Nephelometry and turbidimetry to assess concentration and dispersion of coal dust in mines

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Abstract. The article considers the model of the optical instrument to measure coal dust concentration in mines based on the turbidimetric and nephelometric methods. The calculated data on the intensity of transmitted and scattered waves depending on coal dust concentration and on the size of coal dust particles are presented.

The coal dust explosions are known as the most hazardous emergency events at coal mines, coal processing and utilization plants. The striking after-effects of a combustible dust explosion are shock wave, high temperature, toxic gases, reduction in oxygen concentration in a new-generated gas mixture. The shock wave is capable to overcome large distances, and that is why the combustible dust explosions inflict huge economic damages to industrial plants, lead to multiple injuries with lethal outcomes [1].

Coal dust used to generate in large amounts in coal seam mining, haulage and transhipment operations. A hazard of coal dust explosion arises when concentration of combustible dust reaches the critical level in the air.

The increase in coal production capacity is accompanied with greater emission of gas and coal dust in mine atmosphere. Measurement and monitoring of finely dispersed coal dust concentration is of prime importance for safe underground mining. The measurement and monitoring instruments should be high-speed in operation and provide reliable data, otherwise an intensive dust generation can cause an explosive-hazardous situation.

Nowadays there are a lot of processes to monitor dust emission in mine atmosphere. Each process is distinguished for specific merits and drawbacks [2]. Some of them imply human participation in measurements with large monitoring time with no representative presentation of dust-generation dynamics, because they are based on sampling principle. In other monitoring processes different factors such as temperature, humidity, etc. affecting measurement results should be taken into account. Therefore, it is not a simple problem to develop dust-meters meeting precision and high-speed requirements.

The basic parameters of the mine dust-air atmosphere which demand regular monitoring are coal dust concentration and size of dust particles, as they influence the explosion-proof mine operation.

The physical-chemical properties of coal can vary widely, so the lower concentration level of coal dust explosibility is also not rigorous, but specific for different coal brands. Available publications report different data
on concentration limits of coal dust explosibility. It is experimentally proved that most coal dusts are prone to explode at 10–50 g/m³ dust concentration in the air [3]. In [4] it is stated that coal dust with 16 % volatile yield used to explode at concentration of 125 g/m³, but with 25% volatile yield the concentration of 100 g/m³ is enough for explosion.

In spite of further studies of mine dust explosibility the coal industry professionals: theoreticians and practitioners have different views on many issues especially on a probability of coal dust explosion in a mine when gas is not detected in its mine workings.

In 1906 the explosion of coal dust in Courrieres gas-free colliery, (Northern France), took 1100 lives and put an end to the dispute of supporters and opponents on self-sustained role of coal dust. Comprehensive investigation into coal dust explosibility initiated immediately after the accident made it possible to establish the law that:

– coal dust is prone to explode at absolute absence of methane;
– coal dust can initiate explosion of a small methane amount and turn it into huge-scale explosion;
– fire from combustible dust cloud can reach a spot of methane gas concentration and inflame it;
– content of fine and dry coal dust in air decreases the lower level of methane-air mixture explosibility, it becomes explosive at lower than 5 % gas concentration;
– in coal dust explosion the products of explosion always contain a certain amount of carbon monoxide being the main reason of human deaths (70–80% victims) as a result of gassing.

According to test evidence of MakNII and VostNII laboratories [2] on the maximally explosive coal dust (with volatile yield \( Y^{\text{daf}} \geq 35\% \), ash content \( A' < 5\% \), moisture content \( \varphi \leq 15\% \)) the lower concentration limit for explosibility is equal to \( \delta = 10 \text{ g/m}^3 \)[2]. Given that methane concentration in a face is \( C_{\text{CH}_4}=1\% \), the limit lowers twofold, at 2% it lowers four times. Therefore, in presence of methane the coal dust can explode at concentration of 4–5 g/m³ during face advance; so a new-developed measurement instrument should have the dust-concentration measurement range \( C_{\text{II}} \) from 0 to 3 g/m³.

At present there are two systems: weight-scale and countable ones for presentation of results on dust content in mine air and industrial rooms [2].

In the weight-scale or gravimetric system dust content in the mine air is expressed in weight units, milligrams of a dispersed matter per 1 m³ of air (mg/m³).

In the countable (conimetric) system dust content is expressed in a number of dust particles per a unit of air volume, usually per 1 cm³.

In [2] classification of processes for measurement of coal dust in mines is given including measurement principles, specifications of measurement processes with their merits and drawbacks.

Let consider optic methods based on measurement of absorbed and dispersed light by a dust cloud. The measurement processes based on light absorption are termed turbidimetric and processes based on light dispersion are known as nephelometric ones. The system based on these processes exhibits high precision at high measurement speed and allows registration of particles of tens nanometers in diameter without human participation, viz., a completely automatic system.

Circuitry of the instrument based on both measurement principles is presented in Figure 1.

