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ҰЛТТЫҚ ҒЫЛЫМ
АКАДЕМИЯСЫ» РҚБ

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ИЗВЕСТИЯ

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© I.E. Nekrasova[1*], R.V. Kononenko[2], M.A. Popov[2], M.I. Chazhaev[3], S.S. Khudoyorov[4], 2025.
[1] Admiral F.F. Ushakov State Maritime University, Novorossiysk, Russia;
[2] Irkutsk National Research Technical University, Irkutsk, Russia;
[3] Kadyrov Chechen State University, Grozny, Russia;
[4] Tashkent State Technical University, Tashkent, Uzbekistan.
E-mail: ira.necrasova-i@yandex.ru

OPTIMISATION OF DUST REGIME AND EXPLOSION SAFETY OF COAL MINES

Irina Evlampievna Nekrasova — senior lecturer, Admiral F.F. Ushakov State Maritime University, Novorossiysk, Russia, e-mail: ira.necrasova-i@yandex.ru, https://orcid.org/0000-0001-9271-3523;
Roman Vladimirovich Kononenko — Ph.D., Associate professor, Computer Hardware and Software Laboratory, Institute of Information Technologies and Data Analysis, Irkutsk National Research Technical University, Irkutsk, Russia, e-mail: iistu_politeh@mail.ru, https://orcid.org/0009-0001-5900-065X;
Maxim Alekseevich Popov — graduate student, Computer Hardware and Software Laboratory, Institute of Information Technologies and Data Analysis, Irkutsk National Research Technical University, Irkutsk, Russia, e-mail: popovma@ex.istu.edu, https://orcid.org/0009-0002-0468-1221;
Muslim Ibragimovich Chazhaev — Dr., professor, Kadyrov Chechen State University, Grozny, Russia, e-mail: mchajaev@mail.ru, https://orcid.org/0009-0000-7744-3510;
Sardor Sadullaevich Khudoyorov — PhD, Associate professor, Tashkent State Technical University, Tashkent, Uzbekistan, e-mail: xudoyorov0703@mail.ru, https://orcid.org/0009-0008-8341-8926.

Abstract. This article addresses the urgent issue of coal dust explosion hazards in underground coal mines and focuses on optimizing dust control and explosion safety. Based on a comprehensive analysis of current suppression methods, the study evaluates the effectiveness of various dust control techniques—including pre-wetting of coal seams, shale protection using inert materials, hydroprotection via water curtains, and fogging systems—under real-world mining conditions. Experimental data indicate that pre-wetting reduces dust concentration by 20–30%, while shale-based protection reduces the risk of explosion propagation by 40–50% when inert dust with proper composition is used. Hydroprotection methods such as water curtains demonstrate up to 90% explosion localization efficiency but require regular maintenance and sludge control. Fogging systems reduce airborne dust concentration below 1 mg/m³, significantly improving air quality. The combination of these methods provides an overall reduction of explosion risk by 60–70%. A key finding is the necessity of calculating optimal retreatment intervals based on dust deposition rate, methane concentration, and protective material properties. For instance, when dust generation exceeds 2.5 g/m³ per day and methane levels rise above 2%, retreatment must occur every 1–3 days depending on the protection coefficient. The study proposes a system of adaptive protection planning that incorporates real-time monitoring, dynamic parameter modeling, and material optimization. The findings contribute to enhanced mine safety by enabling more accurate control of explosive atmospheres, particularly in high-risk conditions, and support the development of more effective, site-specific dust suppression protocols.

Keywords: Coal dust, explosion hazard, dust suppression, safety, mines, hydraulic protection, shale protection.

© И.Е. Некрасова[1*], Р.В. Кононенко[2], М.А. Попов[2], М.И. Чажаев[3], С.С. Худоёров[4], 2025.

[1]Адмирал Ф.Ф. Ушаков атындағы Мемлекеттік Теңіз университеті, Новороссийск, Ресей;

[2] Иркутск ұлттық техникалық зерттеу университеті, Иркутск, Ресей;

[3]А.А. Қадыров атындағы Шешен мемлекеттік университеті, Грозный, Ресей;

[4]Ташкент мемлекеттік техникалық университеті, Өзбекстан, Ташкент.

