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ARTIFICIAL INTELLIGENCE USE FOR INCREASING THE EFFICIENCY OF AUTOMATIC CONTROL OF AERODYNAMIC PROCESSES IN MINE WORKINGS OF COAL MINES

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Аннотация.
With the growth of coal production, the load on the production capacity of coal enterprises also increases, which leads to a concomitant increase in dust formation in both opencast and underground methods of mining coal deposits. Dust, generated during drilling, blasting operations, excavation, loading, crushing and transportation of mined rock is one of the factors that has a negative impact on the health of mining workers and on the level of environmental pollution with solid particles. Thus, increasing the efficiency of controlling the concentration of solid particles in the mine atmosphere and dust deposits is an urgent scientific and technical task. In doing so, the use of modern digital technologies within the framework of the industry 4.0 concept makes it possible to develop approaches that can significantly improve the quality of monitoring the state of the mine atmosphere at coal mining enterprises. This article provides a theoretical basis and test results for a system for continuous automatic monitoring of dust concentration in a mine atmosphere as the component of the multifunctional coal mine safety system. It is shown that monitoring the state of mine workings aerological safety can be carried out in real time through the system of the new generation using artificial intelligence. The ability of the proposed system to measure basic physical parameters affecting dust deposition (disperse composition, air humidity, dust concentration and air flow velocity) is noted.

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Introduction

When coal mining increases it is really vital to control dustiness and dust deposition to ensure industrial and environmental safety of coal mining.

In terms of industrial and labour safety management system, gas and coal dust explosions have the most serious economic and social consequences. In recent decades in Russian, Indian, and Chinese mines mixture of dust, methane and air was involved in almost all explosions caused large-scale destruction and workers' injuries and deaths.

In recent years, coal industry has been facing increasing pressure from environmental policies, environmental pollution by solid particles issues in particular. The tiniest suspended particles formed as a result of coal mining are released into the atmosphere of nearby residential areas, which have already been heavily polluted by industrial emissions and exhaust fumes. Environmental deterioration inevitably leads to negative consequences such as increasing disease incident rate (including cancer), deterioration of agricultural land qualities, reduced visibility, reduced quality of drinking water, etc.

Long-term exposure to dust aerosol results in coal miners' occupational respiratory diseases. The risks of occupational diseases caused by dust are really high and socially important, it shows that there are some problems in industrial and labour safety management system and there is no system approach [1].

In underground mining occupational respiratory diseases are reported among workers at the rate of 20.4 to 24.5 per 10,000 medically examined people, these diseases are ranked second in the occupational diseases list apart from historical interstitial lung diseases like pneumoconiosis, silicosis, and mixed dust pneumoconiosis. Miners are also at risk of diffuse fibrosis caused by dust, as well as chronic respiratory diseases including emphysema and chronic bronchitis.

To ensure the workers' safety and prevent potential emergencies (in particular to prevent dust explosions in coal mines), safety regulations must be strictly observed, technical conditions of equipment must be checked up regularly, the staff should be trained how to deal with dust, and special techniques and methods should be used to monitor and reduce dust.

It is also necessary to use protective outfit, install effective air ventilation and scrubber systems. It is also important to train employees to control and prevent dust explosions in coal mines effectively.

Coal dust is especially dangerous, it is formed when coal is mined, transported and processed. Coal dust is a significant threat to the miners' safety because of its flammability and very high explosibility. Therefore, the main concern is to ensure safe coal mining by developing effective coal dust monitoring and preventing coal dust explosions techniques.

Literature review

Dust deposition monitoring in mine working is an urgent task nowadays. To enhance safety, prevent explosions and combustions of coal dust [2] in mines, it is really important to the develop fact-based techniques for sustained monitoring, in order to predict explosion risks and health effects of coal dust [3], [4].

In recent years, due to the increasing use of equipment, automation and intelligent systems in mining, dust pollution is becoming a more and more significant problem. Therefore, a more in-depth study of the issues such as coal dust monitoring, dust deposition, and prevention of dust-methane-air mixtures explosions [5] is required and it should use modern artificial intelligence technologies [6].

Modern technologies allow to investigate hazardous facilities in a virtual environment through computer simulation, then follow development stages ensuring mining safety. It significantly reduces the time to predict hazardous emissions and ensures workplace safety.

Thus, in the study [7] the particle size impact on dispersion was studied in a blasting chamber. The parameters causing dispersion and a coal dust explosion were investigated. In order to understand their impact on coal dust dispersion, the turbulent kinetic energy (TKE) and the velocity vector trajectory of a dust-air mixture and dust-free air were simulated. The contours of TKE and velocity vector trajectories of dust-free air were uniform and symmetrical due to a resistance-free trajectory. The contours of TKE and velocity vector trajectories of the dust-air mixture showed asymmetric contours distribution, caused by air entrained by dust particles. Vortices were observed on the velocity vector trajectories, which gradually decreased with increasing time sequence. These vortices represent dead centers where the velocity and coal dust particles concentration are zero. This study has allowed us to investigate the coal particles size impact on dispersion in a mine and will help avoid accident risks in the future.

The most common way of dust suppression is effective ventilation of mining. Although the technological process of ventilation is not considered as a method of monitoring dust deposition, it plays a crucial role in ensuring mining safety. For instance, in the study [8], the airflow velocity impact on the diffusion principles of dust sources was analyzed by combining numerical modeling methods. The research results suggested that an increase in the air flow supply results in the dust mass concentration reduction, but there is a risk that high air velocity may cause dust loss, working environment pollution.

In the study [9], a forced-draft venting technology was used for dust suppression, the results of its application show that when the air dust was added along the ventilating air head, an air curtain is formed and after entering a continuous miner section, a dust-suppressing curtain is formed. When the axial diameter ratio of the external air is 1:2-1:3, dust can be controlled to the extent of 17 mg/m³, the dust-removal efficiency increases to 93% with this technique.

