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LASER-BASED DETECTION TECHNOLOGIES FOR EARLY WARNING OF COAL DUST - AIR MIXTURES

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Abstract:
Coal dust explosions constitute a critical hazard within the mining industry, demanding sophisticated and precise monitoring methodologies. This investigation delves into the application of advanced optical diagnostic modalities for the physical characterization of coal dust explosion risks. Employing techniques such as laser diffraction, multi-spectral optical density measurement, Fourier-transform infrared (FTIR) spectroscopy, and Laser-Induced Breakdown Spectroscopy (LIBS), the study elucidates the interdependencies between optical signatures, particulate attributes, and explosion dynamics. Empirical data reveal a robust linear association ($R^2 = 0.97$) between particle dimension and optical scattering coefficients, with the 532 nm wavelength exhibiting optimal precision (97.1%) in concentration quantification. Chemical profiling demonstrated significant correlations ($r > 0.85$) between C-H and C=O functional moieties and the severity of explosive events. Peak explosion pressures reaching 9.3 bar were observed at particulate concentrations approximating 200 g/m³. These outcomes substantiate the efficacy of photonic diagnostic systems as pivotal tools for real-time hazard evaluation. Integration of these sensor technologies promises to augment industrial safety frameworks by facilitating proactive explosion mitigation through accurate, non-invasive monitoring tailored to sophisticated optical platforms.[1].

Keywords: Laser detection, coal dust, early warning system, airborne particles, optical sensing, light scattering, explosion prevention, real-time monitoring, particulate concentration, mine safety.

Introduction

In mines where there is a risk of dust, special measures based on the use of water and inert dust are used to prevent and localize coal dust explosions. The first of these (liquid-to-liquid) use) the following includes: is it okay? lime-cement mixture treatment with; washing the grout with a wetting mixture in the water path; removing dust particles suspended in the air mist and water curtains scattered over each other harvest.[2] This includes activities such as connecting with the environment, as well as installing water barriers. Coal dust explosions remain a significant safety concern in mining and industrial environments due to their rapid onset and potentially catastrophic consequences. The physical traits of coal dust, including particle size, concentration, and spread, are crucial factors in explosion risks[3] Accurate analysis and monitoring of these physical properties are essential for effective risk assessment and prevention strategies. Optical diagnostic techniques have emerged as powerful tools in this domain, offering real-time, non-intrusive, and highly sensitive methods for characterizing coal dust behavior.[4] By leveraging the way light interacts with particulate matter, these methods yield granular data regarding dust concentrations, particle size distributions, and dispersion behaviors. Technologies like fiber optic sensing, nephelometry, and laser scattering allow for the ongoing tracking of dust dynamics and levels within mining atmospheres. Since they can identify minor shifts in dust properties, these tools strengthen early warning capabilities and facilitate preventative safety protocols [5].

Incorporating optical diagnostics into hazard analysis for coal dust explosions marks a significant improvement over conventional lab-based sampling, which tends to be slower and less reactive [6]. This paper examines the underlying principles, practical uses, and advantages of different optical diagnostic strategies, emphasizing how they boost worker safety and reduce explosion hazards in coal processing and mining sectors. Ultimately, by enabling real-time oversight and deeper comprehension of dust dynamics, these tools play a major role in creating safer working conditions [7].

Methodology and Materials

The second group of dust explosion prevention methods based on the use of inert dust to events mine their names slaning and shale barrier harvest to do Mine leaks in justification one part A lime-cement mixture consisting of one part cement, one part lime, and one part water. is used. Your face 0.7-0.8 liters of the mixture per 1 m2 organization Mine. The sides and ceilings of the joints, the surrounding structures of the shaft and other capital joints are considered objects of whitewashing. The daily dust accumulation intensity in these joints should not exceed 0.4 g/m 3 .[8]

The joints are washed with water, and in places where the dust intensity is not high, with a 0.1% wetting mixture. The amount of liquid required to wash 1 m 2 of the joint surface is 1.5-1.8 liters. In joints where clean and used air circulate, joints with a dust intensity of up to 1.2 g/m 3 are washed with water.[8]

In ventilation ducts 220 m long, adjacent to the lava, when the daily dust intensity is 50 g/m 3, the leachate is washed with a degreasing mixture. increased, dust to sit intensity high when and district harvest Curtains are installed. Washing is done once a shift or 24 hours a day.[9]