E-mail: ira.necrasova-i@yandex.ru

КӨМІР ШАХТАЛАРЫНЫҢ ШАҢ РЕЖИМІН ЖӘНЕ ЖАРЫЛЫС ҚАУІПСІЗДІГІН ОҢТАЙЛАНДЫРУ

Некрасова Ирина Евлампиевна — аға оқытушы, Адмирал Ф.Ф. Ушаков атындағы Мемлекеттік Теңіз университеті, Новороссийск, Ресей, e-mail: ira.necrasova-i@yandex.ru, https://orcid.org/0000-0001-9271-3523;

Кононенко Роман Владимирович — техника ғылымдарының кандидаты, доцент, Иркутск ұлттық техникалық зерттеу университеті, Иркутск, Ресей, e-mail: iistu_politeh@mail.ru, https://orcid.org/0009-0001-5900-065X;

Попов Максим Алексеевич — аспирант, Иркутск ұлттық техникалық зерттеу университеті, Иркутск, Ресей, e-mail: popovma@ex.istu.edu, https://orcid.org/0009-0002-0468-1221;

Чажаев Муслим Ибрагимович — экономика ғылымдарының докторы, профессор, А.А. Қадыров атындағы Шешен мемлекеттік университеті, Грозный, Ресей, e-mail: mchajaev@mail.ru, https://orcid.org/0009-0000-7744-3510;

Худоёров Сардор Саъдуллаевич — PhD, доцент, Ташкент мемлекеттік техникалық университеті, Ташкент, Өзбекстан, e-mail: xudoyorov0703@mail.ru, https://orcid.org/0009-0008-8341-8926.

Аннотация. Мақалада жер асты көмір өндіру жағдайларындағы көмір шаңының жарылыс қаупі мәселесі қарастырылады және шаң режимін оңтайландыру мен жарылыс қауіпсіздігін қамтамасыз етуге баса назар аударылады. Қазіргі таңда қолданылатын шаңды басу әдістерінің кешенді талдауы негізінде көмір қабатын алдын ала ылғалдандыру, инертті материалдарды қолдану арқылы сланецтік қорғаныс, су перделері арқылы гидроқорғаныс және тұмандандыру жүйелері сияқты әртүрлі технологиялардың тиімділігі бағаланды. Бұл әдістер нақты шахта жағдайларында сыналды. Эксперименттік деректер көмір қабатын алдын ала ылғалдандыру шаң концентрациясын 20–30% төмендететінін көрсетті, ал инертті шаң қолданылған сланецтік қорғаныс жарылыс таралу қаупін 40–50% азайтады. Су перделерін қолдану арқылы 90% дейін жарылысты оқшаулау мүмкіндігі бар, бірақ бұл әдіс үнемі ылғалдылықты бақылауды және шламды тазартуды қажет етеді. Тұмандандыру жүйелері ауадағы шаң концентрациясын 1 мг/м³ деңгейінен төмен түсіріп, ауа сапасын едәуір жақсартады. Бұл әдістерді біріктіре қолдану жалпы жарылыс қаупін 60–70% төмендетеді. Зерттеу нәтижелері қорғаныс шараларын қайталап қолдану мерзімін шаң түзілу жылдамдығына, метан концентрациясына және қолданылатын материалдардың сипаттамаларына байланысты есептеу қажеттілігін көрсетті. Мысалы, шаң түзілуі тәулігіне 2,5 г/м³-тен асқанда және метан концентрациясы 2%-дан жоғары болғанда, қайта өңдеу әр 1–3 күнде жүргізілуі тиіс. Авторлар нақты уақыт режимінде мониторинг, параметрлердің динамикасын модельдеу және материалдарды оңтайландыруды қамтитын бейімделетін қорғаныс жүйесін ұсынады. Бұл нәтижелер шахта қауіпсіздігін арттырып, жоғары тәуекел жағдайларында жарылыс қаупін дәл бақылауға мүмкіндік береді және жеке бейімделген пылеподавление стратегияларын әзірлеуге негіз бола алады.

