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MECHANICAL SPARK ELECTROSTATIC PROPERTY TESTING METHOD

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Abstract:
The article describes an attempt to assess the electrostatic properties of mechanical friction-induced sparking. Such sparks are the cause of numerous accidents in hard coal mines. The article summarizes accidents in hard coal mining in Poland in recent years. In most cases, the initials were mechanical sparks. Mechanical sparks contain energy, a part of which is related to their excess electrostatic charge, whereas the other part is of a different origin (kinetic or thermal energy, for example). The article tries to estimate how much of this energy is energy impact generated by electrostatics impact. It is hard to measure the dynamic electrostatic parameters like electric charge. Authors select four measuring methods. This test methods are prepared based on authors knowledge of electrostatic parameters and European standards dedicated to measure the electrostatics parameters. These circuits were prepared for four different spark parameters. Measurement methods of electrostatic field of sparks stream are not able to measure field potential of sparks. The measuring instruments do not have such a fast response time, adequate to the speed of the sparks. Spark generation and parameter measurement experiments were performed. The only method to determine the amount of electrostatic charge on sparks is to measure the entire charge by collecting sparks at the measuring electrode. The measuring system requires that the entire stream of sparks falls on the electrode. Tested transferred electrostatic charge of stream of sparks is about 10 nC. It means that this charge can be an effective ignition source for some explosive atmospheres. Electrostatic charge with Certain methods were rejected as inadequate following result analysis. A claim for one of the methods was submitted to the Patent Office of the Republic of Poland.

Key words: *electrostatics, sparking, mechanical friction, electrostatic charge*

INTRODUCTION

Mechanical sparking is most often the result of various kinds of technical processes that involve friction, impact and motion. Frequently, mechanical friction-induced sparking becomes a source of explosive atmosphere ignition. The goal of this paper was to develop a method for mechanical spark electrostatic property determination in such a way so as to enable the assessment of an electrostatic hazard level and its subsequent elimination. The research goal is highly complex due to the dynamics of the phenomenon and the low electrostatic potential of the sparks. The picture below (Fig. 1) presents a thermal camera image depicting a cutting process by means of an angle grinder (mechanical spark generation) and the generated spark stream.

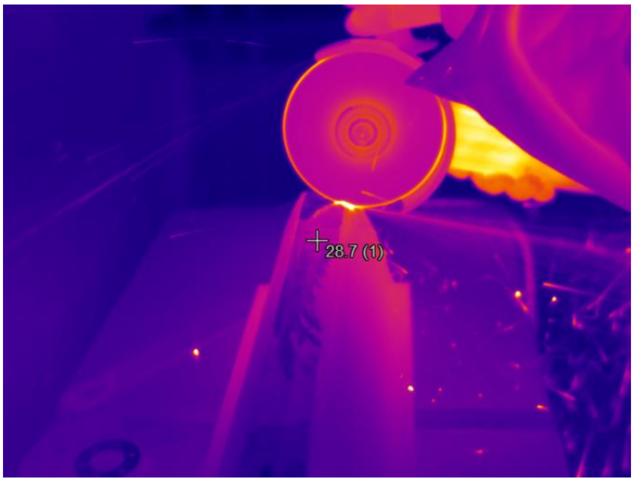

Fig. 1 Mechanical sparks generated by cutting

LITERATURE REVIEW

Measurements of electrostatic charges in dynamic phenomena are difficult to accomplish. Resistance measurement is the most common method for determining electrostatic parameters, due to the ease of applying the method and the repeatability of the obtained results. The development of a method for measuring the electrostatic charge during a discharge or a technical process is difficult to accomplish and often ends in failure. Modern electrostatic sensors operate on acoustic, capacitive, optical and electromagnetic bases. The principles for measuring the electrostatic charge during the pneumatic transport of materials can be found in literature [1]. One such method is the measurement of the surface charge obtained by means of electrostatic field meters [2]. Electrostatic charge measurements also present problems related to the influence of the environment, the flow of the charge between materials or the influence of air on the transferred electrostatic charges [3].

