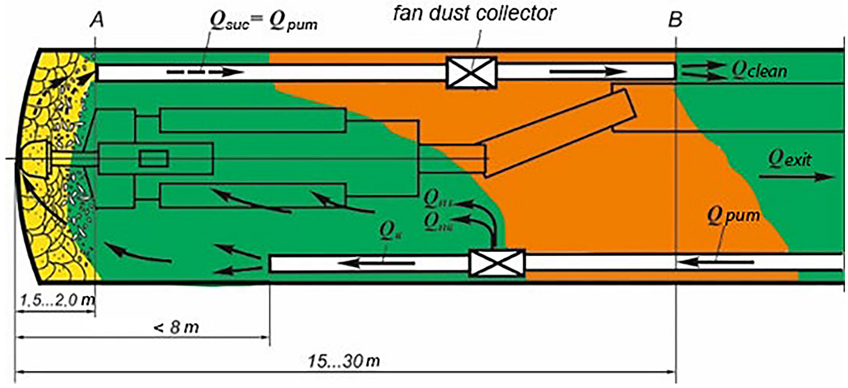

Figure 6. Formation of air movement in the bottomhole space when using a scheme with air refreshment
Notes: provided that $B = 1$
Source: developed by the authors

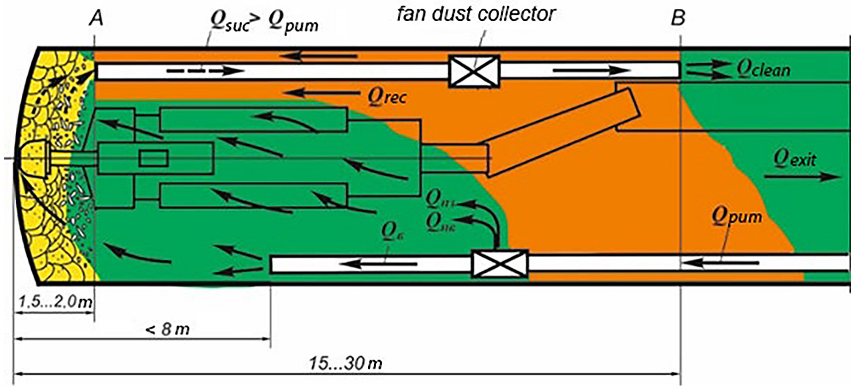

Figure 7. Formation of air movement in the bottomhole space when using a scheme with air refreshment
Notes: provided that $B < 1$
Source: developed by the authors

Figures 8 and 9 illustrate variants of the combined operation of the ventilation and dust extraction systems, depending on their relative arrangement and the "ventilation criterion" *B*. Figure 8 demonstrates that the safest configurations for the combined operation of dust extraction and ventilation systems occur when the ventilation criterion *BBB* exceeds unity. Aerodynamic analysis indicates that in these configurations, hazardous phenomena such as air flow recirculation and stagnant zones, where air movement approaches zero, do not arise. Figure 9 shows that, when employing an air supply scheme into the working face, the zones of the immediate face area with active ventilation are significantly expanded, while conversely, hazardous zones in which air flow recirculation and stagnant areas may occur are substantially reduced. Analysis of the combined operation of dust extraction and ventilation systems indicates that the dust collector will operate effectively only if the condition $Q_{pum}/Q_{suc} > 1$ is satisfied (i.e., the dust collector's flow rate is less than the volume of air entering the working face). An increase in the air volume supplied to the face will lead to dust being carried away without entering the dust collector. Therefore, the difference between the parameters Q_{pum} and Q_{suc} should be minimal. This value is determined in accordance with safety regulations, which require maintaining air movement in the mine working at a minimally permissible velocity. According to NPAOP 10.0-7.08-93 (1993), the air velocity in the immediate face area is taken as 0.5 m/s (for an air temperature of +24°C and relative humidity of 80%). The minimum air velocity in the mine working is 0.25 m/s.