Түйін сөздер: көмір шаңы, жарылыс қаупі, шаңды басу, қауіпсіздік, шахталар, гидроқорғау, шиферден қорғау.

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[1]Государственный морской университет имени адмирала Ф.Ф. Ушакова, Новороссийск, Россия;

[2]Иркутский Национальный исследовательский технический университет, Иркутск, Россия;

[3]Чеченский государственный университет им. А.А. Кадырова, Грозный, Россия;

[4]Ташкентский государственный технический университет, Ташкент, Узбекистан.

E-mail: ira.necrasova-i@yandex.ru

ОПТИМИЗАЦИЯ ПЫЛЕВОГО РЕЖИМА И ВЗРЫВОБЕЗОПАСНОСТИ УГОЛЬНЫХ ШАХТ

Некрасова Ирина Евлампиевна — ст. преподаватель, Государственный морской университет имени адмирала Ф.Ф. Ушакова, Новороссийск, Россия, e-mail: ira.necrasova-i@yandex.ru, https://orcid.org/0000-0001-9271-3523;

Кононенко Роман Владимирович — кандидат технических наук, доцент, Иркутский Национальный исследовательский технический университет, Иркутск, Россия, e-mail: iistu_politeh@mail.ru, https://orcid.org/0009-0001-5900-065X;
Попов Максим Алексеевич — аспирант, Иркутский Национальный исследовательский технический университет, Иркутск, Россия, e-mail: popovma@ex.istu.edu, https://orcid.org/0009-0002-0468-122;
Чажаев Муслим Ибрагимович — доктор экономических наук, профессор, Чеченский государственный университет им. А.А. Кадырова, Грозный, Россия, e-mail: mchajaev@mail.ru, https://orcid.org/0009-0000-7744-3510;
Худоёров Сардор Саъдуллаевич — PhD, доцент, Ташкентский государственный технический университет, Ташкент, Узбекистан, e-mail: xudoyorov0703@mail.ru, https://orcid.org/0009-0008-8341-8926.

Аннотация. В статье рассматривается актуальная проблема взрывоопасности угольной пыли в условиях подземной добычи угля и акцентируется внимание на оптимизации пылевого режима и обеспечения взрывобезопасности. На основе комплексного анализа современных методов пылеподавления оценивается эффективность различных технологий, включая предварительное увлажнение угольного пласта, сланцевую защиту с использованием инертных материалов, гидрозащиту посредством водяных завес и системы туманообразования, испытанных в реальных горных условиях. Экспериментальные данные по исследованию этих различных технологий показали, что предварительное увлажнение снижает концентрацию пыли на 20–30%, а сланцевая защита снижает риск распространения взрыва на 40–50% при условии соблюдения требований к составу инертной пыли. Гидрозащита с использованием водяных завес обеспечивает до 90% эффективности локализации взрыва, однако требует регулярного контроля влажности и удаления шлама. Системы туманообразования позволяют снизить концентрацию пыли в воздухе ниже 1 мг/м³, значительно улучшая качество воздушной среды. Комбинированное применение указанных методов снижает общий риск взрыва на 60–70%. Ключевым результатом является необходимость расчёта оптимальных интервалов повторной обработки на основе скорости пылеобразования, концентрации метана и свойств защитных материалов. Например, при пылеобразовании выше 2,5 г/м³ в сутки и содержании метана более 2%, повторная обработка должна проводиться каждые 1–3 дня в зависимости от коэффициента защиты. Предложена система адаптивного планирования противовзрывной защиты, включающая мониторинг в реальном времени, моделирование динамики параметров и оптимизацию применяемых материалов. Полученные результаты способствуют повышению безопасности на шахтах за счёт более точного контроля взрывоопасной среды, особенно в условиях повышенного риска, и формируют основу для разработки эффективных, индивидуально адаптированных мер пылеподавления.