Solutions involving charge measurement by means of an inductive sensor for examining the degree of electrification of powder particles are also known [4]. This method is not suitable for measuring the degree of electrification of mechanical friction sparks, mainly due to the character of the sparks (their resistance parameters). Pneumatic transport also exhibits a character different than the spark stream. A simpler method is to collect the generated electrostatic charge on a capacitor [5]. This method is easier to apply, while modifying the measurement system may enable the collection of the entire chaotic stream of mechanical friction sparks that carry the electrostatic charge. An interesting method for measuring the amount of electrostatic charge accumulated on a material is the grid probe method [6]. The method consists in passing an aerosol through a metal probe composed of three grids, where the two extreme ones are grounded and the middle one is connected to a multimeter. There are also methods that use specialized cameras and oscilloscopes (up to 2 GS/s) for such dynamic phenomena as electrostatic charge flow [7]. The aforementioned method is similar to one described in this article.

The literature analysis demonstrates that the methods yielding a chance of success will include those involving measuring the total charge carried by the sparks, i.e. performing measurements in such a way so as to determine the electrostatic charge of the spark stream.

METHODOLOGY OF RESEARCH

Background of research

Mechanical sparks are generated as a result of friction and as is well known, one of the basic methods of electrification according to the triboelectric series is in fact contact and friction [8]. During contact and friction electrification an electric double layer is induced on two materials that remain in contact which results in electron transfer [9]. The layer is a factor that leads to the opposite electrification of the two materials.

Mechanical friction-induced sparks contain energy, a part of which is related to their excess electrostatic charge, whereas the other part is of a different origin (kinetic or thermal energy, for example).

Sources from the Polish State Fire Service state that the temperature of white sparks is approximately 1200°C, while the temperature of the remaining orange sparks is 800°C. Experts of the State Fire Service have classified welding and grinding as types of hot work, that produces potential source of ignition, as they involve the generation of mechanical sparks [10]. Such sparks may constitute a source of fires, considering that their temperature can reach 1000°C, whereas the distance over which they are emitted is approximately 10 metres. Even at the point when the sparks are extinguished, they still exhibit a temperature of approximately 500°C [11]. Such a temperature is sufficient to ignite numerous flammable substances, including potentially explosive atmospheres present in mines.

Mechanical sparks occur relatively frequently in underground hard coal mining, often resulting in hazards and accidents, including fatal accidents [12].

Table 1 presents a compilation of accidents in Polish hard coal mines in the years 2002-2013.