As it was already mentioned, ventilation is not effective for dust deposition and concentration measuring monitoring. Therefore, in order to have more efficient dust suppression, new approaches to safe mineral extraction have to be developed. To create a new approach to the issue mentioned, it was necessary to analyze available materials where the problems of effective control of dustiness, dust deposition and prediction of coal dust concentration are clearly reflected [10].

Every mining enterprise tends to increase its extraction rates and strives to create safe production, security risks should be considered at the early stages of system implementation. The study [11] has examined three mine classifications, mine safety and optimal ventilation models using MATLAB and Lingo software. All these examinations were interrelated and carried out to provide reliable recommendations for high-risk coal managing in mining.

To solve the issues of coal gas and dust explosion detection and monitoring in coal mines, as well as to improve the accuracy of explosion detection, a neural networks-based technique has been developed [12]. The sound coefficients of gas and coal dust explosions were analyzed, on its basis a feature extraction model of the Relief algorithm was created. In this study, an experiment was conducted to compare two sound identification algorithms. The sound detection experiment found that the developed algorithm model can accurately distinguish each sound type involved. The average detection response time speed and model accuracy can reach 95%, 95% and 95.8%, it is much better than the comparison algorithm can do and may better meet the coal gas and dust explosion detection needs.

In the study [13], the issue of dust-methane-air mixtures explosion desensitization prevention in mining atmosphere was also investigated. An automated control system for dust-methane-air mixtures explosion desensitization in mining atmosphere was proposed and tested, various sensor parameters, power sources, controllers, communication means, and signal converters were investigated and tested. Thanks to the automated system developed, it was found that the upper and lower explosion limit dependence of dust-methane-air mixtures and a molecular structure of water and methane study allow to estimate methane and dust explosions prevention efficiency in coal mines.

In an on-line coal dust monitoring study [14] some experiments were conducted at a particular mine pit bottom to investigate a negative coal dust exposure impact on miners' health. Three methods to study and assess coal dust concentrations were used. This study found that the ultimate approved concentration in the mine pit bottom was exceeded by 10 times, and a high concentration of an inhalable coal dust fraction was fixed. These fractions remain in the body for a long-lasting period and cause the most severe negative health effects.

In the study [15] test results of surface-active substance coal dust suppression effectiveness are presented. It was found that the surface-active substance effectiveness worsens significantly when coal dust particle size decreases. The dust suppression efficiency of 0.1 to 1.0 μm particles was only half that of 4 to 10 μm particles. The main factors influencing on the result were roughness, specific surface area, air absorption, and number of particles. The study result is that the particle size affects dust suppression effectiveness, because a large surface area, high air adsorption capacity, and low number of coal particles.

According to study [17], dust deposition and coal dust concentration monitoring can be realized by means of ultrasonic control. This article presents a new ultrasonic measurement system developed that ensures reliable air dust concentration change monitoring. The system was tested by a pilot classifier developed for ultradispersed powder air separation and regeneration from pulverized fly ash. The monitoring technique is based on measuring the ultrasonic attenuation by particles suspended in the air stream of the classifier.

Gaussian modeling method was proposed for monitoring dust depositions as it was used at a Serbian mine [16]. This model was tested during the mine opening phase, and it confirmed the application validity for the future monitoring. The Gaussian model can predict the area that will be exposed to dust pollution caused by mining development or stopping activities.

A coal dust suppression technique in mines and quarries is developing rapidly [17]. A new injection head with a swirling core has been developed based on fluid mechanics, rigid solid and liquid coalescence mechanism. The spray-range performance has increased from 5.2 to 5.9 meters, and the sprayed mist saturation has significantly increased too. This substantially enhances the dust control technique effectiveness - known as spraying monitoring, which is really important for the dust prevention and control technology in high-roof mining.

In the study [18] dust concentration reduction in mines was researched. To improve working conditions, the Research Object was a loading and hauling machine with a spraying system installed. The research was carried out with a computer simulation and hydrodynamic equations which were used to simulate airflow velocity fields and air temperature. It was found that the temperature in the working area varied from 302-305 K, this high temperature negatively impacts the miners' performance. The author is sure that it is necessary to use a cooling system to enhance thermal acceptability and reduce the explosively hazardous dust concentration.

A similar study was carried out in mines of New South Wales, where a three-dimensional computation model was developed based on specific conditions of underground mining, mined by a continuous miner, and the dust monitoring data at the site were verified [19]. The simulation revealed that high dust concentration is basically on the left side of the continuous miner, especially in the area about 3 meters from the face. Airflow and dust migration data of the models were exported for further data processing to develop an immersive virtual reality educational tool, allowing to visualize ventilation and dust data, and effectively report dust control measures for continuous miner safety and health. The proposed system is essential for the safety of mining operations and serves as a powerful tool for understanding advanced dust monitoring methods [20].

In the study [21] solid coal particles monitoring at Haerwusu coal mine was reviewed, the ambient temperature in December, January and February was investigated and correlational dependencies were made for solid particles' variation characteristics and their relationship to meteorological factors. The authors found out, that the concentration order of solid coal dust particles is observed in December – January – February. The correlation of on-line monitoring is positive in humid conditions and negative when there is a stiff wind. It was found that a temperature positively correlates with on-line monitoring in December and negatively in January. But then, the temperature difference in December negatively correlates with the solid particle concentration. When multiple meteorologic factors act together, in winter humidity – temperature – wind speed – temperature difference (inverse temperature intensity) the influence the suspended particle concentration at the quarry bottom. The temperature positively correlates with the solid particle concentration in December, while in January it is negative. At the same time the temperature differences in December negatively correlate with the solid particle concentration. When multiple meteorologic factors act together, humidity, temperature, wind speed, and temperature difference (inverse temperature intensity) influence the solid particle concentration at the quarry bottom in winter.

In the article a model for cloud-based coal dust monitoring on a digital platform is proposed. Thanks to this system, employees will be able to monitor the dust condition in real-time mode and ensure continuous control. The long-term occupational risk data accumulation system can be used for a common database, which will show the cumulative dust exposure impact on workers' health and will help reduce the occupational diseases risk in Chinese mines in the future.