The aim of the research modeling is to study influence of the dust particle size on intensity of passed and dispersed laser emission. In future the present research findings can serve the base for development of monitoring of finely dispersed fraction of dust as it is the finely dispersed fraction of dust that is the most explosive hazardous as compared to course-size dust particles.
Figure 1. Circuitry of a measurement instrument based on both turbidimetric and nephelometric methods.

In the turbidimetric process the intensity of a light beam passing through coal dust attenuates due to light dispersion by suspended particles. Intensity of the passed light obeys Bouguer’s law:

$$B = \frac{I}{I_0} = e^{\frac{-a_k}{\lambda}}$$  \hspace{1cm} (1)

where $I$ – intensity of passed light, $I_0$ – intensity of incident light, $\lambda = 0.38 \mu m$ – wavelength \cite{6}, $l = 5$ cm – a laser beam way in a dust medium (Figure 1), $K(\lambda, C_n) = NV$ – spectral parameter of attenuation of a poly-dispersed medium characterizing attenuation of light by a volume of the medium containing random dispersing particles.

The laser beam pipe in Figure 1 is assumed as a volume of the medium, in other words it is cylinder formed by a laser beam of 5 cm in length and 2.5 mm in diameter. $N$ – number of dust particles in the given volume, $V$ – volume of a dust particle equal to a volume of a sphere of 1.36 $\mu m$ in diameter \cite{6}.

$$V = \frac{\pi \cdot (1.36 \cdot 10^{-6})^3}{6}$$  \hspace{1cm} (2)

The nephelometric method is based on registration of the dispersed radiation obeying Rayleigh rating:

$$R = \frac{I_r}{I_0} = \frac{NV^2}{\lambda^4 r^2}$$  \hspace{1cm} (3)

where $I_r$ – intensity of dispersed light, $I_0$ – intensity of incident light, $\lambda = 0.38 \mu m$ – length of radiation wave \cite{6}, $r$ – average distance from particles function in gas dispersers to radiation detector (Figure 1), $N$ – number of coal dust particles in a volume of a laser beam (concentration of coal dust particles), $V$ – volume of a dust particle (2).

In Figure 2 it is shown intensity of attenuation of a passed laser radiation in terms of coal dust particle concentration in diagram of laser beam directionality. $N$ – number of particles, being in a laser beam at the preset wave length, a particle volume, and a beam length in a cloudy medium.

Figure 2. Intensity of attenuation of a passed laser beam versus concentration of coal dust particles.
In Figure 3 intensity of attenuation of a scattered laser beam is plotted versus concentration of coal dust particles in laser beam; the average distance from particles in a laser beam to a laser radiation detector being 2 cm.

**Figure 3.** Intensity of attenuation of a scattered laser radiation versus concentration of coal dust particles.

In Figure 4 ratio \( \frac{R}{B} = F \) versus concentration of coal dust particles in a laser beam is shown.

**Figure 4.** Ratio \( \frac{R}{B} = F \) versus concentration of coal dust particles.

Figures 5–7 illustrate influence of dust particle size on intensity of scattered and passed radiation at constant coal dust concentration \( N = 100 \). The diameter of particles varies within 0.05–5 µm at radiation wave length \( \lambda = 0.38 \) µm. The dust particles are suggested to be of spherical shape. In Figures 5–7 the volume of dust particles in cubic millimeters is plotted on abscissa axis.

**Conclusions**

In the first approximation the characteristics of concentration and dispersion of coal dust were obtained in the mathematical model of the measurement instrument disregarding a number of destabilizing factors: variations in atmospheric pressure, moisture and temperature. The new-developed mathematical model considers variations in the range of measured concentrations, dust particle dispersion, radiation wavelength \( \lambda = 0.38 \) µm and length of the optical channel base \( l = 5 \) cm.

**Figure 5.** Influence of dust particle size on intensity of the passed radiation.

As it follows from modeling results (Figures 2 and 3), the sensitivity of the turbidimetric method to variations in coal dust concentration is higher than that of the nephelometric method due to the exponential character of the relationship for radiation, passing through dust.
Figure 6. Influence of dust particle size on intensity of the scattered radiation.

Figure 7. Influence of dust particle size on ratio $R/B = F$

At low dust concentrations the intensity of the passed radiation exceeds the intensity of scattered radiation. In view of the above, the turbidimetric method should be preferred in design of the instrument to measure low concentrations.

At high dust concentrations the intensity of scattered radiation increases and the sensitivity of the nephelometric method to measure dust concentration can be helpful. However it is worth noting that measurement instruments for low dust concentrations are of high value.

The result in Figure 4 indicates that with growth of dust concentration the intensity of the incident beam undergoes redistribution between intensities of the passed radiation and the scattered radiation with the preference to scattered one.

Results in Figures 5–7 justify the high sensitivity of both methods to variations in size of dust particles.

Considering the above results and relevant experience of the autonomous information and control systems department, Novosibirsk State Technical University, there are grounds to develop measurement instruments sensitive to the size of dust particles. Currently, the present researchers are engaged in studies into scattering and passing of radiation at wave length within $\lambda = 0.38–0.9 \, \mu\text{m}$ in a cloudy medium with the use of injection lasers and low-energy light-emitting diodes [8–10].

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