Table 1
Accidents in hard coal mining

No.	Mine	Date	Initiating event	Course of event	Injuries (fatal/serious/ light)
1.	"Rydułtowy"	23.03.2002	mechanical sparking (from a conveyor)	explosion	3/5/2
2.	"Budryk"	17.07.2002	friction-induced sparking of rocks in gobs	ignition	0/0/0
3.	"Pniówek"	05.09.2002	mechanical sparking (from a shearer)	ignition and explosion	1/7/5
4.	"Bielszowice"	24.02.2003	spontaneous fire	ignition	0/13/19
5.	"Brzeszcze"	01.04.2003	mechanical sparking (from a shearer)	ignition	1/6/5
6.	"Zofiówka"	10.06.2003	mechanical sparking (from a shearer)	ignition	0/0/0
7.	"Sośnica"	07.11.2003	spontaneous fire	ignition and explosion	3/1/6
8.	"Budryk"	17.08.2004	mechanical sparking (from a shearer)	ignition	0/0/0
9.	"Halemba"	03.03.2005	mechanical sparking (from a shearer)	ignition	0/0/0
10.	"Sośnica"	17.05.2005	blasting works	ignition	0/0/0
11.	"Staszic"	25.10.2005	cigarette smoking	ignition	0/2/0
12.	"Zofiówka"	22.11.2005	rock mass pressure	rock and methane outburst	3/0/5
13.	"Szczygłowice"	11.05.2006	electric arc (sparks from a locomotive pantograph)	ignition	0/0/8
14.	"Halemba"	21.11.2006	electric arc (damaged electrical equipment), or electrostatic discharge (utilised screen), or spontaneous fire, or friction-induced sparking of rocks in gobs	ignition and explosion	23/0/1
15.	"Halemba"	23.05.2007	mechanical sparking (from a shearer)	ignition	0/0/0
16.	"Pokój"	28.07.2007	blasting works	ignition	0/0/4
17.	"Bielszowice"	02.09.2007	blasting works	ignition and explosion	0/0/0
18.	"Budryk"	30.10.2007	mechanical sparking (from a shearer)	ignition	0/0/0
19.	"Mysłowice-Wesoła"	13.01.2008	spontaneous fire	ignition and explosion	2/0/1
20.	"Borynia"	04.06.2008	spontaneous fire, or spontaneous binding agent combustion, or electric arc (damaged electrical cables)	ignition and explosion	6/5/12
21.	"Zofiówka"	20.10.2009	mechanical sparking (from a shearer)	ignition	0/0/0
22.	"Wujek" Ruch Śląsk	18.09.2009	electric arc (electrical device short circuit)	ignition and explosion	20/25/9
23.	"Mysłowice-Wesoła" Ruch Wesoła	16.05.2010	spontaneous fire	double ignition	0/0/2
24.	"Murcki-Staszic" Ruch Staszic	13.03.2011	mechanical sparking (from a shearer)	ignition	0/0/0
25.	"Krupiński"	05.05.2011	mechanical sparking (from a conveyor)	ignition	3/9/2
26.	"Bielszowice"	12.08.2011	sparks induced by mechanical friction against rock, or mechanical sparks (metal element friction – shearer, conveyor, longwall support), or friction-induced sparking of rocks in gobs	ignition	0/0/0
27.	"Murcki-Staszic" Ruch Staszic	28.01.2013	mechanical sparking (from a shearer)	ignition	0/0/0
28.	"Murcki-Staszic" Ruch Staszic	06.02.2013	mechanical sparking (from a shearer)	ignition	0/0/0
29.	"Rydułtowy-Anna"	25.02.2013	mechanical sparking (from a shearer)	ignition	0/0/0
30.	"Knurów-Szczygłowice" Ruch Szczygłowice	25.03.2013	mechanical sparking (from a shearer)	ignition	0/0/0

Source: based on [13].

The majority of these accidents were caused by mechanical friction-induced sparking.
Figure 2 presents the types of electrostatic discharges, together with the energy characteristic of such discharges. The minimum energy necessary for methane ignition – 0. 28 mJ [14].

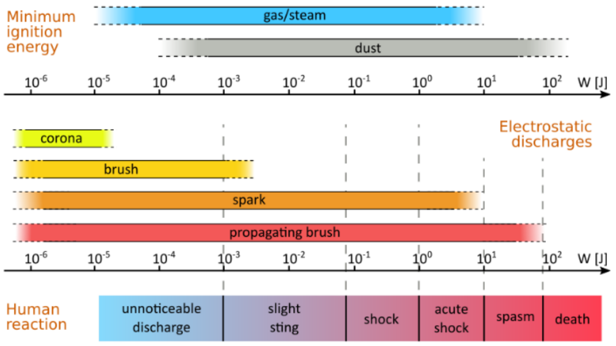

Fig. 2 Compilation of electrostatic discharges with explosive atmosphere ignition energy

Analysis of the data in Table 1 reveals that the mechanical sparks which led to ignition or explosion initiation must have exhibited energy comparable to high-energy electrostatic spark discharges.
An electrostatic spark discharge, also known as a capacitive discharge, occurs between conductive objects with different electric potentials (most frequently an object with high potential and another with potential equal to zero).
A spark discharge is characterised by high instantaneous power, related to a high current pulse.

METHODS

Mechanical spark electrostatic parameter measurements are difficult to perform due to the dynamics of the sparks, their size and velocity, and the limited number of electrostatic parameters characterised by measurements that could be modified and utilised for measuring spark streams.
During the first stage of the work, four methods of mechanical spark parameter measurement were developed based on analyses, with subsequent plans for the assembly of test setups and the conduction of prototype tests. The tests were meant to reveal whether a given measuring method was suitable for performing spark electrostatic property measurements.
Electrostatic property measurements are divided into two categories:

- Material property measurements (resistance),
- Electrostatic charge and derivative measurements (electric field potential and intensity, charge magnitude).

Due to the size of the sparks, it is impossible to measure their resistance.
Electric field potential and intensity measurements are based on the phenomenon of electric induction. An electrostatic voltmeter based on this principle uses a measuring probe to induce a charge of an equal quantity and opposite sign in relation to a charge on a tested object.