In the study [23] it has also been proven that a monitoring measurement system and non-contact proportional differential dual light detection method are required for accurate and efficient monitoring of coal dust. Parameters of the key elements are calculated by a simulation, and an online concentration monitoring system for a wide range of measurements is developed.

A different approach such as a remote sensing technique to monitor mine dust pollution was suggested in [24]. The study aims to reduce risks in the mine, ensure mining operation safety, and protect maintenance personnel health. In the study [25], a Vortecone scrubber was used for dust suppression, its flows were simulated using finite volume method computational calculations in scFLOW software. Some CFD models were developed and examined on a scaled-down Vortecone model using different grids with various packing densities. Grid errors and convergence were calculated and showed high accuracy of the model suggested. Further analysis was carried out with a larger grid to study the flows inside a vortex cone. The simulation results showed complex vortex air and water movements and the dust particle capture by a water film. The CFD models managed to described dust cleaning processes in the Vortecone scrubber accurately.

It is also possible to monitor coal dust with optical microscopy [26]. The authors have found that there are few monitoring techniques of coal dust calculation and classification. Therefore, it was proposed to explore the optical light microscopy and polarized light effectiveness in monitoring. As a result, the potential use of light microscopy and polarized light with image analysis for typical coal mine dust particles calculation and classification was demonstrated.

The study [27] is devoted to sensors review and their use for low-cost coal dust monitoring. Currently monitoring system technologies are very expensive. To monitor coal dust, the authors suggest using light-scattering solid particle sensors, which have demonstrated good results in recent years. Four types of sensors were used in the study: Air trek, Gaslab, SPS30, and PMS5003. The results showed that the Air trek and Gaslab sensors were unsuitable and showed poor correlation. SPS30 can only be used for low concentrations (0-1.0 mg m-3), while PMS5003 can effectively monitor concentrations up to 3.0 mg m-3. This study has confirmed that it is necessary to improve these sensors to facilitate their use to enhance miners' safety and health.

The operational method of settled dust level detection is considered to monitor and reduce explosion risks using a multifunctional safety system in mine working, it allows to prevent potential dust explosions [28]. The research has determined the timeframe for safety measures activities in mine workings to prevent the risk of coal dust-air mixture explosions while drilling with high-performance equipment. However, effective new technological process adoption is impossible without accurate and operational dust level control in mining workings, especially when the impact on a stope increases, and it is necessary to conduct additional fractional composition analysis of coal dust to prevent explosions and spontaneous methane-dust mixture combustion of the [29], [30].

To have accurate mine dust concentration analysis and prediction a study based on the Grey-Markov model was conducted [31]. Grey-Markov model was used to predict mine dust concentration, results obtained were compared with the prediction results of a neural network model, a grey prediction model, and an ARIMA model. The results showed that Grey-Markov model demonstrated more accurate results compared to the other models. Thus, this model accuracy and rationality for dust concentration prediction in a mine were examined.

In research [32], the authors proposed an electrical fire monitoring and detection system design with additional sensor modules, as the mineral resource mining safety depends on it. The developed electrical fire monitoring and detection system is suitable for the mining industry working environment, it consists of monitoring software on the host computer and detectors on a slave computer. Monitoring detectors are produced using embedded technology. The deployed external casings have excellent hull characteristics and explosion-proof properties. The proposed system has met the requirements specified in national standards of such device characteristics and external appearance. The test results show that the use of the electrical fire monitoring and detection system can effectively increase monitoring intensity in mineral resource extraction areas and provide reliable assurance of the systematic mineral resource extraction and physical and property protection safety of citizens in these areas.

However, in the study [33], a new method without any drawbacks mentioned above was developed. A new dust formation control method such as thermo-gravimetric is proposed. Experimental research was conducted. Thermo-gravimetric reaction disjoint intervals were identified: moisture emission (35-132 °C); coal volatile substance emission (38-142 °C), thermal decomposition of limestone with carbon dioxide emission (650-850 °C). Based on experimental data, mathematical dependencies were used for the thermogravimetric curve characteristics processing to determine the non-combustible component content in a sample of mine dust.

To improve monitoring accuracy performance, a system based on the Internet of Things (IoT) is being developed in the study [34]. It suggests the concept of a wireless sensor network internet that helps monitor temperature, humidity, and gas levels in a mine. The monitoring systems used are usually LAN, they play a crucial role in coal mine safety, however, as mining areas expand, it becomes difficult for these systems to ensure safety. Moreover, cable laying is expensive and labor-intensive. Therefore, to improve safety, reduce explosion risks, and monitor dust deposits a coal mine safety monitoring system is being created on the bases of a wireless sensor network and IoT.

In the study [35] based on IoT a complex approach to enhance dust removal intelligence in coal mines is suggested. The research describes key aspects and stages to establish principal element database for dust removal. It also lays special emphasis on the method practical use which can help solve coal dust removal problems.

As an example, it would be appropriate to mention coal dust level and deposition monitoring in quarries. If we compare underground mining with open-pit mining we can say that open-pit mining has a lot more dust sources, and a zone where it spreads can cause large dust concentration fluctuations. Thus, a hybrid model to predict coal dust concentration is suggested in the article [36]. To assess the model accuracy, three models – ARIMA, LSTM, and LSTM-Attention - were compared in absolutely identical conditions. The results showed that LSTM-Attention model is more reliable and has higher predicting accuracy than the models mentioned. The study notes that this model can be used to predict dust concentration in open-pit mining.

Theoretical basis for controlling dust deposition in mine workings. General Information

The coal dust deposition and high concentration issues mentioned above, such as dust formation, and its spread in coal mines and mine working have been solved by scientific works [37], [38]. The solution to the coal dust problem was presented in the form of a developed system of continuous automatic control of dustiness and dust deposition intensity - the test post device with a new generation artificial intelligence system allows to measure basic physical parameters influencing dust deposition in real-time mode. The device is the latest development of the Russian Federation scientists, it has been tested in a laboratory and mining and proved the correctness of the physical model developed.