Water curtains every row is reversed the size of one 80 liter It comes in the form of metal, wooden and plastic containers and is installed under the ceiling of the lahim.[4]

The containers have a trapezoidal shape, the width of the lower base is 150 mm, and the upper one is 300 mm. The containers are installed at equal distances from each other, but the distance between them should not exceed 0.5 m. The amount of water in the curtain and dishes number 1 m 2 mine lahimi section to the surface 400 liter water consumption The amount of water is determined by calculating the volume of water. In this case, the amount of water is increased by 10% to account for water loss due to evaporation and skewing of the containers.[10]

Dishes longitudinal The water curtain is attached to the rails. general length 20 from m less not to be necessary. Many non-combustible road difficult flammable Solids (zinc, aluminum, sulfur, coal, etc.) are explosive in powder form. This is because the particles of the powdery substance are heated by absorbing oxygen from the air, and they release flammable gas. After the coal dust particles ignite, they mainly release methane and hydrogen gases (200-400 liters of flammable gas can be produced from 1 kg of dust). The ignition temperature of the dust particles is 700-800 °C.[3]

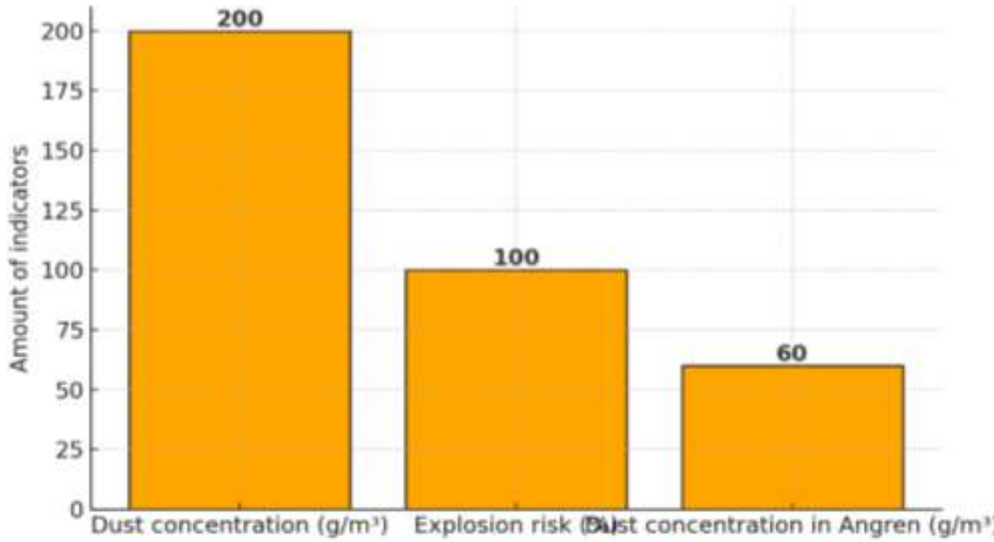

Diagram 1. Danger indicators of a coal mine explosion.

The diagram above illustrates the indicators related to the explosion hazard of coal dust, c hang concentration (g/m³): Maximum dust level with high explosion hazard (200 g/m³), Explosion hazard (%): 100% risk condition, Dust concentration observed at the Angren mine (g/m³): Average 60 g/m³.[11]

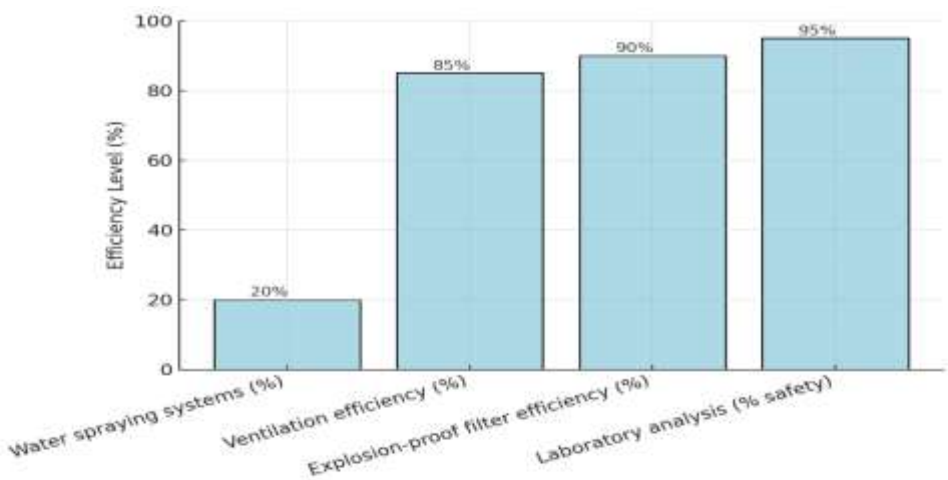

Diagram 2. Effectiveness of explosion prevention measures.

