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Prototype device for measuring the dustiness of stone and lime dust used in explosion prevention

Author(s) ORCID Identifier:
Adrian Toman: 0000-0002-2879-9702
Zdzisław Dyduch: 0000-0003-4097-7193
Tomasz Skowronek: 0000-0002-4684-9208

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Abstract

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Keywords

dust, volatility, measurement, methodology

TECHNICAL NOTE

Prototype device for measuring the dustiness of stone and lime dust used in explosion prevention

Adrian Toman*, Zdzisław Dyduch, Tomasz Skowronek

Central Mining Institute, National Research Institute, Katowice, Poland

Abstract

This paper presents the prototype of a device for measuring the dustiness of powdered materials by means of a new measurement method. The currently employed stationary laboratory device, utilised in KD "Barbara", uses the attenuation of a radiant flux transmitted through a dust cloud induced by a manually generated air blast. The new device uses the same measurement method, but it includes modern elements based on a microprocessor, a laser line generator instead of an LED diode, and a precise multi-channel detector. The generated quantity of the mixture (dust and air) is strictly determined and precisely dosed via buffer containers, pressure sensors, and high-speed solenoid valves. Utilising the new solutions will make it possible to improve the repeatability of the air blast parameters and the detection of the dispersed dust cloud, which will enable a better evaluation of the tested dust quality. The paper presents a prototype of a device for measuring the dustiness of stone and lime dusts. The device can also be used to determine the dustiness of other powdered materials.

Keywords: dust, volatility, measurement, methodology

1. Introduction

The explosions of coal dust and gas have accompanied us since the beginning of mining history. They are the fundamental hazards in coal mines during extraction works. Regardless of the location in the world, mining has faced the same problems. Efforts to combat the threat of explosions in mining have been carried out in many countries in scientific institutes established for this purpose [1]. Years of experimentation and experience in the mining industry have allowed for the determination of certain principles, norms, and procedures to combat these hazards. Currently, in accordance with the applicable regulations, mining facilities with underground coal or lignite deposits organize a service to combat the threat of coal dust explosions [2,3].

Over the course of many years, various attempts have been made to deal with these hazards. One of the initial methods to prevent the occurrence and spread of dust explosions in underground workings is by adding non-flammable stone dust to settled coal dust [4]. The dust mixture becomes non-flammable with the appropriate proportion of stone dust in the settled coal dust [5,6]. Despite many years passing, this method is still used along with other new solutions in areas designed to prevent the spread of coal dust explosions. In workings where maintaining prevention zones is not possible, additional spaced dust explosion barriers are used. In the dust explosion barrier, stone dust is also used as an extinguishing agent, placed on shelves. The effectiveness of halting coal dust explosions by stone dust depends on many physicochemical properties of such dust, e.g., particle size, combustible content, volatility, bulk density, etc. Most parameters corresponding to specific properties are determined during the production of stone dust and do not undergo significant changes during storage. However, parameters such as moisture, cohesion, and dust volatility undergo significant changes, especially during storage in the humid atmosphere of mine workings. Different dusts, depending on the production technology, do not equally succumb to the adverse effects of the mine atmosphere. For example, a higher specific

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* Corresponding author.
E-mail address: a.toman@gig.eu (A. Toman).

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surface area of dust ensures greater effectiveness in halting an explosion by the rising cloud, but as the specific surface area increases, dust cohesion increases, reducing its volatility. The concept of dust volatility is quite commonly used, often with varying meanings, depending on the associated effect. In studies of the properties of stone dusts used as explosion protection, dust volatility is considered one of the parameters characterising a given dust. In colloquial mining language, dust volatility refers to its ability to disperse. The authors of the paper [7], creators of the Barbara-LPW1 device for determining the volatility of stone-lime dusts used for explosion protection, compare the concept of the Polish term "dust volatility" to foreign literature, where they found equivalents such as "dispersibilitè", "dispersibility", "Luftfähigkeit", which highlight the sense of their application in determining dust. Undoubtedly, the concept of volatility is related to the phenomenon of dispersion and lifting of dust. As a result of many years of research conducted at the KD "Barbara", dust volatility was defined as the ability of dust to lift and disperse in the air in the form of a cloud under the influence of a blast of air. A measure of such defined volatility could be, for example, the density of the dust cloud lifted by a blast of air under certain geometric conditions and constant blast energy. A coal or gas dust explosion is characterised by a rapid blast of air (pressure wave) that lifts settled dust and can result in the further spread of the explosion. Introducing non-combustible particles into the coal dust cloud in the form of stone dust in the appropriate proportion extinguishes the explosion. However, this must happen rapidly enough, and the dust must be adequately dispersed.