The charge magnitude measurement is based on collecting a given electrostatic charge and measuring the amount of the charge.
The following were developed and assembled at the Central Mining Institute as part of this work:

- A mechanical spark generation system,
- Spark electrostatic parameter measuring circuits:
  - The circuit for measuring electrification ability in volts employs a test setup according to standard EN 61340-4-5 [15, 16] and is intended for electrostatic voltage measurements using an electrostatic voltmeter with high input impedance. The intention is to generate a spark stream and direct it towards an insulated metal sheet, and subsequently take an electrostatic voltage measurement of the sheet.
  - The circuit for measuring electrostatic voltage in volts utilises an electrostatic fluxmeter and a charged plate monitor (CPM). The intention is to measure the electrostatic voltage of a spark stream at a short distance from where it is generated. Directing the sparks to a metal sheet and measuring its electrostatic voltage, i.e. the field generated by the electrostatic charge, was also planned.
  - The circuit for measuring electrostatic potential in V/m employs an existing electrostatic fluxmeter. The intention is to measure the potential of a spark stream at a short distance from where it is generated.
  - The circuit for testing a generated charge collected on a condenser and measuring the voltage in V employs a measuring circuit in accordance with standard EN 80079-36 [15, 17]. The tests utilise a condenser connected to a laboratory multimeter. The generated sparks are projected towards an insulated metal sheet. Afterwards an electrostatic discharge is directed from the sheet to the grounded condenser connected to the multimeter. The multimeter measures the voltage on the condenser. The amount of the electrostatic charge on the sheet is determined by way of calculations.

Spark electrostatic potential test

The principle of the first proposed measuring method entailed the generation of a spark stream and the measurement of the spark stream electrostatic voltage (potential) [18]. The measurement employed an electrostatic fluxmeter, which is used to measure the electrostatic potential generated by an electrostatic charge, diagram shows Figure 3. After determining the measuring distance from the source of the electrostatic charge, the fluxmeter measures its electrostatic potential in [V]. Test was done by electrostatic field meter EFM51. This electrostatic field meter has rotating chopper to measure electrostatic field.

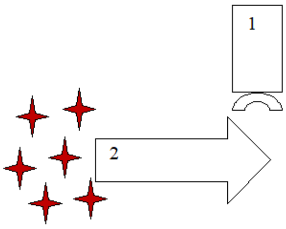

Fig. 3 Spark potential measuring circuit diagram, where: 1 – electrostatic field meter, 2 – mechanical sparks

Considering the high spark velocity and the relatively long measuring time, due to the principle of the operation of the fluxmeter, this measuring method was deemed inadequate and the results obtained deemed unreliable.

Spark electrostatic field intensity test

The second method entailed the intensity measurement of an electrostatic field generated by an electrostatic fluxmeter together with its (automatic) conversion into electrostatic field intensity in [V/m] – diagram on Figure 4.

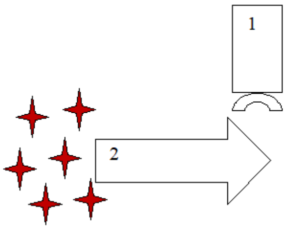

Fig. 4 Spark electrostatic field intensity measuring circuit diagram, where: 1 – electrostatic field intensity meter, 2 – mechanical sparks

In this case the experiment did not yield the expected results due to the principle of the operation of the fluxmeter and the spark velocity [19]. Test was done by electrostatic field meter EFM51.

Electrostatic charge magnitude test

The third measuring method involved the use of an electrostatic property testing method that is common and well-known in mining. The method, according to standard EN 80079-36 [16], involves the electrification of a tested element and the performing of a controlled electrostatic discharge towards a spherical electrode connected to a capacitor – Figure 5. A voltage measurement is conducted on the capacitor. The amount of the electrostatic charge collected on the capacitor in [C] is determined from the ratio of the capacitor capacity and voltage [20].

When considering the law of conservation of energy, it should be assumed that mechanical sparks of a specific electrostatic potential are projected onto an insulated metal sheet (with electrostatic potential equal to 0 V). The electrostatic charge is transferred from the sparks to the sheet. As a conductor, the sheet is capable of carrying electric and electrostatic charges, which makes it possible to easily transfer the entire electrostatic charge from the sheet to the condenser.