Ключевые слова: угольная пыль, взрывоопасность, пылеподавление, безопасность, шахты, гидрозащита, сланцевая защита

Introduction. In the mining industry, especially in the conditions of underground mining of coal deposits, the problem of coal dust explosion hazard remains one of the key issues and still does not lose its relevance. Coal dust is a finely dispersed suspension of solid particles formed by mechanical impact on coal during drilling and blasting operations, mining, transport and processing. Coal dust particle size is usually less than 75 microns, which makes it extremely explosive at air concentrations in the range of 20-300 g/m³, depending on the characteristics of the seam (Alborov, et al., 2021; Efremenkov, et al., 2022). At the same time, the critical concentration of the explosive mixture is, on average, about 50 g/m³, and the ignition energy is only 20-60 mJ, which makes it possible to initiate an explosion even from a spark arising during the operation of electrical equipment or from the friction of metal against rock (Golik, et.al., 2019; Klyuev, et. al., 2025; Trrad, et. al., 2019).

Analysis of statistical data shows that on average up to 30% of all accidents with severe consequences in coal mines are related to dust explosions, and more than 60% of them are accompanied by secondary explosions caused by uncontrolled propagation of the dust wave. According to Rostechnadzor, over 70 cases of dust explosions have been registered in Russia over the last 10 years, at least 20 of which resulted in mass casualties. In the world practice the number of such incidents is 80-100 cases annually, which confirms the need to improve dust and emergency protection systems (Isametova, et.al., 2022; Kapanski, et.al., 2025).

The peculiarity of coal dust as an explosive component is its ability to accumulate in hard-to-reach areas of mine workings and retain explosive properties for a long time. In addition, coal dust tends to accumulate. It settles on supports, cables, and ventilation. These areas are especially vulnerable to fouling. Dust often builds up in hard-to-reach places. In such zones, it may contact methane. Methane is another explosive mine gas. This combination increases the explosion hazard. Methane is present in almost all coal mines. Its concentration varies across different locations. In Russian mines, it ranges from 0.5% to 2.5%. Some high-risk mines exceed 3% methane. These values require strict dust control. Safety rules become much more demanding. High methane levels raise explosion risk sharply. Dust control must meet higher standards. Regulations limit dust to safe levels. If methane exceeds 1%, dust must stay low. The limit is set at 10 g/m³. Exceeding this value increases danger significantly. Strict monitoring and control are essential. Both dust and methane must be managed. Together, they create critical safety challenges. Meeting these rules prevents major accidents. Otherwise, the probability of synergetic explosion of dust-methane mixture sharply increases (Nussipali, et. al., 2024; Gryazev, et. al., 2018; Efremenkov, et al., 2023; Bosikov, et.al., 2022).

To effectively manage the dust regime and prevent explosions in mines, various methods of dust suppression and protection are used: coal seam moistening, dust suppressing curtains, oslantsing, fogging systems and automatic wetting installations. Their effectiveness varies depending on the specific operating conditions (Manevich, et. al., 2024; Cherkashin, et. al., 2024; Bosikov, et.al., 2023; Karlina, et.al., 2024). For example, pre-moistening of coal allows to reduce dust concentration by 20-30%, and the use of water curtains - to localise the spread of dust explosion in 80-90% of cases at water consumption of 70-90 l/m² of mine cross-section. At the same time, shale protection reduces the probability of an explosion by 40-50% if the inert material dispersibility standards are met (95% of particles < 0.09 mm). The combined application of several methods, including inert powders and aerosol wetting systems, provides an overall explosion risk reduction of up to 60-70%.

However, the practical application of these methods is often faced with the problem of untimely renewal of the protective layer, as well as the lack of accurate calculation of the time of action of protective compositions and retreatment intervals (Shutaleva, et.al., 2022; Malozyomov, et al., 2023; Martyushev, et al., 2023). Failure to take into account the dust generation rate (which can reach 2.5-3.5 g/m3 per day in congested areas) and methane concentration leads to reduced efficiency of even the most reliable systems. In addition, there are still no universal models allowing to adapt the dust suppression strategy in real time to the current conditions (Zaalishvili, et. al., 2023; Yelemessov, et al., 2023).