Research related to the introduction of stone dusts in mining has been based on assessing dustiness by measuring the degree of lift based on the ratio of the mass of dust lifted by a blast to the initial mass. Such a method of measuring dustiness and the equipment used are described in works [8–10]. The authors of the mentioned works measured the degree of dust lift using a continuous air stream method, which does not correspond to the definition of dustiness given above. The author of work [11] points out the flaws of such measurement, mentioning that "The study of dustiness in a continuous air stream is a laboratory method that may differ significantly from the conditions existing during an explosion. The blast occurring during an explosion has a completely different character from the air stream used in the laboratory method." He criticised this measurement method for significant moisture loss in the sample and loss of dust mass dependent on fragmentation, which could change during the measurement. Other research methods for determining dustiness are presented, among others, in works [12–16]. However, as the author of work [11] mentioned, the significance of dustiness is given different meanings depending on the effect it is associated with. Another definition, for example, was provided by the authors of work [17], who defined dustiness as: "the propensity of a material to generate airborne dust Turing its handling." As can be seen, this definition differs significantly from the one given earlier. The authors of work [18], who compared three methods of measuring dustiness, stated that the tests of equivalence carried out lead to the assumption that neither of the techniques is comparable, not even those two showing the greatest analogies in handling the test material. They compared two gravimetric methods and one optical method. One of the methods, the continuous drop method, is a reference method given in the standard [12]. Comparing this method with the other two, namely the modified Heubach dust meter, the method with a rotating drum, and the Palas Dustview method, the single-drop method yielded unequal results. However, the Palas Dustview method is an optical method. All of these techniques explore the aerosolization of bulk powders. However, the aerosolization of a dust layer from surfaces is extremely important yet has received limited investigation [19].

The presented work mainly focuses on the method of measuring dustiness described in standard [20]. This standard specifies requirements and tests related to stone dust used for dusting workings and building dust barriers to protect against the possibility of coal dust explosions in the underground workings of mining facilities. The standard outlines the research program and defines the scope for full, qualification, and control tests. All tests described in the standard aim to verify the safety of working with stone-lime dust and to secure the underground workings of mining facilities against the possibility of coal dust explosions. As mentioned earlier, the effectiveness of such protection depends on the parameters of stone dust [21,22]. In each range of tests described in the standard, dustiness is determined according to the guidelines provided. This standard imposes a method for determining dustiness, which is measured after moist storage of the test dust. The method involves "lifting the dust under the influence of a blast of air and assessing the density of the resulting cloud based on the attenuation of a beam of light passing through the cloud." Dustiness is assessed on a three-level scale (insufficient, sufficient, good). The permissible difference between the two results of determination should not change the classification of dustiness on the three-level scale.

The repeated result of two consecutive determinations should be considered as the final result of the determination. If the difference between two results of parallel determinations changes the classification of the sample according to the scale, another determination should be performed, and the repeated results should be considered as the final result.

According to this standard, the Barbara-LPW1 device is constructed. To measure the light flux, a system consisting of a light source and a photoelectric sensor (photodiode assembly) is used. These elements are positioned precisely opposite each other, with the dust cloud lifted between them. Depending on its density, the value of the electric signal generated by the sensor changes. The device only allows for classifying the value measured by the sensor into one of three specified intervals. It should be noted, therefore, that the Barbara-LPW1 device is used not for the "measurement" of dustiness but for its evaluation. In this device, the voltage pulse from the sensor is transmitted to two amplitude discriminators with different discrimination thresholds. The passage of the pulse through the discriminator activates a flip-flop and illuminates the associated indicator bulb. Because the pulse applied to the discriminators is higher, the greater the density of the dust cloud, i.e., the higher the dustiness; for very low dustiness (insufficient), the pulse does not pass through the discriminators, and the indicator diodes do not light up. For dust with sufficient dustiness, the pulse is higher than one of the discriminators, and one indicator diode lights up. If the pulse passes through both discriminators, two indicator diodes light up, indicating good dustiness. Setting the discriminator thresholds to a specified height was preceded by numerous studies of stone-lime dusts with different dustiness, selected based on years of experience with coal dust explosions conducted in the experimental galleries of the Experimental Mine "Barbara". Based on these studies, stone-lime dusts were divided into three categories: insufficient, sufficient, and good. Based on this, standards were prepared, which, when properly set in the light beam of the LPW1 device, cause its attenuation to the extent described by the critical density of the dust cloud. One of the standard plates was prepared for the critical value of triggering one discriminator and the other for the threshold of triggering two discriminators, i.e., the illumination of two indicator diodes.