According to safety requirements dust explosion safety monitoring in mining is carried out by special devices or other equipment. To increase a dust explosion protection level, an objective instrumental method is necessary to monitor dust explosion safety, it must be highly accurate, efficient, and easy to use. The continuous automatic control of dustiness and dust deposition intensity technique, which also allows to detect explosive dust deposit is the most suitable one. It allows to develop and take operational measures to neutralize dust deposition violations.

To provide instrumental monitoring of explosive coal dust deposit level in mining, a supplementary device for DPV1instrument has been developed at Eastern Research Institute for Mining Safety. Its operation principle is based on removing dust deposits with a high velocity air stream from an injection head, then dusty air is sucked onto a filter, the scale is read, and dust deposition amount per unit surface is calculated.

To monitor the presence of explosive coal dust amounts in underground mines, instruments have been developed, as a portable analyzer “Inflabar” (Poland), the portable radioisotope device KOP-1 and KPR-1M (Makeevka Research Institute for Mining Safety), and dust control systems and express radioisotope dust meters. In Russia, PRIz, IKAR, RKP-5, IKAR-FB-01, and Prima devices have been developed; in France, tMPS1-100 (Environment); in Italy, MRS 100 (ELRKOS SpA); in the USA, Mass Monitor RDM-101, RDM201, RDM-301; in Germany, Beta-Staubmetr, Staubmonitor, FH-62A, FH-62C; and in the Netherlands, beta-dust monitor mod. 9700 (Philips).

However, the devices mentioned above, and newly created modern devices do not have dust deposition intensity autodetection.

In recent years, thanks to the development of digital technologies and Industry 4.0, there is a clear trend towards safety and labor protection systems automation in coal mining enterprises, new remote dustiness monitoring technologies of in mining atmospheres are being developed, they transmit information to air and gas control (AGC) systems of enterprises. Such systems should consist of air dust sensors, controllers, data collection and transmission units in AGC systems. The software should process and present the results to a dispatcher in a readable and understandable way. The main element of this system is a sensor for air dustiness or deposited dust measuring. All dust control experience in in coal mines indicates that dust sensors in automated systems can be of two types: optical or radioisotope-based [39].

According to paragraph 22 of the Federal norms and rules in industrial safety "Safety rules in coal mines" approved by the order of Rostechnadzor dated 8.12.2020 № 507, registered by the Ministry of Justice of Russia 18.12.2020 № 61587, (hereinafter - Safety Rules), modern multifunctional safety systems (MFSS) of coal mines must include a subsystem that must ensure the mine safety parameters monitoring and prevent aerological hazards, and MFSS must provide safety parameters monitoring of a mine. Paragraph 23 of the Safety Rules in coal mines enshrines the requirement to comply MFSB with the norms of industrial safety and technical regulation, ensuring the measuring instruments and standards uniformity for explosion-proof electrical equipment, automated control systems, information technology, measuring systems and gas analytical equipment [40].

Federal norms and rules of industrial safety "Aerological safety instruction for coal mines", approved by the order of Rostechnadzor dated 8.12.2020 № 506, registered by the Ministry of Justice of Russia on 29.12.2020 reg. No. 61918 (hereinafter – Instruction), establishes the requirements to provide systems for continuous automatic measurement of dust concentration in mine atmosphere and (or) dust deposits, all dust sensors telemetering; tele-signaling (light and / or sound) when the dust concentrations and (or) dust deposits in the mining atmosphere exceed threshold values and in case of dust sensors failure, as well as monitor (control) safety parameters remotely, information about threshold values of dust concentration in mine atmosphere and (or) dust deposits should be automatically transmitted in real-time mode via communication channels to the coal mining organization.

Current dustiness and dust-explosion safety control methods and means in mine workings can't meet the regulatory documents requirements in full, so the aim of the research is to solve this problem. It is necessary to investigate and establish the regularities of the dust deposition process of airborne coal dust particulates depending on various factors affecting the dust distribution in mine workings, the grade composition of coal in particular, a technological parameters set such as face output , ventilation rate and atmospheric parameters. At the next stage it is necessary to develop new methods and means to assess and control the state of dust-explosion safety of mine workings.

There are two types of methods to determine aerosol concentration in combination with particle size-consist for suspended in the atmosphere (free particles): contact and non-contact. Contact methods include sampling methods, while non-contact methods are optical and partially triboelectric.

The optical method of disperse composition and aerosol concentration measuring does not affect the particles in the flow, the registration speed allows to have real-time measurements.

Let's define the particle distribution function for a polydisperse system:

$$\int_0^\infty f(x)dx = 1 \tag{1}$$

Let's define the particles fraction $df(x) = f(x)dx$ from the size range $(x, x + dx)$.

Also, let's define the orders of moment by the following formula:

$$x_{mn} = [\frac{\int_0^\infty x^m f(x)dx}{\int_0^\infty x^n f(x)dx}]^{\frac{1}{m-n}} \tag{2}$$

where n, m – designations of the order of the moment of the distribution function

Main orders of moment: x_{10}– Medium-sized, x_{30} – medium-volume, x_{43} – medium-mass.

Scientific literature data analysis has shown that the descriptions of various granulometric systems with unimodular distribution can be described by the following generalized distribution laws: gamma distribution, logarithmic normal distribution, normal distribution.

At the same time, the initial radiation flux is attenuated due to the radiation absorption by the particle itself, as well as due to the scattering of radiation on the particle. Let's introduce quantitative parameters for assessing the particle influence on the radiation field:

$$Z_{attenuation} = Z_{scattering} + Z_{acquisitions} \tag{3}$$

Here $Z_{scattering}$ – fraction of radiation escaped from the beam under consideration, $Z_{acquisitions}$ – radiation fraction absorbed from the beam.

Let's rewrite the estimation of the interaction of particles with radiation through the coefficients by relating the surface area of the particles to the incident or dispersed radiation:

$$K_X = \frac{\pi D^2}{4} Z_X \tag{4}$$

where Z_X – appropriate radiation assessment.