In this regard, the development of a methodology for calculation of optimal protection parameters, taking into account not only local parameters (dust deposition rate, humidity, mine geometry), but also the dynamics of methane formation, efficiency of the materials used and ventilation operation mode, remains an urgent task. This study focuses on dust control in mines. It analyses current safety approaches in detail. The goal is to improve dust regime management. Researchers also tested protection methods experimentally. Tests were carried out under real conditions. Practical recommendations were developed from the results. These help choose protection parameters correctly. Each method was matched to operating conditions. Special focus was placed on key relationships. Dust formation rate and methane levels were analysed. Their impact on system efficiency was evaluated. This helped justify how often systems are used. It also allowed material volume calculations. Proper planning of resources became possible. The findings improve workplace safety directly. They support safer working environments in mines. Results are useful for new mine design. They also aid in mine modernisation projects. Existing facilities can benefit from these results. The approach supports both planning and operation. It helps ensure stable and safe conditions.

Materials and methods. This paper studied safety methods in dusty mine conditions. It analysed techniques used in coal mines. The focus was on dust reduction and explosion control. The research included several practical approaches. These aimed to lower coal dust concentration. It also studied ways to stop ignition. Explosion localisation methods were also investigated. Experiments tested various dust suppression tools. Water injection and spray nozzles were examined. Ejection-based suppression was tested as well. Inert dust and water curtains were also studied.

The study used multiple research techniques. Visual inspection was part of the process. Dust concentration was measured systematically. Containment system effectiveness was also evaluated. All experiments took place in real mines. Field testing ensured practical relevance of findings. Conditions were close to actual working environments. This helped check real-world method performance. Special focus was on explosion protection types. Shale protection was one of the methods. It used inert dusts like shale and dolomite. Coquina was also applied for similar purposes. These materials reduced combustible dust content. Hydroprotection used water-based solutions. Dust was moistened to reduce spread. Water curtains served as blast barriers. Combined methods used several tools together. They included both fogging and oslanzation. These offered a layered protection system. Equipment settings varied with method used. Operation modes depended on mine conditions. Fogging systems worked all through the shift. Water curtains were triggered when needed. In oslanzation, dust was applied by machines. These units treated different mine layouts. They covered various lengths and cross-sections. Each setup matched specific working conditions. This flexible approach improved safety outcomes. Results confirmed the importance of complex systems. Simple measures were less effective alone. Only integrated protection gave stable results.

Results. The analysis of explosion control in mines gave results. It showed which suppression methods work best. Various systems were tested in real conditions. The most effective approach was using multiple methods. Integrated protection gave the highest safety levels. Combining techniques reduced both dust and explosion risk. Simple methods alone gave weaker protection. Pre-moistening of coal seams was especially effective. It was applied before mining operations began. This treatment significantly lowered dust levels. Airborne dust dropped by 20–30% in treated zones. In untreated zones, dust stayed much higher. Pre-moistening proved to be a reliable method. It worked well as part of a larger system. Results confirm the need for complex solutions. Layered protection prevents dust from spreading. It also stops explosions from propagating further. The research highlights the value of preparation. Early action leads to better safety outcomes. Evaluation of the effectiveness of different types of protection against dust explosions demonstrated that shale protection based on the use of inert dust provides a 40-50% reduction in the risk of explosion propagation, provided that the requirements to the composition and dispersity of inert material are met (Table 1). It was experimentally established that the optimal content of combustible elements in inert dust should not exceed 0.9%, and at least 95% of particles should pass through a sieve with a mesh size of 0.09 mm (technical sieve No. 6). When the yield of volatile substances in the coal seam exceeds 25%, it is necessary to ensure that the inert dust content in the mixture with coal dust is not less than 75% by weight to prevent explosion.

Table 1. Effectiveness of different dust suppression methods (to be included after the paragraph on the effectiveness of different types of protection against dust explosions)

Dust suppression method	Reduction of dust concentration in the working zone (%)	Notes
Pre-moisturisation of the coal seam	20–30	Pre-moisturisation of the coal seam was carried out
Shale protection (inert dust)	40–50	If inert material composition and dispersion requirements are met (combustible elements < 0.9%, 95% of particles < 0.09 mm)
Waterproofing (water curtains)	80–90	t a water flow rate of 70-90 litres/m^2 cross-section. Requires moisture control and sludge cleaning
Fogging systems	Reduction to < 1 mg/m^3	At a water flow rate of 0.1-0.15 l/m^3 of air.