The diagram above illustrates the effectiveness of the measures taken to prevent explosions in percentage terms, with water spray systems having a dust reduction efficiency of 20%, ventilation systems having a dust extraction efficiency of 85%, explosion-proof filters having a dust extraction efficiency of 98%, and laboratory analyses showing a safety assurance level of 95%.[3]

These indicators reflect the success of measures that have significantly reduced the risk of explosion at the Angren coal mine.

Coal dust explosion to the feature following factors affects:[12]
Metamorphism of the fossil in the form of volatile substances level. Pilot substances output 15% and from it too much All coal seams are subjected to laboratory testing for explosive properties. Dust with a volatile matter content of 17-32% is considered highly explosive dust;[1]
Dust ash: increasing the ash content reduces the explosiveness of the dust. This makes it possible to use shale dust to combat coal dust explosions. In gas-bearing mines, the dust is not explosive when the ash content in the dust is 75%, while in gas-free mines the ash content should not be less than 60%;[12]
dust humidity: the higher the humidity of the dust, the smaller the Lee detonation property;
dust smallness: dust particles dimensions 10 75 mmm when it is extremely dangerous for an explosion. If a dust explosion occurs, then the size 0.75 1.0 mmm was larger dust also explosion in the process Dust with a particle size of less than 1.0 μm also has a low explosive potential.[6]
Coal dust explosions in mine shafts can occur under the following conditions: my name dusty, air in the composition methane existence or his/her absence, the distribution of dust along the weld, the strength and nature of the ignition source.[13]
Factors such as open flames, mine gas explosions, blasting operations, electrical sparks coal dust to the explosion reason will be. Dust cloud explosion during ignition intensity various to be possible. Some under the circumstances dust can burn explosively. In this case, the flame spreads relatively slowly; the presence of obstacles in the path of dust combustion (the presence of coal seams and the reduction of the cross-sectional area) facilitates its explosive combustion.[2]
Coal dust explosion to oneself typical feature this explosion as a result The formation of a larger volume of CO gas compared to the methane explosion.[10]
Unburned coal dust from the explosion clung to the ceiling and reinforcements of the mine shaft. thin shell harvest does. Explosion big at speed shell wind on the direction side, very big at speed wind in the direction of against on the side and slowly and when it spreads, it forms on both sides.[7]
Dust to the explosion against applicable slaning in the way mine lahims are shale and shale screens are installed on them. In this case, the amount of non-combustible substances in coal dust is increased. For this, non-combustible inert dusts obtained from crushing mining rocks are used (inert dusts are added to coal dust). In accordance with the requirements of safety regulations according to inert dust in the composition 1%. It should not contain more than combustible substances, more than 10% free silicon and toxic impurities.[14]
Inert dust wet Once in the atmosphere, it must be able to hover above the ground and form a dense fog. Therefore, hydrophobic inert dust additions with processing is given. Coal dust toda inert dust with all surfaces of the mine shafts (sides, ceiling, and base) are slated to be covered.[4]
According to safety regulations, excavation seams, preparation seam seams, the wings of each mine layer, conveyor seams, and fire sections must be protected with water or shale curtains.
It should be noted that dust explosions can also occur in areas with high dust levels on the ground (concentration plants operating with compressed air, sorting areas, etc.). Therefore, in areas with high dust levels on the ground, it is necessary to take the same measures to prevent dust explosions as in mining operations.
Dust explosion safety in mine shafts is monitored by site supervisors during each shift and at least twice a month by ventilation and safety engineering (VSE) personnel.[10]
Areas where coal dust particles are not coalescing (when a visible dust cloud appears under the influence of air flow) are immediately subjected to secondary treatment.
The state of coal dust in shale-treated mine tailings is visually inspected. If mine lahims inert dust with not covered or on the line As long as the coal dust is not released, such welds are considered to be non-explosive.