Let's define scattering indicatrix as a function of the ratio of light flux intensity reflected from each value of the angle θ to the total radiation flux directed at the particle. This function is dimensionless for the dispersion angle θ, and the sum of its integral over the dispersion is equal to unity. The quantitative ideal particle characteristics – homogeneous and spherical shapes, are determined by two parameters – the refraction index of the particle composing material and the dimensionless diffraction parameter:

$$m = n - in' \tag{5}$$

$$\alpha = \frac{\pi D}{\lambda} \tag{6}$$

where n – refraction index, n' – absorption index, λ – probing radiation wavelength.

The particles radiation dispersion takes place on can range from a molecule to hovering tens of micrometers coal particles in size, as well as various optical inhomogeneities can be. If the particle size is less than λ/15, Rayleigh scattering is observed. At values greater than λ/15 Mie scattering is observed, when particle sizes are comparable to the wavelength λ – diffraction scattering prevails. Also, the Rayleigh theory has a limited use for real dust aerosol measurements, it can be used only under certain conditions: the environment where the probing radiation spreads and the particles must not have free charges; the magnetic permeability of the environment and particles is the same; the size of the scattering particle is not more than 10% of the wavelength; the intensity of scattered light is calculated for points very distant from the disturbing particle (in the far zone kr >> 1).

The analytical solution of the scattering efficiency and obtaining scattering indicatrix problem was founded solving the problem of electromagnetic wave scattering with a given direction on a homogeneous particle of spherical shape. Analytical form numerical solving requires a high computing capacity.

Fist, we consider a monodisperse medium with uniform filling with particles diameter D and number of particles C_n,, where a parallel probing beam with wavelength λ spreads through an aerosol layer of thickness l. To describe the beam attenuation, we use Bouguer law.

$$I(l) = I_0 e^{-k\lambda l} \tag{7}$$

where $I(l)$ – intensity of light passing through a substance layer with thickness l; $k\lambda$ – spectral attenuation index depending on a probing beam wavelength, provided that there are particles independently scattering the beam.

Let's spell out spectral refractive index and relate it to the particles amount and size:

$$k_\lambda = \frac{\pi D^2}{4} C_n Q(a, m) \tag{8}$$

where $Q(a, m)$ - attenuation efficiency factor with diffraction parameter and the complex refraction index for coal m = 1,54–0,5i.

The monodisperse medium radiation characteristics are obtained by summing up the results of individual interactions with each particle.

Working with polydisperse media, we assume that particles have a spherical shape, and the light scattering of each particle is independent. The aerosol layer is assumed to be thin enough to eliminate the second and higher-order scattering impact.

Let's move from number concentration to mass concentration:

$$C_m = C_n \frac{\pi p k C_n^2}{6} \int_0^\infty D^3 f(D) dD \tag{9}$$

and write the formula of polydisperse system spectral attenuation index of mass concentration.

$$k_\lambda = \frac{\pi C_m \int_0^\infty Q(a,m) D^2 f(D) dD}{2pk \int_0^\infty D^3 f(D) dD} \tag{10}$$

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where pk – particle density.

Obtaining this indicator, we determine the dust particles dispersion in a mine atmosphere. Particle size distribution and humidity indicators are essential, because they influence the dust deposition intensity. Particle size distribution and humidity have a significant impact on dust blowing. If dust is dry, the speed it starts to blow off is much lower. At the same time, as dusty air moves along mine workings, its Particle size distribution changes. This happens due to that the largest dust fractions fall out.

Dust deposition intensity obtained are based on the laboratory results and mine studies and determined by the following formula:

$$P_t = 86{,}4 \frac{f(r) v l^B}{S(W+W_B)}, \text{ g/m}^3\cdot\text{day}. \quad (11)$$

where v – air velocity along the mine, m/s; l – distance from the source of dust formation, m; S – excavation cross-section, m²; B – coefficient taking into account the influence of the degree of coal metamorphism; $f(r)$ – total value of particle size distribution function at the moment of concentration measurement, mg/m³; W – natural moisture content of coal, %; W_B – relative humidity in the mine workings, %.

It provides the basis for the creation of a system for controlling the intensity of dust deposits [41].

The results of theoretical and laboratory studies on the study of dust deposition patterns are realized in the system of continuous automatic control of dustiness of the mine atmosphere and dust deposition intensity (hereinafter – the Scanning Contactless Inductive Probe (SKIP), the scheme is presented in Fig. 1. The main metrological characteristics of the test post are shown in Table 1.

The high-tech innovative next-generation system with artificial intelligence developed allows to measure basic physical parameters affecting dust deposition such as particle size distribution, dust concentration, air flow velocity, etc. The self-learning artificial neural network automatically evaluates all dominant surrounding environment parameters and polydisperse system dynamics, enabling to determine the main measurable parameter physical principle – dust deposition intensity with minimal error, and trains neural network to assess dust deposition correctly under constantly changing external conditions.

The main measuring unit of the system has a solid-state laser, an optical mirror and filter system, a laser radiation stabilization system, photodetector blocks responsible for collecting scattered radiation, a computing device, a stabilized power supply unit, and interfaces to connect to electronic scales and external devices. The operation principle the measuring device is based on registering scattered laser radiation to calculate the suspended dust concentration and assess the dispersion particle size distribution - this measurement method is called low-angle light scattering. The measured radiation level from the photodetectors (768 pieces) and the photomatrix is transmitted to a computing device, which directly calculates the current dust concentration and particle size distribution. These data are then combined with air flow rate, humidity, as well as weight measurements and transmitted to a unit responsible for neural network training. The system includes a set of specialized scales for continuous dust deposition measurement to train the neural network. The original scales design and algorithms allows to measure only settling dust and recognize unwanted particles on the scales platform.

