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SELECTION OF DESIGN FEATURES AND CONFIGURATIONS OF THE CORONA ELECTRODES OF INDUSTRIAL ELECTROSTATIC PRECIPITATORS USED IN POWER INDUSTRY

Key words: electrostatic precipitator, discharge electrode, emissivity, migration velocity.

Abstract: The article presents the studies results of corona electrodes used in industrial electrostatic precipitators (ESP). For selected types of mast electrodes, measurements of their electrical parameters have been performed. Based on the analysis of measurement data, the effect of the geometry (shape and position emission elements) on the emissivity of the discharge electrode was established. The influences of the geometry and configuration of the electrodes on the current density distribution at the surface of the collecting electrodes of an ESP have also been investigated. The results were based on the determined change of the power spectral density magnitude *PSD* (*Power Spectrum Density*) as a function of the distance between the emission electrodes and the distance between the electrodes. This allows the selection of the corona electrodes geometry and their configurations to ensure high efficiency electrostatic precipitator. ESP efficiency and migration velocity of fly ashes from industrial combustion of fuels were studied, including lignite, coal, mixed coal with biomass, and biomass. The data obtained allowed the determination of indicators for the selection of the geometry of the discharge electrode, depending on the physicochemical properties and concentrations of separated fly ashes.

Wybór cech konstrukcyjnych i konfiguracji elektrod ulotowych w elektrofiltrach przemysłowych wykorzystywanych w energetyce

Słowa kluczowe: elektrofiltr, elektroda ulotowa, emisyjność, prędkości migracji.

Streszczenie: Artykuł przedstawia wyniki badań elektrod ulotowych wykorzystywanych w przemysłowych elektrofiltrach (ESP). Pomiary parametrów elektrycznych przeprowadzono dla wybranych typów elektrod masztowych. Na podstawie analizy danych pomiarowych ustalono wpływ geometrii (kształt i położenie elementów emisyjnych) na emisyjność elektrod emisyjnych. Zbadano także wpływ geometrii i rozmieszczenia elektrod na rozkład gęstości prądu na powierzchni jego elektrod zbiorczych w ESP. Wyniki bazowały na ustalonej zmianie magnitudy gęstości widmowej mocy (PSD) jako funkcji odległości pomiędzy elektrodami emisyjnymi raz odległości pomiędzy tymi elektrodami. Umożliwiło to wybór korzystnych parametrów geometrycznych i konfiguracji elektrod ulotowych w celu zapewnienia wysokiej efektywności elektrofiltru. Przeanalizowano efektywność ESP i prędkość migracji popiołów lotnych powstałych w wyniku spalania paliw: węgla brunatnego, węgla, mieszanki węgla i biomasy oraz biomasy. Uzyskane wyniki umożliwiły wyznaczenie warunków selekcji parametrów geometrycznych elektrody emisyjnej, w zależności od właściwości fizykochemicznych i koncentracji rozdzielonych popiołów lotnych.

Introduction

Electrostatic methods of flue gas cleaning are commonly used in the energy sector (coal fired power plants) [1] and many industries, e.g., heat production, metallurgy, chemical plants, cement and paper production and so forth. In power plants, due to the amount of exhaust gas generated during the production, the only reasonable economic solution is gas purification using electrostatic precipitators (ESP-s).

ESP-s are structures, which are designed for use in the specific energy installation. The selection of the ESP design, corona electrodes, collection electrodes, and power systems, are determined by the type of boiler and the type of fuel combustion in the boiler, and consequently, the properties of the resulting fly ashes, which are separated in the ESP.

Combustion of types of fuel other than the one for which the individual devices were designed, for example, burning coal of different chemical compositions [2] or the addition of additives to the primary fuel, i.e. biomass, will disturb the fly ash collection process. Action to meet the conditions for proper operation of the ESP can be divided into two basic groups. The first of these are issues related to the design of ESP [3], and in particular, the selection of discharge and collecting electrodes [4, 5, 6]. The electrode arrangement must meet the criteria of the principle of the operation of the electrostatic precipitator, i.e. allowing the generation of the required electric field and its distribution in the space between electrodes [7, 8, 9].

The requirements for the correctness of mechanical design, mechanical strength (including resistance to corrosion), division for collection zones, and sections of joint regeneration devices, as well as high voltage power supply must be fulfilled.

The second group is the activities involved in the technological process, which is the source of the fly ash. They result from the characteristics of the aerosol, i.e. pressure and temperature, the chemical composition of collected fly ash, the particle size distribution, shape and resistivity [10, 11], and the surface properties of the ash particles [12]. Hence, in the design and selection of equipment, it is necessary to know the characteristics and properties of fly ash, including their changes in the technological process [13]. The main criterion for the selection of the configuration of discharge and collecting electrodes of an electrostatic precipitator is to achieve such conditions that the ash grains entering the electrostatic chamber obtain an electrical charge sufficient for their migration and deposition on the collecting electrode.

The main role is played by charge transfer processes from gas ions to fly ash grains. The source of gas ionization phenomena lies in the proximity of the discharge electrode, and more specifically from points on its surface, which develop an electron avalanche.

The charged fly ash particles move towards the collecting and corona electrodes. The vast majority of dust particles are negatively charged and deposited on the grounded collecting electrodes with positive potential.

Due to the strength criteria, contemporary-operated electrostatic precipitators are equipped mainly with mast type corona electrodes. These electrodes have a circular cross section of the supporting mast with welded emission elements, which are the source of the corona discharge [14].