The objective of the work titled "Design of a prototype device for measuring the dustiness of powdered materials (primarily stone and lime dusts used in explosion prevention)" was to optimise and improve the quality of this test method by introducing the extinction measurement of a laser plane transmitted through the tested cloud while retaining the optical parameter stability, the sample volume repeatability (and manner of insertion into the device) and the pneumatic cloud induction parameter consistency. Another significant element was the digital system for the measurement process control and data analysis and visualisation, including the control of optical, electrical, and pneumatic parameters. The proposed measurement method was based on the prior experience of the GIG Laboratory of Laser Technology, obtained from the use of ultrasounds and laser light in the assessment of suspension density as well as dust and water-sludge suspension particle size analysis [23–26]. The prototype design, as well as the test and calibration method, factor in the standard requirements and the solutions of the currently employed Barbara-LPW1 measurement device designed at the KD "Barbara" Department of Dust Hazard Control. The currently utilised stationary device uses the attenuation of a radiant flux transmitted through a dust cloud induced by a manually generated air blast.

2. Descriptive and design documentation of the prototype device

2.1. Laser light scattering measurement in dust suspensions

Introducing a monochromatic laser beam into a medium containing a dust suspension enables the determination of a number of its parameters – by measuring the intensity of the light dispersed in the said medium. The most important of these concerns particle geometry and concentration in the suspension [27–31]. The reduction of the electromagnetic radiation intensity along the beam's path is described by the following relationship:

$$I_1 = I_0 e^{-\gamma 1} \tag{1}$$

where γ is the absorption coefficient, which is independent of the light intensity but is closely related to the parameters of the medium passed by the beam. To analyse the particle composition of a dust suspension in the air or water, the basic aspects (parameters) of the influence of an electromagnetic plane wave on a single particle with a specific diameter and a complex refractive index should be taken into consideration. Several particle size ranges can be identified in static and dynamic light scattering. The light scattering intensity and the character of its dependence on the particle size differ between individual ranges [27,32]. The scattering intensity in the Rayleigh range is relatively small, and in the Mie theory range, where the particle size is comparable to the wavelength, the relationship between the intensity of scattered light and the particle size is complex and dependent on the optical cross-section of the sample (related to the particle shape). In Fraunhofer's diffraction, the particle diameter is greater than the incident light wavelength, whereas the scattered light intensity is relatively high and proportional to the square of the particle diameter [27]. The directional light scattering distribution depends on the particle size. It is characterised by high scatter angles in relation to small particles and low scatter angles in the case of big particles [28,29]. An example of an actual angular distribution of scattered light intensity on a polystyrene particle with a diameter of 12.5 μm is presented in Figure 1.

A special case regarding the topic discussed above is extinction – a value describing the intensity attenuation of monochromatic radiation during its transmission through a medium. It is evaluated by measuring the radiant flux exiting the medium at an angle of 0° or at very low angles close to 0°. Extinction (E_λ) can be described using the following formula [27]:

$$E_\lambda = \ln\, \ln\, (I_t / I_0) = -\, K_{\text{ext}}(a) A_p n L \tag{2}$$

where:

E_γ – absorbance at a specific wavelength (λ),

K_{ext} – molar extinction coefficient of the absorbing species. Depends on the particle size a, wavelength λ and the refractive index,

L – path of the light in the medium,

A_p – optical particle cross-section optimised to Πa^2,

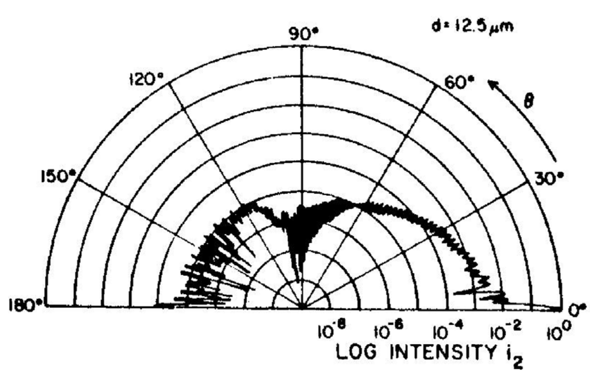

Fig. 1. Angular distribution of scattered light intensity in a selected polarization plane for a polystyrene particle with a diameter of 12.5 μm [28].

n – number of particles in the medium (concentration).

In prior years, the following issues were studied using the equipment at the GIG Laboratory of Laser Technology:

- the suitability of directly measuring the intensity of light transmitted through a suspension – extinction – for assessing the concentration of particulate matter in low-density suspensions,
- the suitability of dynamically measuring forward scattered light on single particles,
- the suitability of dynamically measuring backscattered light on single particles transmitted through a laser beam focus.

The possibility of using high-power lasers and linear photodiodes with high sensitivity, dynamics, and short reaction time was determined during studies on the concentration of dust particles in clouds with very high densities. A laboratory array for measuring the total extinction of light transmitted through a suspension is presented in Figure 2.