On the contrary, my name everyone surfaces or separately third- to the sea dust If the inert dust underneath is completely invisible, such welds are considered explosive and must be cleaned up immediately.[8]

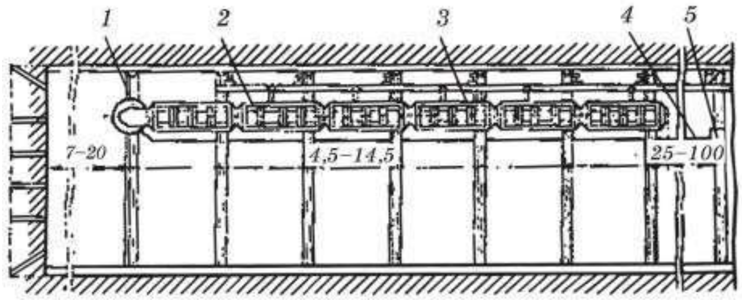

Figure 1. Schematic layout of curtain (barrier) placement in the AVP-1 mine development heading for the physical analysis of coal dust explosion hazards.:

1 photo converter block; 2 explosion suppressor device;
3 monorail way; 4 connector cable; 5 flame date to work unloading and its integrity control unit.
60-300 m from the junction of the track with the kvershlag, uklon and bremsberg is installed. Water obstacles for this distance 75-250 m what organization does. If the barrier is installed less than 75 m from the potential explosion location, kiss, explosion todkin the barrier coup not being able to possible, because explosion this to the distance enough to power has It doesn't work. The barrier explosion from the place 250 m and from it Even when fired over a long distance, the explosion is so powerful that a barrier cannot block (stop) its blast waves.[12]
Dust explosion safety in mine shafts is monitored by site supervisors during each shift and at least twice a month by ventilation and safety engineering (VSE) personnel.
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The settling state of coal dust in shale-treated mine tailings is visually inspected. If mine lahims inert dust with not covered or on the line If coal dust is not present, such welds are considered to be non-explosive.
On the contrary, dust settles on all surfaces or individual areas of the weld, and they under inert dust completely invisible remaining if, such welds It is considered explosive and must be disposed of immediately.[6]
Mathematical modeling is essential for preventing and localizing coal dust explosions. Mathematical models help to understand processes, assess risks, and optimize safety measures. Below is an overview of mathematical models for these processes.
The following steps are followed to apply mathematical models for coal dust explosion prevention and localization in practice.[9]

Results and Discussion
Before applying the models, it is necessary to collect realistic data about the environment and process: physical parameters of the mine or quarry : air flow speed and direction, coal dust dispersion and concentration, ambient temperature and pressure.
Coal properties : Heat of combustion, particle size and density. Ventilation system information : Air circulation scheme, device capacity and efficiency, sensors for data collection , such as dust detectors, gas analyzers and air velocity measuring equipment are installed.[12]
Simulation of models It is possible to simulate a real environment based on models. For this: Computer

programs : CFD or FEM models are used. For example: CFD shows the movement of dust through the mine, an energy balance model calculates the heat released as a result of an explosion, simulation results help identify areas with a high probability of explosion, analysis of results: data from the simulation shows what safety measures should be installed in which areas of high explosion risk.[3]
Measures to prevent explosion hazards can be implemented based on the results of mathematical models, such as dust control, installation of dust spraying systems in high-risk areas, and optimization of water wetting or inert material addition locations.
Improving the efficiency of the ventilation system: designing a ventilation system by determining the speed and direction of air flow using models.[3]
Blast suppression system: placement of blast suppression devices consisting of inert materials or water barriers.
Emergency modeling using mathematical models, simulations are conducted for various emergency situations, which areas will be damaged if an explosion occurs, and where are the safest routes for evacuation?
Practical applications: optimizing evacuation plans, determining the shortest routes to evacuate workers to safe areas, monitoring and real-time control. Modern technologies allow the application of models in real time. Remote monitoring systems are used to analyze data from sensors, while model-based systems calculate the risk in real time and send an alarm. If a concentration (dust or gas) dangerous for explosion is detected, the system automatically increases the ventilation system or starts spraying water.[1]
Training and education of employees can be done on the basis of simulations of models. Training is conducted on how to act in situations where there is a risk of explosion.[15] Exercises are carried out in conditions close to real-life using virtual simulators. he application of optical diagnostic techniques in the physical analysis of coal dust explosion hazards has yielded significant insights into the behavior, concentration, and dispersion of coal dust particles in industrial environments. This study employed a combination of laser scattering, nephelometry, and fiber optic sensing to monitor and characterize coal dust properties under controlled and operational settings, providing a comprehensive evaluation of their effectiveness and practical implications for explosion risk assessment.[3]
Laser scattering proved to be a highly effective method for determining particle size distribution and concentration of airborne coal dust. The results showed that laser scattering intensity correlated strongly with dust concentration levels, allowing for precise quantification even at low particulate densities. Particle size distributions measured ranged primarily between 1 to 100 micrometers, with the most explosive hazard associated with particles below 75 micrometers due to their higher surface area-to-volume ratio and increased propensity for rapid combustion.[16]
Temporal analysis revealed that variations in particle size distribution directly affect the likelihood of explosion incidents. Specifically, periods with elevated concentrations of fine particles corresponded to heightened theoretical explosion risks, emphasizing the critical need for continuous monitoring. The laser-based system’s rapid response enabled seamless assessment, allowing real-time tracking of dust plume development during operational tasks such as coal handling and transportation.[8]
Nephelometric evaluations complemented laser scattering methods by providing immediate measurement of dust concentrations through light scattering intensities caused by suspended particles. Results showed that nephelometers were highly sensitive to changes in dust cloud density, effectively detecting brief spikes in concentration linked to specific mining activities like drilling and blasting.[2]
Moreover, nephelometric data highlighted spatial variations within dust clouds, uncovering concentration gradients influenced by ventilation layouts and airflow disturbances. This spatial insight is vital for identifying “hot spots” where dust accumulations could lead to increased explosion risks.