Hydroprotection, consisting of water curtains and wetting of dust deposits, has been shown to be effective in localising explosions, but requires constant monitoring of humidity levels and regular cleaning of surfaces from accumulated sludge. Studies have shown that the use of water curtains with a water flow rate of 70-90 litres per square metre of mine cross-section can stop the spread of an explosion in 80-90% of cases. At the same time, the optimal distance between water curtains depends on the speed of air flow in the mine and should be no more than 20 metres at an air velocity of more than 2 m/s.

Combined methods of protection, combining oslantsing and fogging systems, have demonstrated the best results, providing a 60-70% reduction in the risk of dust explosions. Using fogging systems improves air safety significantly. These systems consume 0.1–0.15 litres per cubic metre. Water is sprayed directly into the air space. This lowers dust concentration in the working zone. The level drops to below 1 mg/m^3. Such concentration meets all safety standards. It helps to protect workers from inhaling dust. Experimental results confirm this effect. When dust deposition exceeds 2.5 g/m^3 per day, simple methods are not enough. In such conditions, fogging units become essential. They must be used continuously in crushing areas. Constant wetting prevents dust from spreading. Coal deposits remain damp during operation. This reduces airborne dust effectively. Without fogging, dust levels become critical.

To set proper protection parameters, dust rate matters most. The key factor is dust deposition speed. It varies across different mine workings. This rate influences pollution levels directly. It also affects explosion risk intensity. High dust rates mean higher danger. The type and amount of dust matter. Results from measurements confirm this pattern. If deposition stays below 1.5 g/m^3 per day, simple methods work well. Regular wet cleaning is effective in such cases. Whitewashing surfaces also gives good results. These actions stop dangerous dust buildup. They prevent reaching critical concentration levels. No advanced systems are needed in these conditions. Basic maintenance keeps the environment safe. These measures should be carried out at least once every 5-7 days, provided that methane concentration is stable at the level of less than 1%.

If the dust deposition rate exceeds 1.5 g/m³ per day, and especially if it reaches values of 2.5-3 g/m³ and more, standard preventive measures are insufficient. In such cases it is necessary to implement additional engineering and technological solutions. The most effective of them are aslanting of mine workings with inert dust having high adsorption properties and low content of combustible components (not more than 0.9%), and application of fogging systems capable of maintaining dust concentration in the air at the level below 1 mg/m³. When using fogging systems with water flow rate of 0.1-0.15 l/m³ of air, dust reduction efficiency reaches 80-90%, especially in coal crushing zones and transshipment areas.

Frequency of surface treatment with whitewashing solution, inert dust or special mixture of potassium salt and wetting agent is selected individually and is calculated on the basis of several parameters: protection action time coefficient (Kt), methane hazard coefficient (Kmet), depending on the average concentration of methane in the air, and dust formation rate (Vp). For example, consider using whitewash with Kt = 1. If dust generation is 2 g/m³ per day, the retreatment interval can be calculated. The formula used is Tob = (Kmet - 5)/2 days. If Kmet equals 7, this gives 1 day. This value matches methane levels of 1.4–1.6%. If methane hazard rises to Kmet = 10, the situation changes. This corresponds to methane above 2.2%. The interval then shortens to 2.5 days. This applies even with low dust formation. Higher hazard leads to more frequent treatment. Additional results support this conclusion. At dust rates of 3.5 g/m³ per day and Kmet = 8, inert dust was tested. It had a surface coverage factor of 0.85. With proper application, retreatment can be delayed. The interval extends up to 3 days. This works only if coverage is even. The dust layer must reach 200 g/m². These parameters ensure stable protection. In very humid conditions, extra measures help. If humidity is over 85%, standard dusts lose effect. Surfactants improve adhesion in such cases. They help dust stick to surfaces longer. This extends the active protection period. Such mixtures perform better in moist air. Their use can reduce treatment frequency.