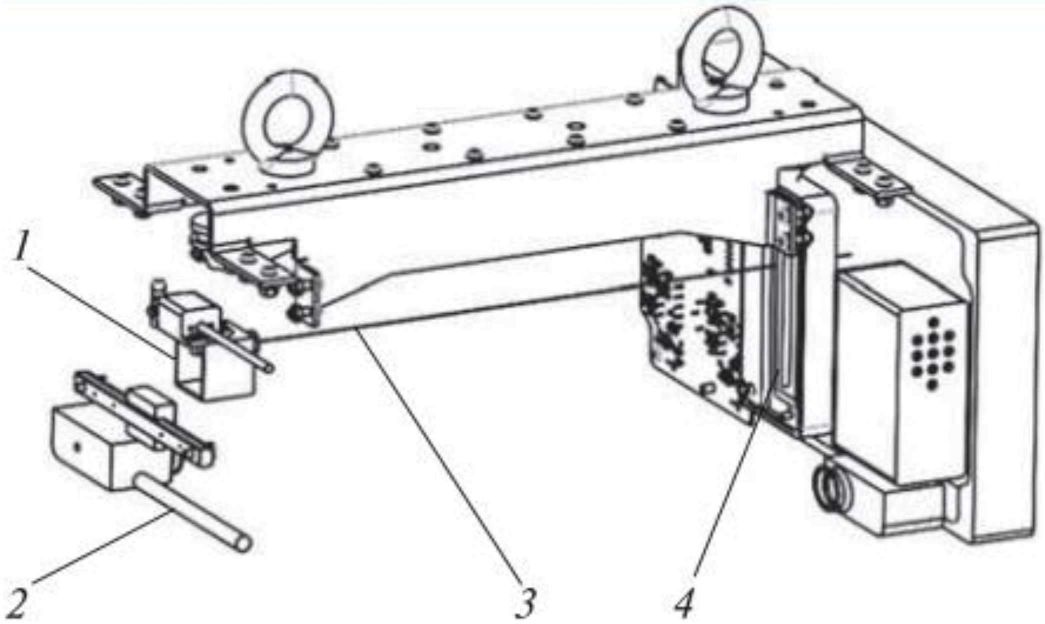

Fig. 1. Schematic diagram of dustiness and dust deposits intensity monitoring test post: 1 – radiation source (laser); 2 – laser positioning system; 3 – probing beam; 4 – photodetectors
Рис. 1. Схема контрольно-измерительного пункта для мониторинга интенсивности запыленности и пылевых отложений: 1 - источник излучения (лазер); 2 - система лазерного позиционирования; 3 - зондирующий луч; 4 - фотодатчики

Table 1. Main characteristics of the test post
Таблица 1. Основные характеристики контрольно-измерительного пункта

Characteristic, unit	Measurement range
Amount of deposited dust, g/m^3 per day	to 150
Mass concentration of suspended dust, mg/m^3	0-3000
Air flow velocity, m/s	from 0,1 to 20
Air flow temperature, t^o C	from -40 to +40
Relative humidity of the air flow, %	from 20 to 90 at +20^o C
Particle diameters, µm	0-150

Having trained the neural network, the scales disconnect from the system, and it continues to function autonomously, using the trained neural network for calculations. Subsequently, the scales are used to verify the system accuracy and if necessary, train the neural network again.

The system developed helps solve the dust concentration and dust deposition measuring problem in a mine with constantly changing working conditions and equipment location. It allows to measure marginally error-free and not only to record the suspended dust concentration, but also to expand the particle size visible ranges of 0-150 µm. It allows to carry out practically instant analysis of hovering dust disperse composition, which are necessary for dust deposition intensity calculation up to the next intensive dust emission source.

The fundamental scheme of the continuous automatic dust deposition intensity monitoring system proposed is presented in Fig. 2, illustrating the signal transmission and processing scheme.

Optical sensors respond to opaque and semi-transparent objects, water vapor, smoke and aerosols. An object entering the active zone of the optical sensor causes changes in beam transmission. In this case, they are dust particles of various sizes. The sensor operates based on the optical method of small angle scattering principle to determine the dust dispersion.