As follows from the law of conservation of energy, the total charge collected on the condenser is equal to the charge on the sheet, which in turn is equal to the charge carried by the sparks that were projected onto the sheet. The method for testing electrification ability and measuring electrostatic charges collected on a measuring condenser is commonly employed in hard coal mining to assess the degree of product electrification. All materials are capable of electrification. The purpose of the test method, as per standard EN 80079-36 [16], is to assess the magnitude of an electrostatic charge generated on a product and to compare it to a boundary value – the amount of charge that is capable of igniting an explosive atmosphere. Transferred charge was collecting on metal plate, which was used as capacitor. Charge from metal plate was collected to electrode with capacitor, whose capacity was 0.1 µF. Voltage on capacitor was tested by electrostatic voltmeter with range 0 V to 10 V and input resistance higher than 10^9 Ω. Electrostatic charge was calculated by voltage on it and its capacitance. Tested transferred electrostatic charge of stream of sparks is about 10 nC. It means that this charge can be an effective ignition source for group I or IIC explosive atmospheres, described in [17].

Electrification ability test

The fourth method of measuring spark electrostatic parameters entailed the measurement of the electrostatic voltage (Fig. 6) generated by the sparks. The measuring circuit was similar to the circuit described. It was assumed that the mechanical friction-induced [21] sparks would be projected onto a metal sheet insulated from the ground and connected to an electrostatic voltmeter with high input impedance. An input impedance greater than 100 TΩ ensures that any losses on account of the electrostatic voltmeter are minor and it also enables the measurement of such small and short surges in the first place. A standard electric voltmeter would not be sufficient for this type of measurement.

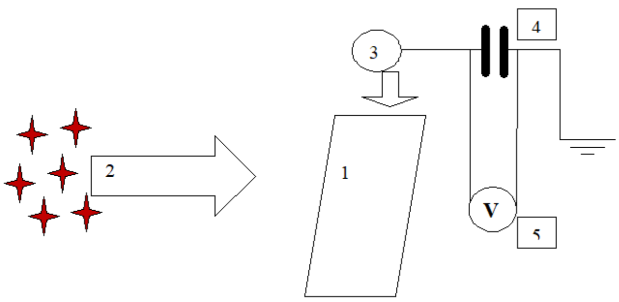

Fig. 5 Spark electrostatic charge magnitude measuring circuit diagram where: 1 – metal plate, 2 – mechanical sparks, 3 – electrode, 4 – capacitor, 5 – electrostatic voltmeter

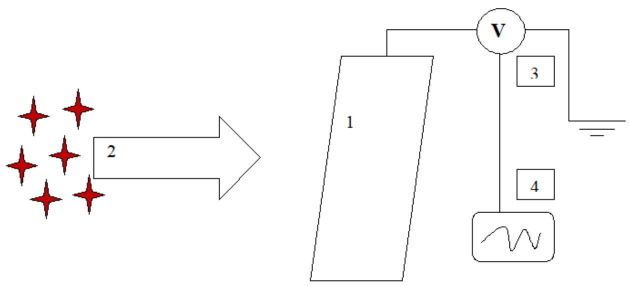

Fig. 6 Spark electrification ability measuring circuit diagram where: 1 – metal plate, 2 – mechanical sparks, 3 – electrostatic voltmeter, 4 – osciloscope

The electrification ability measuring circuit (together with the electrostatic voltmeter) is employed in the walking test as defined in standard EN 61340 [15]. The test entails the measurement of electrostatic voltage generated on the human body.
The electrification ability measuring circuit using an electrostatic voltmeter and insulated metal sheet involves the measurement of the electrification produced by sparks that collide with the sheet (contact and friction electrification). Voltage on plate was tested by electrostatic voltmeter with range 0 V to 500 V and input resistance higher than 10^9 Ω

RESULTS OF RESEARCH

Four described in this paper measuring circuits were designed and assembled as part of the work. Measurements of four different electrostatic parameters of sparks were conducted using the circuits.
An analysis of the obtained results suggests that not all of the designed test methods are adequate and suitable for the assessment of spark electrostatic properties.
Direct methods, involving spark stream measurements, are characterised by errors related to the phenomenon dynamics – spark velocity is much greater than the electrostatic fluxmeter measuring rate.
Intermediate methods, involving the electrification of an insulated metal sheet by means of spark projection, do not provide a direct result concerning spark electrostatic properties, but instead offer data about an object (the sheet) electrified by the sparks.
The Table 2 presents a compilation of the maximum measurement values obtained according to the methods described in the article.