It consisted of a laser emitter, a cell with a sample and a laser light meter. The source of the coherent light with a length of 658 nm and output power of 5 mW (spot with a divergence of 0.2 mrad and cross-section of 15 × 5 mm) was a laser diode. The suspensions were poured into measurement cells with a space of 50 mm between the parallel flat walls formed from fused quartz and with a volume of 251 cm^3. The light intensity was measured by means of the SCIENTECH LTD and NewPort laser power meters as well as on the 16 segments of the Hamamatsu silicon photodiodes. This method for measuring suspensions was compared to a measurement chamber with a space of 50 mm between the parallel flat walls formed from fused quartz and a volume of 251 cm^3 for testing the Barbara coal dust of class 0–1 mm. The same lasers and detectors were applied for samples of water and dust-air mixture suspensions. The generation of temporary dust-air mixtures in the chamber, as presented in Figure 2, was challenging. Significant issues

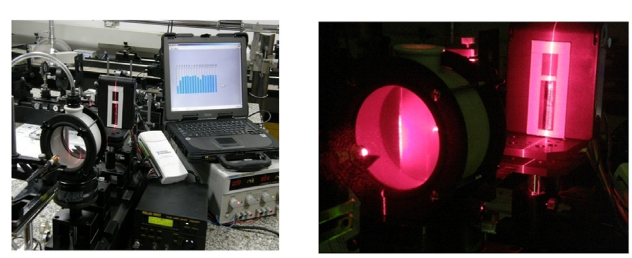

Fig. 2. Array for the optical measurement of particulate matter concentration in a suspension.

included the temporal repeatability of the moment of measurement (relative to the moment when the dust was dispersed by the compressed air), the rate of dust settlement on the walls, and gravitational settling (including the influence of micelle formation, generated by small particle aggregation by van der Waals forces). As a result of these factors, different regression charts were obtained in this case compared to water suspensions as well as considerably worse fitting parameters, as presented in the chart below (Fig. 3).

Laboratory testing of the signal level in 16 channels in 1 ms windows made it possible to conduct a detailed qualitative and quantitative analysis of the occurring processes and the distribution of concentrations in the cross-section encompassed by the measuring channels [26]. Figures 4 and 5 illustrate the signal change at 3 and 20 s after the air blast

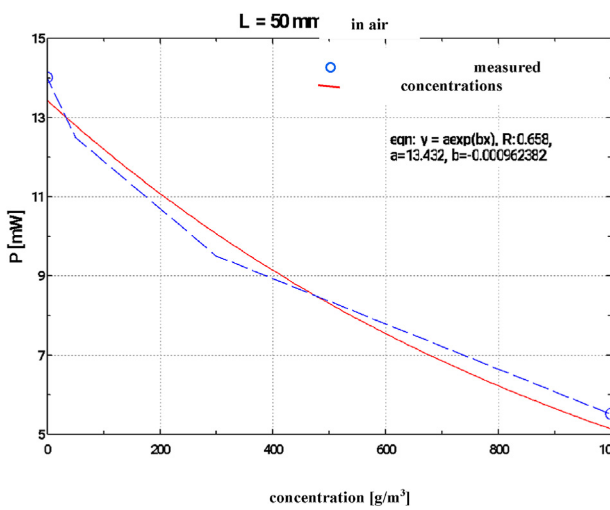

Fig. 3. Laser light transmission variation in the cloud of coal dust of class 0–1 mm from KD "Barbara" [26].

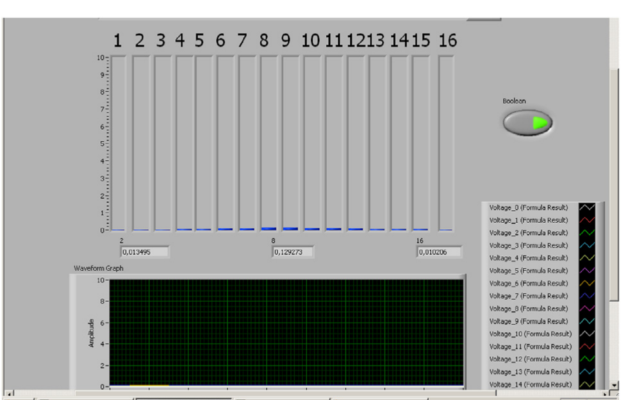

Fig. 4. Measurement signal level (mV) at 3 s for a nominal output concentration of 500 g/m^3.