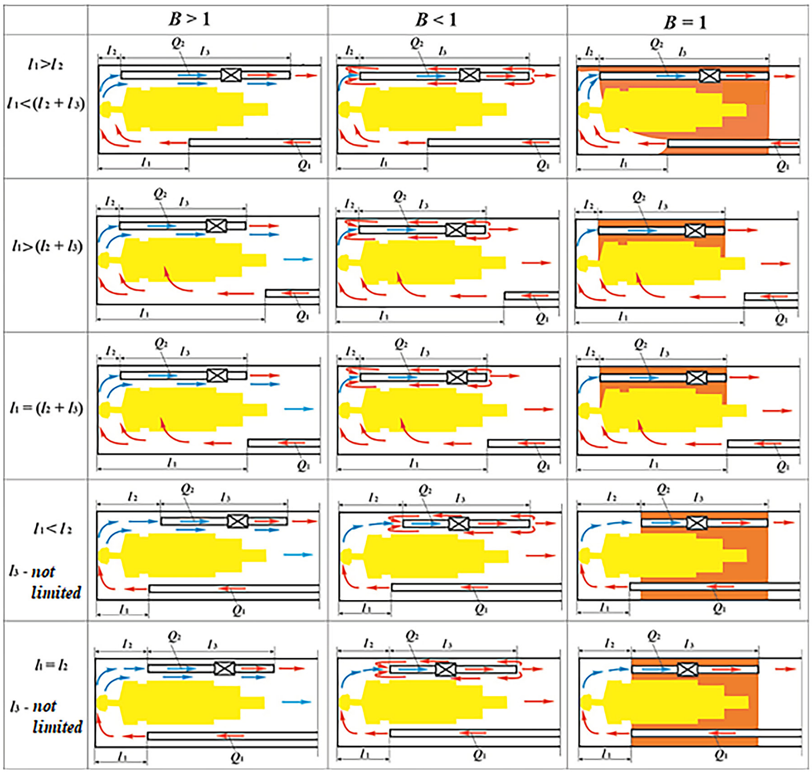

Figure 8. Variants of joint operation of ventilation and dust collection systems depending on the mutual location of these systems and the "ventilation criterion" *B* in a scheme without air freshening
Source: developed by the authors

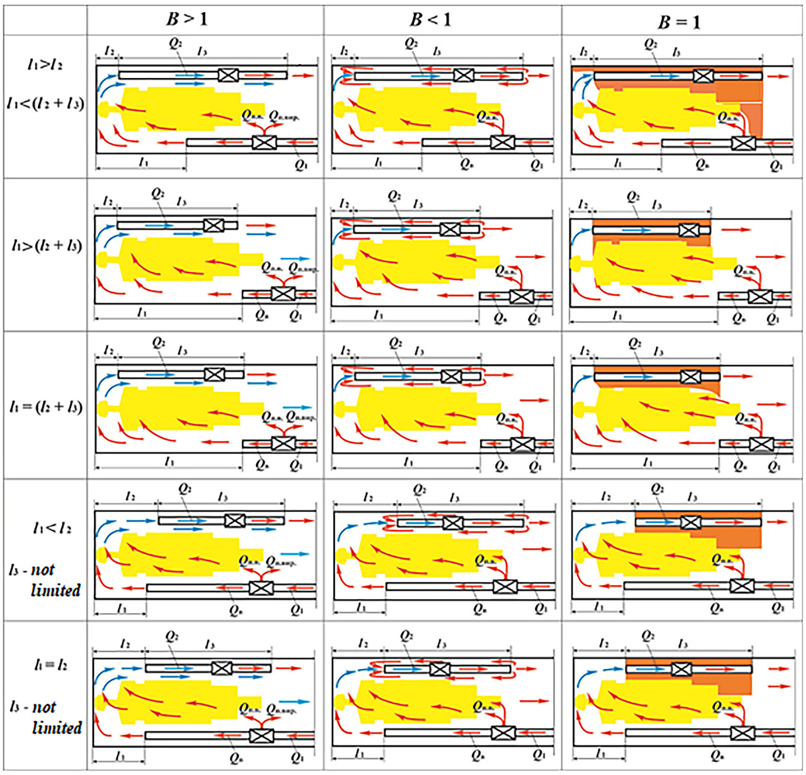

Figure 9. Variants of joint operation of ventilation and dust collection systems depending on the mutual location of these systems and the "ventilation criterion" *B* in the scheme with air refreshment
Source: developed by the authors

Among the variants considered, the most effective configuration, in terms of the relative arrangement of the systems, is that in which the distance from the face to the end of the supply duct exceeds the combined length of the dust collector and the distance from the face to the inlet of its suction pipe, i.e., when:

$$l_1 > (l_2 + l_3) \tag{11}$$

where l_1 – the distance from the face to the end of the supply duct, m; l_2 – the distance from the face to the inlet of the suction pipe, m; l_3 – the length of the dust collector, m. The results of the conducted study allow for the effective selection of optimal solutions to ensure the atmospheric conditions in the mine in accordance with regulatory requirements.