Table 2
Spark electrostatic property measurement results

Parameter	Result	Unit
Spark electrostatic potential test	-51	V
Spark electrostatic field intensity test	0.43	kV/m
Electrostatic charge magnitude test	10	nC
Electrification ability test	-40	V

By analysing the results in Table 2, it can be concluded that the measurements entailing electric induction by means of an electrostatic fluxmeter provide understated values. Four measured parameters determine a completely different electrostatic spark properties, hence it is hard to compare them. It seems that the measurement of the spark stream is not reliable, because the stream can have different forms and density. The EFM51 meter only measures in a specific space around it. In the author's opinion, the last two methods are reliable, which determine the entire stream, because all sparks fall on the measuring electrode, and the assessment is comprehensive.
The results obtained by means of intermediate measurements provide real values. This is guaranteed by the measuring method, as the measurement includes the entire spark stream.

DISCUSSION

Measurements of dynamic electrostatic parameters are not easy. Most of the phenomena accompanying dynamic processes, such as cutting, impact or friction, are impossible to model due to their dynamic character.
Work was undertaken at the Central Mining Institute to verify whether mechanical friction sparking results in the presence of a friction-induced electrostatic charge on the generated sparks, or whether all the energy of the sparks is thermal and related to their temperature.
The work was of an experimental nature, and its result could be the conclusion regarding the impossibility of performing such tests.
Four methods that provide the highest chances of accomplishing the experiment and performing the measurements were selected based on a literature analysis.
The two proposed methods involving the measurement of the electric potential and the electrostatic voltage of the spark stream did not yield the expected results. The faults of this system included the high spark stream velocity and the slow measuring instrument response time.
The other two methods determine the actual electrostatic charge level exhibited by the spark stream.
The charge level expressed in coulombs can be directly transposed into the minimum explosive atmosphere ignition energy.

CONCLUSIONS

As a result of the measurements conducted under various generated spark configurations, the following results were obtained:

1. The spark stream electrostatic field intensity measurement does not register any values, which consequently means that this measuring circuit is not suitable for assessing mechanical spark electrostatic properties,
2. The spark stream electric potential measurement does not register any values, which consequently means that this measuring circuit is not suitable for assessing mechanical spark electrostatic properties,
3. An insulated metal sheet exposed to a spark stream was capable of collecting an electrostatic charge, which was subsequently collected on a condenser by means of a controlled electrostatic discharge, and the electric voltage on the condenser was then measured. Under no circumstances did the determined electrostatic charge exceed a value of 10nC, which constitutes a safe value that is incapable of initiating methane explosion [21], as per applicable laws.
4. The electrostatic potential measurement of the metal sheet exposed to sparks yielded results at a level of – 0 V and continued to increase together with the spark generation time.

The electrostatic charge magnitude measurement method is well-known, and testing conducted at the Central Mining Institute has proven its suitability for measuring the amount of electrostatic charge carried by sparks [23].

The electrification ability test method was developed at the Central Mining Institute. Testing conducted at the Central Mining Institute has also proven the method's suitability for spark stream electrostatic parameter determination. A setup for the mechanical spark test with a suggested performance method was submitted as a patent claim to the Patent Office of the Republic of Poland [24].

REFERENCES

[1] Y. Yong, H. Younghui, W. Lijuan, Q. Xiangchen, Z. Wenbiao, R. Kamel, W. Jiali, Z. Ge. "Electrostatic sensors – their principles and applications." *Measurement*, vol. 169 (108506), pp. 1-83, 2021.

[2] R. Blacker, A. Birley. "Electrostatic charge occurrence, significance and measurement." *Polymer testing,* vol. 10, pp. 241-262, 1991.

[3] A. Bailey. "The charging of insulator surfaces." *Journal of Electrostatics*, vol. 51-52 pp. 82-90, 2001.