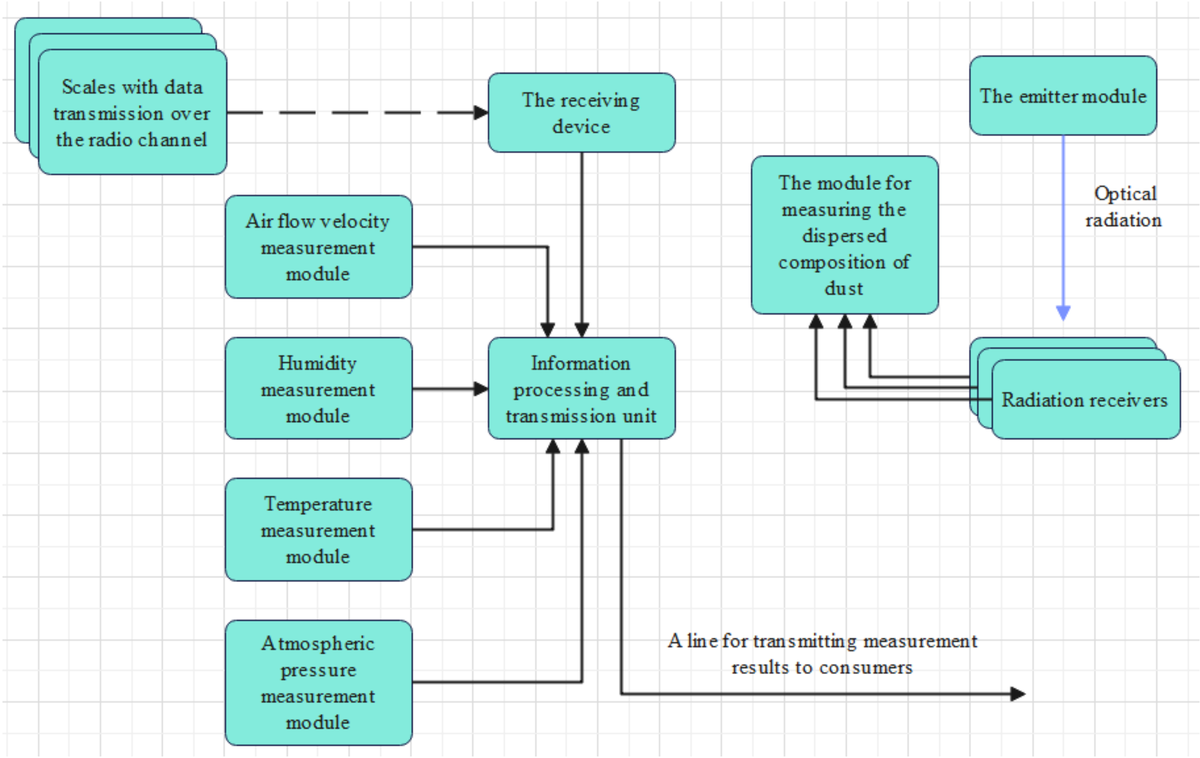

Fig. 2. Principle diagram of the test post with artificial intelligence
Рис. 2. Принципиальная схема, описывающая пути передачи сигнала

Changes are detected by receivers positioned at different angles to the beam. After processing the emerging signal is sent to the dust particle size distribution calculation module, where the signal is processed, converted from analog to digital and compared, then coarsness of grading of the dust is determined. The data then are sent to the information processing and transmission block, where the information is analyzed together with the incoming information from the air flow rate modules, humidity measurements, temperature, and atmospheric pressure. Depending on the atmospheric coarsness of grading, air flow rate, and air humidity, the dust deposition distribution character is computationally determined.

The air flow velocity measurement module is based on the ultrasonic anemometer principle.

The humidity and temperature measurement modules have humidity and temperature sensors.

The atmospheric pressure measurement module has a pressure sensor. Signals from the sensors are processed and transmitted to the display by the information processing and transmission unit, where along with information about a dust deposition nature, information about dust dispersion are simultaneously displayed.

The information processing and transmission unit performs mathematical processing, and the information is displayed on the screen in digital and graphical forms to present the information clearly. Dust disperse state analysis takes into account air velocity and humidity and allows to determine the dust deposition intensity index promptly and most accurately.

In the artificial neural network software complex configuration files, error messages, and statistical data are also available. The digital data collection block can receive data from the system using serial protocol commands or record them automatically in online mode.

The software products of the system allow to operate of devices, collect and process data, simulate, and predict dustiness dynamics, dust deposition intensity, and microclimatic parameters. The system software complexes solve technical (hardware), and informational tasks in real-time mode (online).

Results

Dust deposition intensity measurement was carried out by dust mass concentration and particle size distribution measuring. The testing methodology was as follows: at the test site in the mine workings, the SKIP device / test post was installed on plastic or metal bases. The SKIP device / test post was connected to a power supply unit, and the results of air dustiness measuring at the installation site, processing followed to determine dust deposition intensity (amount of deposited dust) in the mine workings, were recorded inside the device measuring block. The first 12 bases were placed every 10 meters in such a way that their open surfaces were not shielded from the ventilation flow by set members and various objects. Then, two bases were fixed every 50 meters at a 200-meter distance from the SKIP device / test post installation site. All bases were placed on the ground in a mine working at 10 to 50 cm distance from the edges of the working. Coal dust sampling had been carried out daily for five days: after dust explosion protection measures were taken (rock-dusting of mime working), numbered coal dust free bases installed at the sampling site; a day later, before the next dust explosion protection measures they were collected, hermetically packed in individually numbered bags, which were then packed into one bag with a label containing information on the sample name, sample number, sampling location, and date.

The SKIP device / test post tests results carried out in a mine to get approval of the dustiness and dust deposition intensity monitoring method in mine workings proposed is presented in Table 2 and Fig. 3.

Table 2. Test post tests results in a mine.
Таблица 2. Результаты испытаний на шахте.

The number of the substrate	Distance from SKIP, m	Initial weight, g	Final weight, g	Weight gain, g	The intensity of dust deposition, $g/m^3 \cdot day$	SKIP readings, $g/m^3 \cdot day$
1	0	7,1772	7,8753	0,6981	71,3550	67,1760
2	10	7,0750	7,7402	0,6653	67,9950	65,8600
3	20	7,1547	7,7575	0,6028	61,6140	62,0680
4	30	7,2555	7,8196	0,5641	57,6590	56,2320
5	40	7,1095	7,6569	0,5474	55,9500	48,9820
6	50	7,3670	7,8234	0,4564	46,6490	41,0350
7	100	6,9936	7,1072	0,1136	11,6090	9,7311
8	150	7,0949	7,1067	0,0119	1,2143	3,4780
9	200	7,1463	7,2540	0,1077	11,0050	2,7623
10	250	6,9055	6,9534	0,0478	4,8895	2,7403
11	300	7,2079	7,2344	0,0266	2,7136	2,7400
12	350	7,1493	7,1871	0,0377	3,8579	2,7300
13	400	7,1497	7,2417	0,0920	9,4060	2,7100
14	450	7,2354	7,3994	0,1640	16,7630	2,7100
15	500	7,2652	7,2753	0,0100	1,0268	2,7000
16	0	7,0825	7,7705	0,6880	70,3160	67,1760
17	10	6,9705	7,6704	0,6999	71,5330	65,8600
18	20	7,2570	7,8874	0,6304	64,4290	62,0680
19	30	7,1748	7,7376	0,5628	57,5270	56,2320
20	40	7,2798	7,8500	0,5701	58,2710	48,9820

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The number of the substrate	Distance from SKIP, m	Initial weight, g	Final weight, g	Weight gain, g	The intensity of dust deposition, g/m³·day	SKIP readings, g/m³·day
21	50	7,0310	7,5396	0,5087	51,9890	41,0350
22	100	7,1689	7,2593	0,0904	9,2388	9,7311
23	150	7,0615	7,1106	0,0491	5,0136	3,4780
24	200	7,2930	7,3033	0,0103	1,0575	2,7623
25	250	7,0739	7,1665	0,0926	9,4676	2,7403
26	300	7,1295	7,2226	0,0931	9,5165	2,7400
27	350	7,0983	7,1503	0,0520	5,3174	2,7300
28	400	7,2593	7,2680	0,0087	0,8915	2,7100
29	450	7,1914	7,2146	0,0232	2,3686	2,7100
30	500	7,0195	7,0985	0,0790	8,0716	2,7000