Calculations performed using the proposed methodology enabled the construction of ventilation zones, which are critically important for ensuring the safety and efficiency of ventilation systems in mines. Zones filled with clean air are depicted in green, indicating effective ventilation. The dynamics of air flows in the immediate face area largely depend on the value of the ventilation criterion *B*. When $Q_{pum}/Q_{suc} > 1$, ventilation flows are established that provide the required air velocity (not less than 0.15 m/s), in compliance with safety regulations. However, in this case, a certain amount of fine dust is dispersed along the full length of the dead-end working. When the criterion $B = 1$, all air supplied to the face is captured by the dust extraction system, resulting in the formation of stagnant zones with zero air velocity. This creates a high risk of elevated methane concentrations, which is particularly hazardous in gas-bearing mines. When $B < 1$, air recirculation occurs, which can also lead to increased methane concentrations in specific zones.

The implementation of an air supply scheme into the immediate face area significantly improves the atmospheric conditions in the mine. The introduction of fresh air through a lateral inlet in the supply duct expands the ventilated zone in the immediate face area. This reduces stagnant and recirculation zones, thereby enhancing working conditions and safety. The most effective configuration for the combined operation of ventilation and dust extraction systems is that in which the distance from the face to the end of the supply duct exceeds the combined length of the dust collector and the distance from the face to the inlet of its suction pipe (11). This arrangement ensures maximum ventilation efficiency and minimises the risk of hazardous zones forming. X. Yang *et al.* (2024) employed orthogonal numerical modelling to optimise ventilation and dust removal parameters in inclined mines with ultra-long tunnels. They demonstrated that advanced modelling techniques, such as CFD, combined with hybrid technical solutions, substantially improve occupational safety and reduce dust accumulation under complex mining conditions. However, optimisation models based on advanced methods like CFD do not fully address the removal of the fine dust fraction from the air in the immediate face area.

G. Li *et al.* (2020) investigated the significant increase in dust levels in mechanised roadway faces and analysed the effectiveness of localised dust extraction as a supplement to conventional supply ventilation. They noted that standard ventilation systems do not always achieve adequate air purification, particularly under conditions of intensive dust generation, typical of modern mechanised faces. Consequently, the implementation of combined ventilation solutions is recommended, including the use of local filtration units directly at dust sources, which effectively reduce the concentration of harmful particulates in the air and enhance worker protection in high-risk zones. The effectiveness of local filtration units at dust sources is primarily achieved through the substantial reduction of coarse dust fractions, but it is less effective for respirable dust compared with local suction dust (dust extraction).

Yu. Cheberyachko *et al.* (2024) proposed a mathematical model of the dust generation process occurring during rock fragmentation by the cutting head of a heading machine. The model allows for determining the distribution of dust fractions across the cross-section and along the length of the mine working, taking into account the velocity of the ventilation flow and the distance over which different dust particles settle. This enables a better assessment of dust transport dynamics within the mine atmosphere and supports the development of more effective dust extraction strategies. Particular attention must be paid to the insufficient interaction between dust extraction and local ventilation systems. The mutual influence of these systems is often neglected, which can lead to a significant reduction in their efficiency, local dust accumulation, and potentially hazardous situations. Furthermore, this increases the risk of fibrogenic lung diseases among miners working in areas with high dust concentrations. However, the proposed mathematical model of dust generation does not allow for the investigation of aerodynamic processes necessary to justify the placement parameters of ventilation and dust extraction systems under conditions of their mutual influence on the ventilation regime.