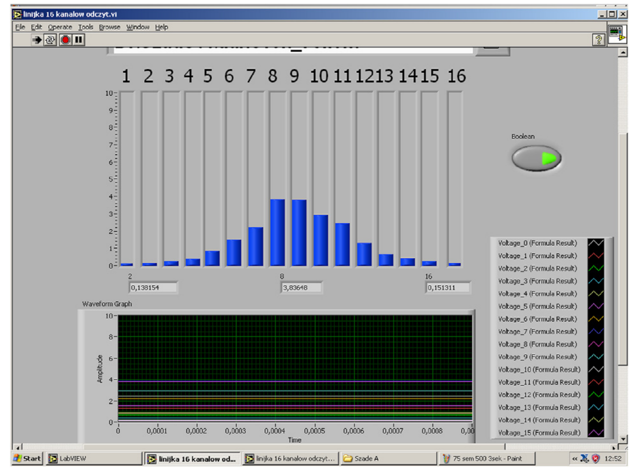

Fig. 5. Measurement signal level (mV) at 20 s for a nominal output concentration of 500 g/m^3.

(gravitational dust settling) for a concentration of 500 g/m^3.

These experiments demonstrated that crucial conditions for the appropriate measurement include known (zero) optical output parameters for the empty chamber, repeatable sample insertion parameters (quantity – weight/volume), compressed air pressure, and an extinction measurement time delay defined at a constant level in the chamber. This has also been confirmed by other experimenters [32,33]. The obtained information makes it possible to establish an algorithm for determining the effective value of the parameter Lef – (effective dustiness) that constitutes a criterion of dustiness. To fulfill these conditions, a number of measurement chambers were constructed for the purposes of the new device, differing in dimensions, the manner of sample insertion, and the material from which they were formed. Several detectors characterised by various sensitivities were tested in them using two different laser emitters of different wavelengths. The performed tests made it possible to determine the final measurement chamber construction, reflecting the conditions closest to those found in the existing Barbara-LPW1 measuring instrument.

2.2. General description of the prototype, with the test procedure

Figure 6 presents a diagram of the prototype device for dustiness measurements. The measurement procedure is as follows. A stone dust sample of 2 g is placed in the cavity (Φ 25 × 5 mm) of the feeder P2, which is then inserted into the measurement chamber P1. The front feeder wall closing

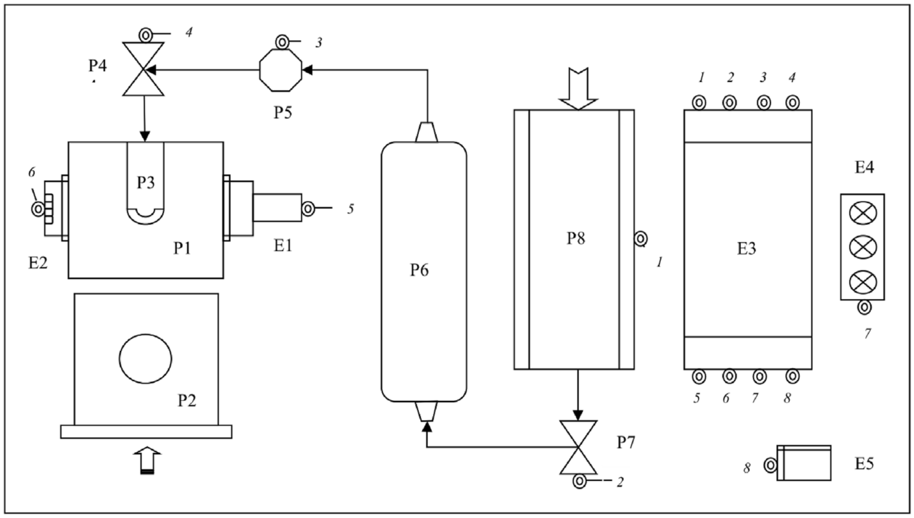

Fig. 6. Overview drawing of the measurement device (design): P1 — measurement chamber, P2 — sample feeder, P3 — air blast nozzle, P4 — drain solenoid, P5 —pressure control, P6 — pressure tank, P7 — check valve, P8 — compressor, E1 — laser emitter, E2 — segment detector, E3 — power supply, control and analysis system, E4 — measurement result signalling device, E5 — ON/OFF button, 1, 2, 3, 4, 5, 6, 7, 8 — electrical connections (power supply, control, data).

the chamber is equipped with a breather (VF1 TACHI). The measurement chamber P1 is constructed based on a PA38 60 × 60 × 3 mm hollow section. Windows formed from N-BK7 ND 201B Thorlabs glass with a transmittance $T = 79\%$ are installed in the side walls in the edge trim seals. The linear laser E1 ($L = 45$ mm, $\Phi = 12$ mm) is installed behind them on one side, emitting a horizontal plane of coherent light with a length of 520 nm and an output power of 5 mW (spot with a divergence of 90°), while the 16-segment detector E2 (HAMAMATSU 25 × 20 mm) is installed on the other side. The idea of the transmission through the chamber with a circular cross-section is presented in Figure 7.