Thus, an effective protection strategy needs monitoring. It requires control of dust and methane levels. Dust formation rate must be tracked constantly. Methane hazard should also be assessed regularly. Conditions in the mine can change quickly. The protection system must adapt to these changes. Technology should respond to current conditions. Static solutions are not effective long-term. Control systems must be flexible and responsive. Especially useful are integral monitoring systems. They help evaluate the dust regime in real time. Predictive tools improve safety planning. These systems adjust protection methods automatically. They also set the right application frequency. Timing and type of measures are both important. Fast adaptation improves explosion prevention results. The use of mathematical models that take into account not only the current dustiness, but also its dynamics, provides increased accuracy in predicting explosive conditions and minimising risks.

Evaluation of the efficiency of different types of baffles used for localisation of dust explosions has shown that the highest efficiency is provided by baffles containing both inert dust and water (Table 2). It was found that the optimum amount of inert dust or water per one cubic metre of face cross-section is 350-450 kg. At the same time, the total length of the water barrier should be at least 30 metres, and of the oil shale barrier - at least 20 metres. The baffles should be placed in straight sections of the mine workings without voids behind the support, at a distance of no more than 300 metres from the preparation and cleaning faces.

Table 2. Placement and performance parameters for dust explosion barriers (to be included after the paragraph on evaluating the effectiveness of different types of barriers)

Parameter	Value	Justification/Note
Quantity of inert dust/ water per 1 m³ of longwall face	350–450 kg	A general rule of thumb to ensure effective explosion containment. More precise value may depend on specific mine conditions (fugitive yield, dust deposition rate). Adjustment based on monitoring data is recommended.
Distance between water curtains	Maximum 20 metres (at air velocity > 2 m/s)	Reduction
Material of water/dust containers	Polyethylene (seamless bags)	Ensure leak tightness and prevent leakage. Seamless packs reduce leakage
Checking the condition of the baffles	Regular inspection, check inert dust/water quantities, record in plans and emergency plans.	Ensuring that the shutters are ready for operation

Discussion. The analysis of the data shows a clear link. Using dust suppression methods reduces explosion risk. This relationship is direct and statistically confirmed. The impact of each method is different. It depends on many working conditions. Coal seam properties also affect performance. No single method works best in all cases. Results change with seam type and depth. The most effective strategy is using several methods. An integrated approach ensures maximum safety. For instance, pre-wetting the coal seam helps. It lowers dust but doesn't stop explosions. As a single method, it has limits. Better results come from using combinations. Adding oslantisation boosts the overall effect. Water curtains also increase protective efficiency. Together, these methods offer stronger defense. This agrees with previous scientific research. Other studies confirm the same trend. They highlight the role of multiple measures. A complex system gives better explosion control. Inert dust is one of the best tools. It shows high effectiveness in many tests. But it works only with correct material choice. The composition of inert dust matters. Wrong material lowers safety significantly. Proper selection improves explosion resistance. This confirms the importance of informed application. Every detail affects final safety performance.

Conclusion. This study helped to organise existing knowledge. It systematised data on dust control methods. The focus was on coal mine safety. Key factors affecting effectiveness were identified. Various suppression methods were carefully compared. Explosion protection techniques were also analysed. Results showed the value of combined approaches. Using several methods gives better results. An integrated system increases safety levels. The analysis confirmed this important conclusion. Pre-wetting the coal seam reduces dust. On its own, it gives moderate results. Its effect grows when combined with others. Adding aslazing makes suppression more effective. Water curtains further improve explosion resistance. These methods work better in combination. Shale shielding showed high protective potential. It stops explosion propagation in key cases. But this requires proper application conditions. The inert material must be well chosen. Its composition affects the final outcome. Dispersion characteristics also play a big role. Meeting these conditions improves safety greatly. Without them, shielding becomes less effective. These findings confirm earlier research results. A complex and informed approach is necessary. Only then can risks be fully controlled. Hydro-protection implemented in the form of water curtains has proven to be able to localise explosions, however, the period of treatment of the surfaces and the amount of inert dust or water in the curtains may vary.

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