Based on the research of P. Vrtalova *et al.* (2023), effective strategies for managing ventilation flows have been developed to ensure safe working conditions and the continuity of mining operations in the Ostrava-Karviná district (Czech Republic). The proposed approaches take into account the specific geological and mining conditions and allow for the regulation of air distribution within the workings, which is critically important for the effective functioning of the ventilation system and the reduction of extraction-related risks.

However, it should be noted that the primary function of the ventilation system is the dilution and removal of harmful air contaminants from the immediate face area, particularly through the implementation of combined ventilation and dust extraction systems.

P. Wang *et al*. (2020), using CFD-based numerical modelling, substantiated the optimal parameters for the placement of ventilation ducts in fully mechanised working faces. The modelling results demonstrated a significant improvement in dust dispersion control and an enhancement of air exchange efficiency within the working area. This confirms the potential of computer modelling for optimising engineering solutions in ventilation systems and highlights the need for further research aimed at improving ventilation while taking into account the spatial characteristics of extraction and development faces. However, optimisation of engineering solutions in ventilation systems does not address the issue of respirable dust entering the immediate face area of dead-end workings, which necessitates the implementation of dust extraction systems to mitigate its presence.

Despite numerous studies aimed at reducing dust levels, improving ventilation, and deploying local dust extraction units, the problem of integrating these systems into a single, coordinated ventilation and dust extraction complex remains unresolved. Research conducted by Z. Qian *et al*. (2020) and X. Lu *et al*. (2025) indicates that the interaction between dust extraction and local ventilation systems is often overlooked during design and operation. This leads to a reduction in the overall effectiveness of both systems, localised dust accumulation in the faces, recirculation of dust flows in the area of the heading machine, as well as an increased risk of accidents and the development of occupational respiratory diseases among workers.

The study systematically analysed the combined operation of ventilation and dust extraction systems depending on their relative arrangement, based on the ventilation criterion proposed for the first time. This criterion characterises the relationship between the volume of fresh air supplied through the supply duct and the volume of air extracted by the dust extraction system. The proposed criterion enables a quantitative assessment of the efficiency of integrated systems and the determination of optimal conditions for their interaction in various configurations of the working face.

Conclusions

When using modern dust extraction systems in conjunction with localised ventilation, their mutual influence must be considered. Accounting for this interaction can significantly enhance system efficiency, prevent hazardous situations, and markedly reduce the risk of occupational diseases caused by the fibrogenic effects of fine dust. This article examined potential impacts of the combined operation of dust extraction and local ventilation systems on the quality of the mine atmosphere in the immediate face area of dead-end workings during heading machine operations. It was established that certain aerological conditions may arise in the immediate face area under the combined operation of these systems, provoking hazardous phenomena. Such phenomena include the recirculation of ventilation flows and near-zero air velocities, which substantially deteriorate safety levels and the occupational hygiene conditions for miners.

Based on the conducted research, a criterion for air purification from dust was developed. The value of this criterion directly affects the concentration of fine dust in the outgoing ventilation flow. Additionally, a ventilation criterion was established, which determines the dynamics of ventilation flows in the immediate face area. This criterion defines the atmospheric conditions in the immediate face area. It has been demonstrated that the efficiency criteria for the combined operation of dust extraction and local ventilation systems can be employed in the design of effective systems. These systems ensure a high level of mine air quality.

The research further provided recommendations for the optimal placement of ventilation equipment. The use of variable-frequency drives for main ventilation units can result in significant energy savings – up to 2.54 million kWh per year. Moreover, the rational selection of cross-sectional dimensions of mine workings can reduce overall energy consumption nearly fourfold over 35 years of operation. Modelling results show that the optimised algorithm allowed for a reduction of the main fan power by 333 kW, which represents 17.83% of total consumption. These findings indicate that the proper selection of equipment and parameters-such as positioning the supply duct 8 m from the face at a height of 1.5 m, is critical for minimising dust concentrations to 39 mg/m^3 and ensuring occupational safety in accordance with regulatory requirements, which establish a minimum air velocity of 0.25 m/s in the working and 0.5 m/s in the immediate face area.

Implementing these measures ensures a high quality of the mine atmosphere at workplaces in the immediate face area of dead-end workings during core technological operations. Adherence to these recommendations will enhance safety and comfort for miners while reducing the risk of occupational diseases. Prospects for further research include the development of innovative dust extraction and ventilation technologies, automation of their monitoring and control, and improvement of ventilation equipment designs. Special attention should be given to creating methodologies for assessing and forecasting mine atmospheric conditions to further improve occupational safety and comfort.