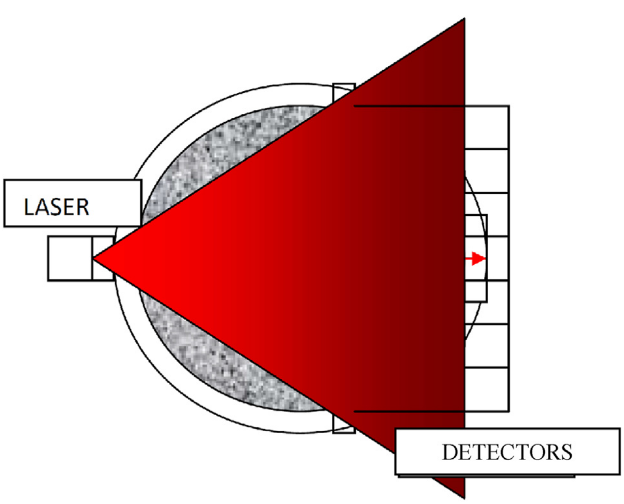

Fig. 7. Idea of the measurement system using a linear laser and a line of multi-segment photodiodes (for a chamber with a circular cross-section).

The device is activated with a single ON/OFF button E5. Before the actual dustiness measurement, the control, power supply and data processing system E3 performs a reference measurement of light intensity for the empty chamber I_A through connections 5-5 and 6-6. The next step of the control algorithm activates the air compressor P8 (explosion-proof CO_2 cylinder pump) that generates a pressure of 0.9 bar by the check valve P7 in the pressure tank P6. After reaching the defined pressure, the signal from the set pressure control P5 starts the opening procedure of the high-speed membrane solenoid P4 that directs the compressed air blast through the elbow nozzle P3 onto the tested sample. The measurement of the light intensity I_B after transmission through the dust cloud is conducted in a predefined time in the range of 0.5–1 s. I_B is the sum of all the values obtained in each segment of the linear photodiode E2. The dustiness L is calculated as the difference $L = I_A - I_B$ over a three–level scale (insufficient – red diode colour, sufficient – yellow, good – green) by comparing the limit values of these three thresholds, recorded and defined as a result of calibration measurements using a reference plate (three-level optical grey filter). Each measurement recorded by the data acquisition system installed in the device can be transmitted to a computer. The signals registered by the individual linear detector segments can be analysed in detail by means of software specifically adapted for this purpose.

To illustrate the internal and external structure of the prototype device, the article includes Figures 8–10.

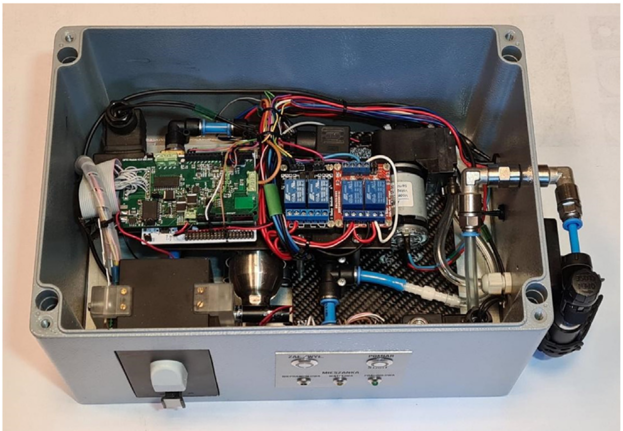

Fig. 8. Internal appearance of the device.

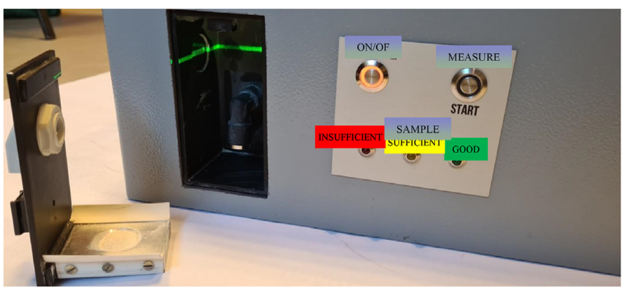

Fig. 9. Front panel of the device with an open chamber and the dust panel removed from the dust chamber.