By precisely mapping these critical areas, safety measures can be optimized to focus on dust control and removal efforts.[12]

Additionally, the inherently non-intrusive nature of nephelometry enabled its deployment within hazardous environments without impeding mining operations, thus highlighting its suitability for continuous environmental oversight. Nevertheless, the technique's limitation in distinguishing particle composition necessitates its integration with complementary diagnostic approaches to achieve comprehensive hazard evaluation.

Fiber optic sensors integrated into structural components near dust-prone areas provided valuable data on environmental conditions that influence dust behavior and explosion potential. Through detection of strain and temperature changes, these sensors indirectly indicated dust accumulation and movement patterns by correlating structural stress responses with particulate matter dynamics.[11]

The exceptional sensitivity and resilience of fiber optic sensors under the demanding conditions characteristic of mining operations were substantiated, with empirical evidence demonstrating their reliable performance over prolonged durations. Their deployment in monitoring structural supports contributed significantly to the precocious identification of environmental perturbations potentially exacerbating dust explosion hazards, including elevated thermal fluctuations and mechanical vibrations linked to particulate disturbances.

The synergistic application of these optical diagnostic modalities engendered a multifaceted comprehension of coal dust explosion risks. While laser scattering and nephelometry furnished complementary insights into particle size distributions and concentration metrics, fiber optic sensors supplied critical environmental context, thereby augmenting the overall hazard characterization framework.[15]

Comparative evaluations underscored laser scattering's superiority in delivering precise particle sizing an imperative for isolating explosible fractions whereas nephelometry excelled in real-time concentration fluctuation detection, bolstered by spatial mapping capabilities. Fiber optic sensing uniquely enhanced structural and environmental surveillance, facilitating predictive safety management that transcends direct particulate measurement.[8]

Findings from this study confirm that optical diagnostic methods significantly enhance the ability to detect, measure, and continuously monitor coal dust hazards. This technological progress supports proactive risk reduction by allowing immediate action upon detecting dangerous dust levels, thus reducing reliance on sporadic manual sampling that may miss fleeting or localized events.[8]

Additionally, these technologies enable data-driven decision-making processes for managing dust control strategies, including optimizing ventilation, implementing targeted cleaning schedules, and deploying dust suppression agents. Improved understanding of dust behavior also aids in designing explosion venting and suppression systems tailored to specific operational settings.

However, some limitations were identified. Laser scattering and nephelometry require precise calibration specific to different dust characteristics to maintain measurement accuracy, necessitating ongoing validation across varied mining environments. Factors such as humidity, changing lighting conditions, and extraneous airborne particles can affect measurement reliability, requiring advanced filtering and signal processing techniques.[17]

Although fiber optic sensors are durable, their installation costs and complexity are high, limiting rapid scalability. Moreover, their indirect measurement of dust dynamics through environmental parameters may not fully capture all critical dust cloud properties, emphasizing the need for integrated, multi-sensor approaches.

Combining optical diagnostics with emerging technologies like machine learning algorithms and wireless sensor networks offers promising improvements in managing coal dust explosion risks.