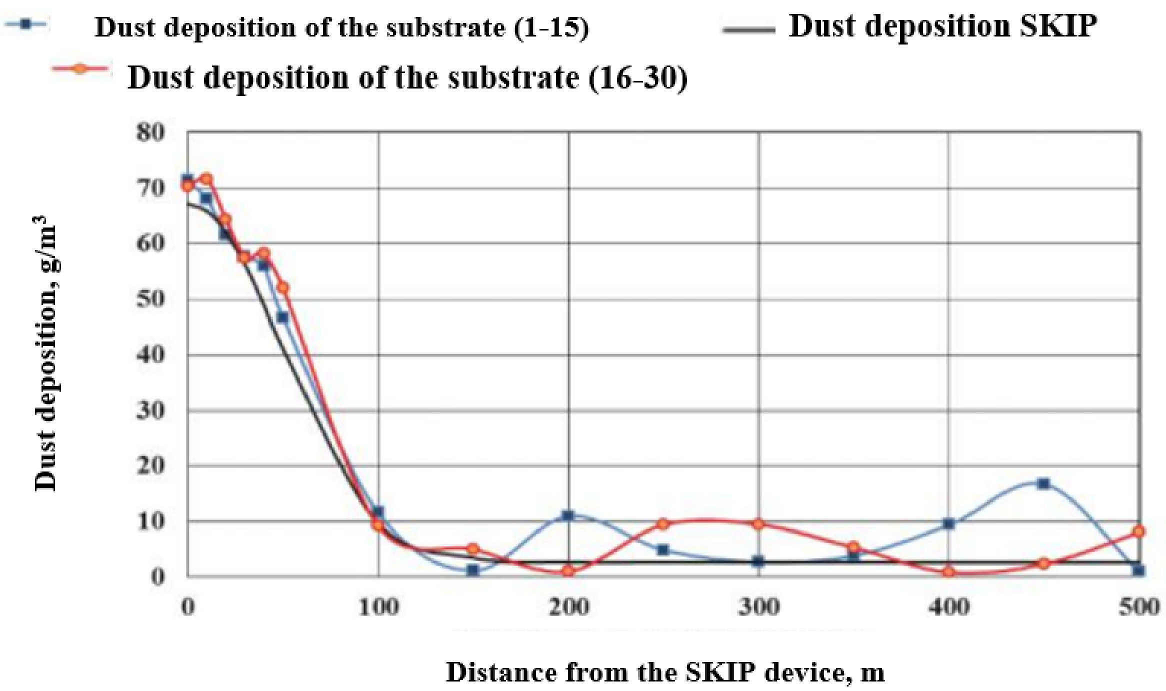

Fig. 3. Comparative analysis results of dust depositions intensity measuring using the SKIP and the calculation method using baseses.
Рис. 3. Результаты сравнительного анализа измерений интенсивности пылевых отложений с использованием СКИП и расчетного метода с базисами.

Conclusions

The full laboratory and mine research complex of the continuous automatic dustiness and dust deposition intensity monitoring system has confirmed the correctness of the physical model developed for assessing the dust state and explosion safety of coal mine workings. This system is equipped with various modifications markers for the air and gas control systems and is certified as a means of declared parameters measuring within these systems, it allows the readings to be displayed on the coal enterprise dispatcher monitor.

The continuous automatic dustiness and dust deposition intensity monitoring system developed meets modern safety requirements in coal mines for monitoring the air dustiness and dust deposits, as well as aerological safety instructions for coal mines, which require the automatic continuous dust concentration and/or dust deposit measurement in the mine atmosphere, telemeasuring, telesignaling when the threshold values of dust deposits are exceeded, or in case of dust sensor failure. Additionally, the system includes local light and/or sound alarms, automatic data transmission of exceeding threshold values of dust and/or dust deposits concentrations in the mine atmosphere in real-time through communication channels to the coal mining organization.

Conflicts of Interest

The authors declare no conflict of interest.

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ИСПОЛЬЗОВАНИЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ АВТОМАТИЧЕСКОГО КОНТРОЛЯ АЭРОДИНАМИЧЕСКИХ ПРОЦЕССОВ В ГОРНЫХ ВЫРАБОТКАХ УГОЛЬНЫХ ШАХТ

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Аннотация.
С ростом добычи угля увеличивается и нагрузка на производственные мощности угольных предприятий, что приводит к одновременному увеличению пылеобразования как при открытом, так и при подземном способах разработки угольных месторождений. Пыль, образующаяся при бурении, взрывных работах, выемке, погрузке, дроблении и транспортировке добытой породы, является одним из факторов, оказывающих негативное влияние на здоровье горнорабочих и на уровень загрязнения окружающей среды твердыми частицами. Таким образом, повышение эффективности контроля концентрации твердых частиц в рудничной атмосфере и пылевых отложениях является актуальной научно-технической задачей. При этом использование современных цифровых технологий в рамках концепции Индустрии 4.0 позволяет разработать подходы, способные существенно повысить качество мониторинга состояния рудничной атмосферы на угледобывающих предприятиях. В статье приведены теоретические основы и результаты испытаний системы непрерывного автоматического мониторинга концентрации пыли в рудничной атмосфере как компонента многофункциональной системы безопасности угольной шахты. Показано, что мониторинг состояния аэрологической безопасности горных выработок может осуществляться в режиме реального времени с помощью системы нового поколения с использованием искусственного интеллекта. Отмечена способность предлагаемой системы измерять основные физические параметры, влияющие на осаждение пыли (дисперсный состав, влажность воздуха, концентрацию пыли и скорость воздушного потока).

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