[4] X. Chaulong, W. Shimin, T. Guanhua, Y. Daoye, Z. Bin. "Sensing characteristics of electrostaticinductive sensor for flow parameters measurement of pneumatically conveyed particles." *Journal of electrostatics*, vol. 65, pp. 582-592. 2007.

[5] F. Vera, M. Ortiz, D. Romero-Maltrana, A. Horta-Rangel. "Using capacitors to measure charge in electrostatic experiments." *The physics teacher*, vol. 56, pp. 525-527, 2018.

[6] M. Murtomaa, S, Strengell, E. Adrian, A. Bailey. "Measurement of electrostatic charge of an aerosol using a grid-probe." *Journal of Electrostatics*, vol. 58, pp. 197-207, 2003.

[7] Sz. Ptak, A. Smalcerz, P. Ostrowski. "Feasibility study on the use of fast camera and recording in time-domain to characterize ESD." *MATEC Web of Conferences* 247, 00028, 2018.

[8] Y. Soong, T.A. Link, M.R. Schoffstall, L. Turcaniova, P. Balaz, S. Marchant, R.R. Schehl. "Triboelectrostatics Separation of mineral matter from slovakia coals." *Acta Montanistica Slovaca*, vol. 3, pp. 393-400,1998.

[9] P. Kędzierski. "Review of electrostatic hazards in hard coal mining." *Mining – Informatics, Automation and Electrical Engineering*, vol. 2, pp. 534, 2018.

[10] A. Fernandez-Pello. "Wildland fire spot ignition by sparks and firebrands." *Fire safety Journal*, vol. 91, pp. 2-10, 2017.

[11] K. Wingerden. "Mechanical sparks as an ignition source of gas and dust Explosion". *Chemical engineering Transaction*, vol. 77, pp. 133-138, 2019.

[12] S. Trenczek, R. Mann, E. Krause. "Mining the sparking rocks in the context of most frequent cases of methane ingition." *New trends in production engineering*, vol. 2, pp. 460-471, 2019.

[13] S. Trenczek. "Methane ignitions and explosions in the context of the initials related to technical and natural hazards." *Przegląd Górniczy*, vol. 2, pp. 87-88, 2015.

[14] Z. Grabarczyk, A. Kurczewska. „Wyładowania elektrostatyczne" in *Zagrożenia elektrostatyczne w strefach zagrożonych wybuchem*. Warszawa, Polska: CIOP PIB, 2008.

[15] P. Holdstock. "A review of electrostatic standards." *Journal of Electrostatics*, vol.115, pp. 103652, 2002.

[16] PN-EN IEC 61340-4-5:2018, Electrostatic Part 4-5: Standard test methods for specific applications – Methods for characterizing the electrostatic protection of footwear and flooring in combination with a person.

[17] PN-EN ISO80079-36:2016, Explosive atmospheres – Part 36: Non-electrical equipment for explosive atmospheres – Basic method and requirements.

[18] K. Makhudov. "Wire-free method of measurement s of weak electrostatic values under stationary and dynamic conditions." *Journal of physics: conference series*, vol. 1400, pp. 077057, 2019.

[19] M. Noras. "Measurement of flowing charges with an electrostatic voltmeter." *Eenrgy Procedia*, vol. 4, pp. 2714-2716, 2004.

[20] M. Noras. "Non-contact surface charge/voltage mauserement." *Capacitive Probe*, vol. 3001, pp. 1-8, 2002.

[21] R. Kacprzyk. A. Pelesz. "Human body electrification in vicinity of charged container – medium charge density limits." *Journal of Electrostatics*, vol. 115 pp. 103658, 2022.

[22] L. Bowen. L. Yanzhong. "Flow electrification characteristics of hydrogen in pipe flow." *International Journal of Hydrogen Energy*, 2023

[23] N. Gharib. J. Derakhshandeh. P. Radziszewski. "Chapter 5 – charging techniques and measurement." In *Electrostatic Dust Mitigation and Manipulation Techniques for Planetary Dust*. Elsevier, 2023.

[24] P. Kędzierski. "Stanowisko do badania właściwości elektrostatycznych iskier mechanicznych" PL Patent P.430643, 2019.

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