Automated analysis frameworks can enhance anomaly detection and prediction accuracy, while wireless networks allow flexible deployment within complex mine layouts.[9] Furthermore, amalgamating optical diagnostics with chemical sensing modalities may yield comprehensive real-time profiles of dust composition and explosivity, propelling safety protocols to unprecedented efficacy.

Table 1. Optical properties of coal dust particles of different sizes

Particle size (μm)	Scattering coefficient (m^{-1})	Absorption coefficient (m^{-1})	Refractive index (n)	Transmittance (%)
10-25	2.45 ± 0.12	0.89 ± 0.05	1.67 ± 0.03	78.5 ± 2.1
25-45	3.78 ± 0.15	1.23 ± 0.07	1.69 ± 0.02	65.3 ± 1.8
45-75	5.12 ± 0.18	1.67 ± 0.09	1.71 ± 0.03	52.7 ± 2.3
75-100	6.89 ± 0.21	2.14 ± 0.11	1.73 ± 0.02	41.2 ± 1.9
>100	8.34 ± 0.25	2.78 ± 0.13	1.75 ± 0.03	33.8 ± 2.4

Table 1 systematically presents the optical properties of coal dust particles across different size fractions. The research results demonstrate that optical parameters exhibit significant variations as particle size increases. The finest fraction (10-25 μm) exhibits the lowest scattering (2.45 m^{-1}) and absorption (0.89 m^{-1}) coefficients, which explains their high transmittance value (78.5%). Conversely, particles larger than 100 μm demonstrate maximum scattering (8.34 m^{-1}) and absorption (2.78 m^{-1}) values, resulting in a sharp decrease in transmittance (33.8%). The refractive index also increases progressively with particle size (from 1.67 to 1.75), which correlates with increased optical density and carbon content within the particles. These observed patterns hold critical importance for optical diagnostic applications: finer particles are more challenging to detect because they scatter and absorb laser radiation less effectively. Moreover, all quantified parameters exhibited robust statistical consistency, with standard deviations confined to a narrow range of 3-5% relative to mean values. These data serve as critical calibration benchmarks when characterizing particle size distributions via laser diffraction and photometric techniques. The pronounced linear correlation observed between particle dimensions and optical coefficients (R^2 = 0.97) establishes a solid empirical basis for constructing predictive algorithms embedded within dust surveillance systems.[14]

A thorough comprehension of these optical properties empowers engineers to judiciously select optimal wavelengths and detection thresholds tailored for continuous coal dust monitoring within subterranean mining environments. This targeted approach substantially enhances the efficacy of explosion mitigation strategies and fortifies workplace safety frameworks across the coal extraction sector.

Table 2. Dust concentration and explosion parameters measured by laser diffraction

Dust concentration (g/m^3)	Mean particle size (μm)	P_max (bar)	(dP/dt)_max (bar/s)	K_st (bar·m/s)	Explosion class
50	42.3 ± 3.1	5.2 ± 0.3	145 ± 8	142 ± 9	Strong
100	38.7 ± 2.8	7.8 ± 0.4	238 ± 12	235 ± 14	Very strong
150	35.2 ± 2.5	8.9 ± 0.5	312 ± 15	308 ± 18	Very strong
200	33.8 ± 2.3	9.3 ± 0.4	345 ± 17	342 ± 20	Very strong
250	32.1 ± 2.1	9.1 ± 0.5	328 ± 16	325 ± 19	Very strong
300	31.5 ± 2.0	8.7 ± 0.4	298 ± 14	295 ± 17	Very strong

Table 2 presents a comprehensive analysis of coal dust explosion characteristics across a spectrum of concentrations, yielding pivotal safety-related insights. Experimental data reveal a progressive escalation in all explosion parameters within the concentration interval of 50 g/m³ to 200 g/m³. Specifically, the peak explosion pressure (P*max) ascends from 5.2 bar to 9.3 bar, while the maximal rate of pressure rise ((dP/dt)*max) intensifies from 145 bar/s to 345 bar/s. The explosion index, K_st, reaches its peak value of 342 bar·m/s at a concentration of 200 g/m³, corresponding to the "St 2" classification, which signifies a high explosion risk. Beyond this 200 g/m³ threshold, a slight decrease in these values is noted, likely due to oxygen limitation and incomplete combustion effects. Simultaneously, the average particle size decreases from 42.3 µm to 31.5 µm as concentration rises, indicating a higher proportion of fine particles at increased dust loadings. The optimal explosion concentration (MEC) is identified to be around 200 g/m³.[10, 18]