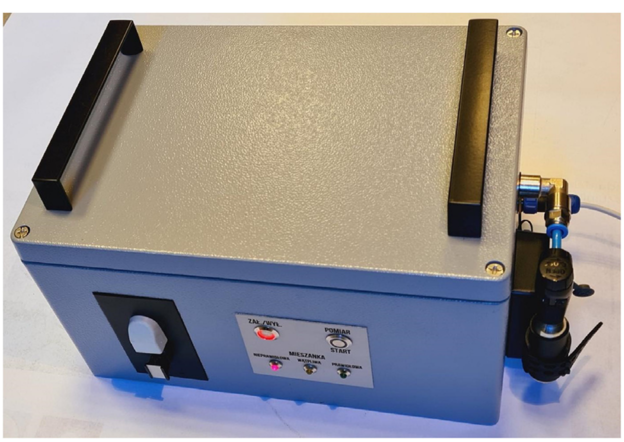

Fig. 10. View of the complete device.

3. Calibration and comparative testing

Introducing a new device intended for dustiness measurements requires finding the relationship between the indications of this device and those of the Barbara-LPW1 device currently used in testing. The reason for this is the necessity to preserve continuity with the prior results of stone and lime dust testing where the older device was applied.

Before calibrating the prototype device, control readouts of the reference plates (grey filters) were performed on the Barbara-LPW1 device. The device is equipped with an analogue gauge with a range of 0–10 and a division into three areas (Fig. 11) that constitute the basis for classifying a given type of dust.

To thoroughly inspect the correct operation of the gauge, control measurements of the reference plates were performed by directly recording the signals from the detector by means of an oscilloscope. Several tests were conducted for each reference plate.

The performed reference plate control tests confirmed the correct operation of the Barbara-LPW1 device. They also indicate the voltage values corresponding to the thresholds between the individual areas. Minor differences between the tests may be attributed to the noise of the device itself.

Similar measurements were performed using the reference plates of the prototype device. The measurement results for both devices are presented in Figure 12. This made it possible to obtain thresholds for the signals, dividing their range of variability in a manner similar to the case of the older device. With this division, it will be possible to maintain the current method of dustiness classification introduced by the application of the Barbara-LPW1 device.

Comparative tests of stone and lime dusts of various origins were then performed for the thus-calibrated device. The dusts were prepared in such a way as to ensure a significant differentiation of their dustiness, e.g., by changing the degree of their moistness [34]. Three measurements were performed for each dust, and the results were averaged. The tests served to inspect the conformity of the results obtained by means of both devices when testing the properties of dusts. Figure 13 presents the comparative results of the conducted tests.

The obtained results appear similar, though two dusts whose dustiness was deemed *sufficient* by the old device were evaluated as *good* by the new one. These differences may be attributed to the inaccuracy of the measurement and the quality of the

Insufficient	Sufficient	Good
< 4	4–7.8	> 7.8

Fig. 11. Barbara-LPW1 device scale division.

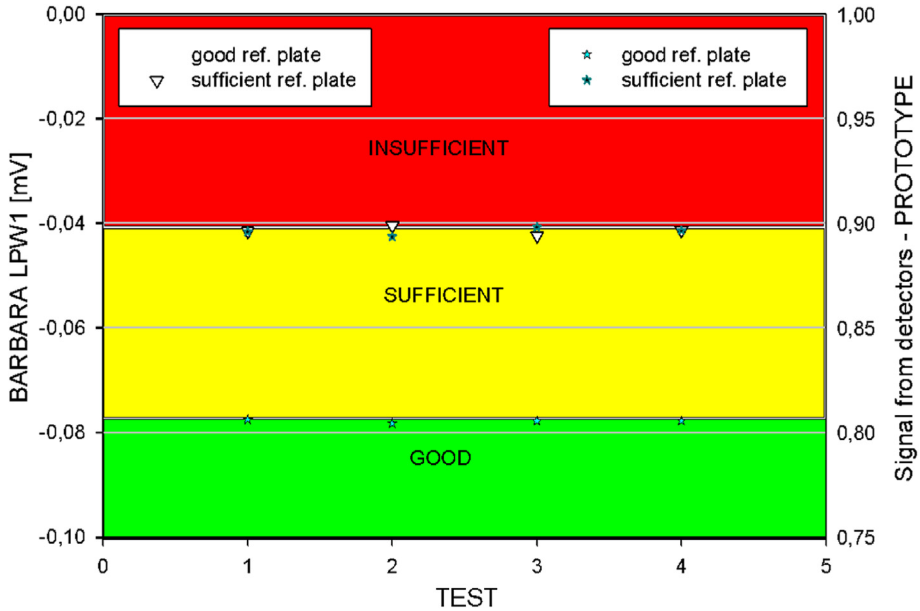

Fig. 12. Reference plate test results for the Barbara LPW1 and the prototype.