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Conflict of Interest

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References

[1] Bhukya, P., & Bhukya, K. (2024). Enhancing ventilation fan performance in underground coal mines: A hybrid approach. *Electrical Engineering*, 106, 4969-4992. doi: 10.1007/s00202-024-02268-0.

[2] Brodny, J., & Tutak, M. (2020). Analysis of dustiness state in a driven underground dog heading ventilating by auxiliary air-duct. *Management Systems in Production Engineering*, 28(2), 73-77. doi: 10.2478/mspe-2020-0011.

[3] Chatterjee, A., Zhang, L., & Xia, X. (2015). Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff. *Applied Energy*, 146, 65-73. doi: 10.1016/j.apenergy.2015.01.134.

[4] Cheberyachko, Yu., Mukha, O., Shustov, O., & Bednyuk, O. (2024). Analysis of the processes of dust formation and spread during the operation of a mining combine harvester in a dead-end production. *Collection of Research Papers of the National Mining University*, 76, 115-126. doi: 10.33271/crpnmu/76.115.

[5] Huang, R., Tao, Y., Chen, J., Li, S., & Wang, S. (2024). Review on dust control technologies in coal mines of China. *Sustainability*, 16(10), article number 4038. doi: 10.3390/su16104038.

[6] Li, G., Hu, J., Hao, X., & Qu, H. (2020). Application and research of swirling curtain dust collection technology in mines. *Applied Sciences*, 10(6), article number 2005. doi: 10.3390/app10062005.

[7] Li, Y., Wang, J., Li, Z., & Mo, H. (2024). Dust concentration distribution and analysis of influencing factors in the heading face of Shangwan coal mine. *Frontiers in Earth Science*, 12, article number 1512101. doi: 10.3389/feart.2024.1512101.

[8] Liu, J., Yang, P., & Lv, W.S. (2013). Energy saving in mine ventilation roadway and its optimization model solving. *Advanced Materials Research*, 868, 291-295. doi: 10.4028/www.scientific.net/amr.868.291.

[9] Liu, Q., Liu, S., Zheng, M., Nie, W., & Yan, Y. (2025). Study on the multifactor parametric of a transverse air curtain dust control technology during tunnel boring. *Powder Technology*, 465, article number 121281. doi: 10.1016/j.powtec.2025.121281.

[10] Lu, X., Xiao, J., Miao, J., Chen, Z., & Wang, S. (2025). Study on the mining dust release behavior under the top coal continuous caving coupling the dynamic hydraulic support advancing. *Process Safety and Environmental Protection*, 195, article number 106755. doi: 10.1016/j.psep.2025.01.009.

[11] Mukha, O., Cheberiachko, Y., Sotskov, V., & Kamulin, A. (2019). Studying aerodynamic resistance of a stope involving CAD packages modeling. *E3S Web of Conferences*, 123, artcle number 01048. doi: 10.1051/e3sconf/201912301048.

[12] NPAOP 10.0-1.01-10. (2010). *Safety regulations in coal mines*. Retrieved from https://dnaop.com/html/54542/doc-%D0%9D%D0%9F%D0%90%D0%9E%D0%9F_10.0-1.01-10.

[13] NPAOP 10.0-7.08-93. (1993). *Guidelines for the design of ventilation in coal mines*. Retrieved from https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=47105.

[14] Qian, Z., Wang, J., & Hu, L. (2020). CFD modeling of ventilation and dust removal in coal mines with wet suppression systems. *International Journal of Environmental Research and Public Health*, 17(16), article number 6006. doi: 10.3390/ijerph17166006.

[15] Sun, H., Liu, Y., Jiang, T., Liu, T., & Liu, D. (2023). Application of dust control method based on water medium humidification in tunnel drilling and blasting construction environment. *Building and Environment*, 234, article number 110111. doi: 10.1016/j.buildenv.2023.110111.

[16] Tkachenko, S., & Stepanova, D. (2012). *Hydrohydrodynamics (examples and tasks)*. Vinnytsia: VNTU.