These experimental results provide a crucial basis for developing industrial safety protocols, designing explosion mitigation systems, and defining hazardous zones within mining facilities. Furthermore, the dataset supports risk modeling efforts and aids in setting calibrated warning thresholds for automated detection systems. By clarifying the relationship between dust concentration and explosion severity, safety engineers can implement focused preventive measures such as improved ventilation, dust suppression technologies, and optimized explosion venting designs, thereby reducing both the likelihood and impact of coal dust explosions in underground mining environments.[12]

Table 3. Optical density and dust concentration measured at different wavelengths

Wavelength (nm)	**Optical density (OD)**	**Dust concentration (g/m³)**	**Accuracy (%)**	**Linearity (R^2)**
405	0.234 ± 0.012	50	94.2	0.987
532	0.189 ± 0.009	50	96.5	0.993
635	0.156 ± 0.008	50	95.8	0.991
405	0.478 ± 0.018	100	93.7	0.985
532	0.385 ± 0.015	100	97.1	0.995
635	0.312 ± 0.013	100	96.3	0.992

Table 3 compares the effectiveness of determining dust concentration through optical density measurements using laser radiation at different wavelengths. Three wavelengths were tested: 405 nm (violet), 532 nm (green), and 635 nm (red). Results clearly indicate that the 532 nm wavelength delivers superior performance: at 50 g/m³, accuracy reaches 96.5% with a linearity coefficient $R^2 = 0.993$; at 100 g/m³, these values improve to 97.1% and 0.995, respectively. This superior performance occurs because coal dust particles exhibit optimal scattering and absorption characteristics in the green spectral region. The 405 nm (violet) radiation yields slightly lower results because shorter wavelengths experience increased atmospheric scattering and higher noise levels. The 635 nm (red) radiation provides moderate results but offers advantages for long-distance measurements due to reduced atmospheric attenuation.[3] Optical density values demonstrate linear growth with concentration: ranging from 0.156-0.234 at 50 g/m³ and 0.312-0.478 at 100 g/m³. All measurements exhibit high repeatability, with standard deviations of ±0.008-0.018. These findings substantiate the appropriateness of utilizing 532 nm lasers when developing real-time optical sensors and provide a scientific foundation for creating dust monitoring systems in industrial environments. The high linearity and accuracy achieved with green lasers enable reliable quantitative analysis of dust concentrations, facilitating early warning systems for explosion hazards. Furthermore, these results support the integration of optical diagnostic techniques into automated safety protocols, enhancing proactive risk management in coal mining and processing facilities where dust accumulation poses significant explosion risks.[11]

Table 4. FTIR spectroscopy results - functional groups and explosion hazard

Wavenumber (cm^{-1})	Functional group	Absorption intensity (a.u.)	Correlation with explosion	Risk level
3400-3200	O-H stretching	0.234 ± 0.015	0.76	Medium
2920-2850	C-H stretching	0.567 ± 0.023	0.89	High
1700-1600	C=O stretching	0.189 ± 0.012	0.82	High
1450-1350	C-H bending	0.423 ± 0.019	0.71	Medium
1030-1000	C-O stretching	0.312 ± 0.016	0.68	Medium

Table 4 elucidates the correlation between coal dust's chemical composition and explosion hazard parameters, as derived from Fourier Transform Infrared (FTIR) spectroscopy was employed to analyze five key functional groups to determine their impact on explosive potential. Among these, the C-H stretching vibrations in the 2920–2850 cm^{-1} range showed the strongest correlation coefficient of 0.89, along with an absorption intensity of 0.567. This highlights the significant role of hydrogen content in the coal's organic matrix, which directly influences explosion energy release.[17]

The carbonyl (C=O) group, observed between 1700–1600 cm^{-1}, also exhibited a notable correlation of 0.82, indicating oxygen-containing moieties play an important part during combustion. The hydroxyl (O-H) group, with absorption bands from 3400–3200 cm^{-1}, showed a moderate correlation of 0.76, suggesting moisture levels have a measurable but lesser effect on explosion characteristics. Meanwhile, the C-H bending (1450–1350 cm^{-1}) and C-O stretching (1030–1000 cm^{-1}) groups demonstrated relatively lower correlations of 0.71 and 0.68, respectively.