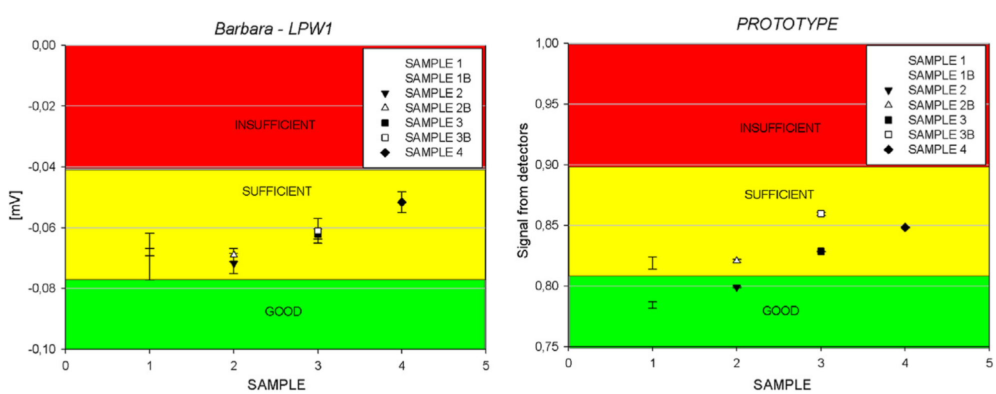

Fig. 13. Comparative results for both devices after testing the same dusts.

dispersion in the Barbara-LPW1 device. To resolve this, more comparisons need to be made for more dust.

A more direct comparison of the two devices was performed using the Lambert-Beer law:

$$A = \ln\frac{I_0}{I} \tag{3}$$

where:

A – light absorbance, I_0 – intensity of monochromatic radiation incident upon a homogeneous attenuating medium [W/m^2], I – radiation intensity after transmission through the attenuating medium [W/m^2].

In this comparison, replacing the ratio of radiation intensities with the ratio of signals obtained from the detectors in the case of an empty measurement

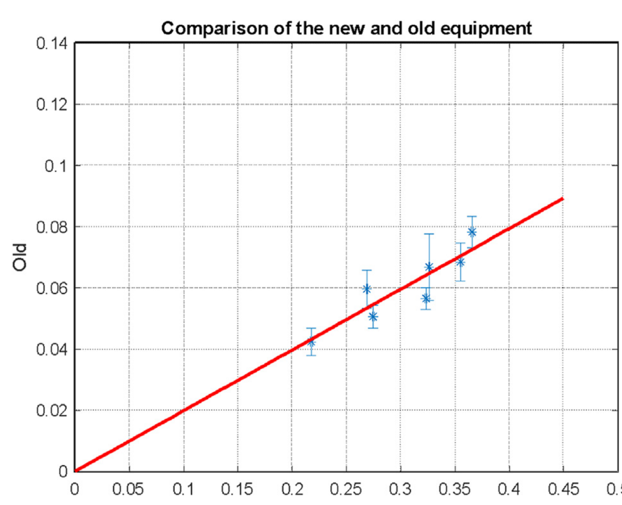

Fig. 14. Comparison of the Barbara-LPW1 device with the prototype.

chamber and the presence of dust is an acceptable approximation. The results of this comparison for the reference plates and dusts are presented in Figure 14. Though the number of the compared dusts is not high, it would appear that a linear relationship between the indications of both the devices can be assumed, which is a very favourable result.

4. Summary and conclusions

Generally speaking, the notion of dustiness is related to the tendency of dust to become airborne. This phenomenon may adopt various forms; therefore, dustiness can be interpreted in different ways: as a physical parameter of dust or as the effect of specific acting forces. When testing the properties of stone dusts used as protection against the propagation of coal dust explosions, dustiness is acknowledged as one of the parameters characterising a given dust. As the stone dusts permitted for use do not exhibit particularly major differences in the size distribution, their optical properties should also be similar – with a certain deviation, the light extinction should be dependent only on the dust cloud density.

A next-generation prototype device for determining the dustiness of stone and lime dust used in explosion prevention was constructed according to the basic premise of this work. The device can also be usedtor determine the dustiness of other powdered materials.

To maintain continuity and conformity with the results of prior stone and lime dust testing, the design of the pneumatic system and the dimensions of the measurement chamber of the new device are a reflection of the same elements used in the Barbara-LPW1 device.

The results obtained following the first measurements demonstrate the correct operation of the device. The distribution of the results from the measurement series is within the limits appropriate for a device of this type.

The device is portable, and after the appropriate adjustments it can be permitted for use in underground mining plants.

The functionality of the device could be expanded in a way that would enable the application of its coupled software for measuring the fragmentation of dust, within defined ranges of particle sizes.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflict of interest

The authors declare no conflict of interest.

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