[17] Vrtalova, P., Palicka, D., Hrinko, M., & Bubnik, J. (2023). Ventilation of the Ostrava-Karvina coal mine in order to ensure the operation and extraction during mining in the Czech Republic. In *Proceedings of the 23rd international multidisciplinary scientific geoconference-SGEM 2023: Modern management of mine producing, geology and environmental protection, book 1.1* (pp. 495-502). Albena: STEF92 Technology. doi: 10.5593/sgem2023/1.1/s03.60.

[18] Wang, P., Gao, R., Liu, R., & Yang, F. (2020). CFD-based optimization of the installation location of the wall-mounted air duct in a fully mechanized excavation face. *Process Safety and Environmental Protection*, 141, 234-245. doi: 10.1016/j.psep.2020.04.049.

[19] Wang, Q., Zhang, X., & Sun, H. (2022). Configuration and selection of surfactant for coal powder in Xinxing coal mine. *Integrated Ferroelectrics*, 226(1), 63-71. doi: 10.1080/10584587.2022.2061193.

[20] Wei, J., Xu, X., & Jiang, W. (2020). Influences of ventilation parameters on flow field and dust migration in an underground coal mine heading. *Scientific Reports*, 10(1), article number 8973. doi: 10.1038/s41598-020-65685-4.
[21] Yang, X., Jiang, Z., Chen, J., Chen, Y., & Yang, B. (2024). Optimization of ventilation and dust removal parameters in plateau extra-long tunnel inclined shaft based on orthogonal numerical simulation test method. *Construction and Building Materials*, 455, article number 139131. doi: 10.1016/j.conbuildmat.2024.139131.
[22] Yu, B., & Shao, L. (2022). A mine ventilation system energy saving technique based on an improved equilibrium optimizer. *Frontiers in Energy Research*, 10, article number 913817. doi: 10.3389/fenrg.2022.913817.
[23] Zheng, H., Jiang, B., Wang, H., & Zheng, Y. (2024). Experimental and numerical simulation study on forced ventilation and dust removal of coal mine heading surface. *International Journal of Coal Science & Technology*, 11, article number 13. doi: 10.1007/s40789-024-00667-z.

Дослідження ефективності сумісної роботи систем пиловловлювання і вентиляції місцевого провітрювання при роботі прохідницького комбайна

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Анотація. Інтенсивна проходка гірничих виробок супроводжується виділенням великої кількості пилу різної дисперсності. Крупний вугільний пил, осідаючи на поверхнях гірничих виробок і обладнання може підвищувати небезпеку вибухів та пожеж. При цьому, дрібнодисперсний пил активно поширюється вентиляційними струменями, погіршує умови праці на робочих місцях і сприяє розвитку професійних захворювань органів дихання. Метою було наукове обґрунтування ефективних параметрів сумісної роботи систем вентиляції місцевого провітрювання і пиловловлювання для зниження запиленості рудникової атмосфери тупикових гірничих виробок. У роботі використано аналітичні методи для дослідження процесів формування рудникової атмосфери у привибійному просторі при роботі прохідницького комбайна. Встановлено, що для вибору оптимальних рішень, які забезпечують стан рудникової атмосфери згідно з нормативними актами, необхідно враховувати багато різних параметрів (положення повітроводу і пиловловлювача відносно площини забою, фізичні властивості пилу, місцезнаходження виконавчого органу комбайна і режим його роботи, швидкість руху повітря в привибійному просторі виробки, тощо). Обґрунтовані критерії ефективності сумісної роботи систем вентиляції місцевого провітрювання і пиловловлювання при роботі прохідницького комбайну, які враховують основні параметри впливу на стан рудникової атмосфери у привибійному просторі та дозволяють оцінити її якість з метою забору оптимальних рішень, що забезпечують аерологічну безпеку та ефективність роботи систем. Практичне значення отриманих результатів полягає в тому, що отримані критерії ефективності дозволяють визначити оптимальні положення пиловловлюючого і вентиляційного обладнання відносно джерела пилоутворення для їх ефективного використання, а також оптимальні аеродинамічні параметри, з метою підвищення якості рудникової атмосфери у привибійному просторі тупикової виробки

Ключові слова: пилоутворення; повітряні течії; відбійка гірських порід; умови праці; дрібнодисперсний пил