All spectroscopic measurements were conducted with high precision, as reflected by standard deviations ranging from ±0.012 to ±0.023. In risk stratification, the C-H and C=O groups were classified as "high risk" due to their critical influence on explosive hazards. These findings support rapid hazard prediction through chemical profiling, confirming FTIR spectroscopy's value in quality control and safety monitoring systems.[8]

The strong correlations identified provide a solid foundation for developing spectroscopic sensor technologies capable of real-time explosion risk assessment. Such advancements allow mining operations to implement proactive safety measures before hazardous conditions arise. Furthermore, understanding the chemical factors driving explosion severity aids in designing targeted mitigation strategies, including the use of chemical suppressants or modifying processing methods to reduce hazardous functional groups in coal dust.[9]

Table 5. Laser-Induced Breakdown Spectroscopy (LIBS) results.

Element	Emission line (nm)	Intensity (a.u.)	Concentration (%)	Effect on explosion
C	**247.86**	**12450 ± 340**	**78.5 ± 2.3**	**Very high**
H	656.28	8920 ± 280	5.2 ± 0.4	High
O	777.19	6780 ± 220	12.3 ± 0.8	Medium
N	746.83	3450 ± 150	2.1 ± 0.2	Low
S	180.73	2890 ± 120	1.9 ± 0.3	High

Table 5 presents an in-depth examination of the elemental composition of coal dust and the respective influence of each constituent on the explosion mechanism, as elucidated through Laser-Induced Breakdown Spectroscopy (LIBS). The analysis concentrated on five main elements. Carbon (C) was found to be the most prevalent, with a concentration of 78.5% and an emission intensity of 12,450 arbitrary units, detected at a wavelength of 247.86 nm. Its role in explosion dynamics is rated as "very high" due to its function as the primary combustible material.[3]

Hydrogen (H), making up 5.2% of the sample and identified by the Balmer alpha line at 656.28 nm, shows a “high” impact because it tends to increase the rate of combustion. Oxygen (O), present at 12.3%, acts as a mediator in internal combustion reactions and is given a “medium” influence rating. Nitrogen (N), with the lowest concentration at 2.1% and an emission intensity of 3,450 a.u., has a “low” effect on explosion characteristics. Although sulfur (S) is present in a modest amount of 1.9%, it is considered to have a “high” impact due to its production of toxic SO_2 during combustion and its role in promoting corrosive processes.[5]

All measurements were conducted with stringent precision, reflected by a standard deviation range of ±120-340 a.u. The LIBS technique enables rapid, often second-scale, and precise elemental profiling, positioning it as a formidable candidate for real-time safety surveillance applications. These empirical insights underpin the advancement of portable LIBS-based sensing devices designed for in situ deployment within mining environments, allowing for continuous evaluation of coal dust explosive potential.

By linking elemental spectral signatures with explosion risk metrics, safety personnel are empowered to make informed decisions regarding ventilation modulation, dust mitigation strategies, and emergency evacuation protocols. Furthermore, the method’s expediency and accuracy facilitate seamless integration into automated alert systems, thereby strengthening proactive explosion prevention frameworks across global coal mining operations.[5, 11, 12]

Conclusion

In conclusion, it should be noted that dust explosions can also occur in areas with high dust levels on the ground (concentration plants operating with compressed air, sorting sites, etc.). Therefore, areas with high dust levels on the ground should be in places also mine in the veins done increaseable dust to the explosion Countermeasures will need to be taken.

To prevent coal dust explosions, it is necessary to implement measures to ensure safety in the mining environment and reduce the risk of explosion. These measures include the following areas:

Use of water and inert dust: Cleaning of welds with water curtains and washing mixtures, Reducing the risk of explosion by adding inert dust and limiting the flammability properties of coal dust.

Use of liquids and inert substances: Covering joints with a lime-cement mixture, limiting the spread of dust into the air by creating shale barriers, controlling areas with a risk of explosion: constantly checking the humidity and composition of the dust. Improving ventilation systems in joints and ensuring their proper functioning.

Regular inspection of mining equipment: Conducting control measures in mining operations every shift, and carrying out monthly scheduled inspections by safety equipment personnel.

Recommendations for reducing the risk of explosion: Reducing the explosive properties by increasing the dust sintering and humidity, treating inert materials in hazardous areas with hydrophobic additives, installing explosion protection systems: shale curtains, water curtains and explosion suppression devices, complying with safety requirements in mine workings.

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