The article presents the results of research conducted for three selected industrial mast types of corona electrodes:

– SPIKE, type with elements in the form of sharpened rods $Ø = 4$ mm and length $L = 100$ mm;
– DELTA, shape of emission elements is delta (Δ) with a height of 70 mm made of steel rod having a diameter of $Ø = 4$ mm; and,
– U-type with emission elements in a U-shape, made of steel wire with a diameter of $Ø = 4$ mm. The height of the emission element is about 100 mm, and the bending radius is about 25 mm.

The diameter of the supporting mast in the case of all electrodes was the same and was $Ø = 40$ mm.

1. Research methodology

For each of the three mast type electrodes, the following electrical parameters were investigated:

– Current-voltage characteristics (changes in current as a function of electrostatic voltage applied to the electrode), and
– Current density at the surface of the collecting electrode.

The study of electrical parameters of discharge electrodes were carried out on a test station and the schematic is shown in Fig. 1.

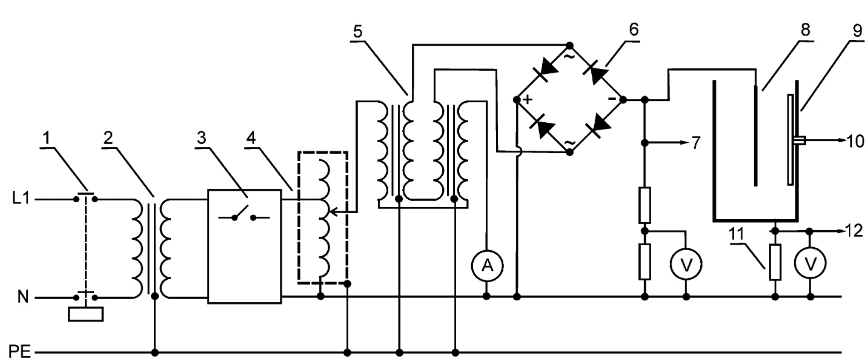

Fig. 1. Schematic of the equipment to test corona electrode parameters: 1 – switch power supply circuits, 2 – isolation transformer, 3 – circuit for over-current protection, 4 – high voltage control loop, 5 – set of high voltage transformers, 6 – set of HV rectifiers, 7 – HV measuring circuit, 8 – corona electrode, 9 – collecting electrode, 10 – current measuring circuit (current density at the surface of collecting electrode), 11 – decade resistor, 12 – current measuring circuit (I-U characteristic)

Current-voltage characteristics show the intensity of the electric field generated by the discharge electrode. The intensity of the electric field affects the time for obtaining the fly ash particles charge allowing them to migrate and deposit on the collecting electrode. The current density on the surface of the collecting electrode affects the mechanical properties of the deposited dust layer on the surface of the collecting electrode. The value of current density at the surface of the collecting electrode is affected by the emissivity of the electrode and the conductance of two-phase medium present in the inter-electrode space for a particular electrode configuration. Current-voltage characteristics are determined by recording the voltage at the discharge electrode and the current in the inter-electrode space. The value of this current is calculated from the voltage drop across grounded decade resistor box (11 Fig. 1). Voltage signals from the voltage measuring circuit of a discharge electrode and the current flowing between the electrodes and the ground of the circuit is fed to the input of the NI USB-6039 card connected with the computer.

The measurement is conducted for supply voltages of the discharge electrode in the range of 0-75 kV. For each of the measuring points, measured in increments of ΔU = 500 V, the card working with a sampling rate of 2 kS/s registers the average value of the measured voltages. The program for the acquisition enables the visualization of the data recorded on-line. The recorded data is stored in a file in order to undergo further analysis. Current density distribution at the surface of collecting electrode is determined on the same station. The circuit diagram of measurement is shown in Fig. 2. On the surface of the collecting electrode (1) is 16 measuring fields (2) arranged with a constant interval.

The currents flowing between each of the sensors and ground are provided by the multiplexer 16 to 1 to the measuring amplifier, build on the integrated circuit INA 114 Burr-Brown. The measuring signals are switched sequentially. The amplified signal is recorded by measuring card NI USB-6039 using a computer. Data are recorded five times in the cycle, which means that the measured value of the current corresponding to the value of current flowing through each of the measurement field is the average of the 10 000 measurements.

Analyses of the current density distribution on the surface of the collecting electrode were performed using a program developed for this purpose with advanced statistical functions, serving for the time series analysis TSA (Time Series Analysis) of the LabView program [15]. This program, after the initial processing of measured data, allows their smoothing determining for the analysed magnitude of power spectral density *PSD* (*Power Spectrum Density*), time series X_t.

For the calculation of the power spectrum and power spectral density, the procedures contained in the libraries of the LabView program were used.

Analysis of the measurement results allowed the determination of the effect of the distance between the

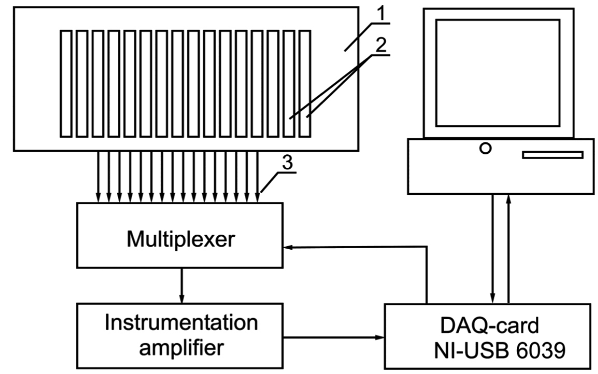

Fig. 2. Schematic of the circuit current density distribution measurements on the surface of the collecting electrode, 1 – collecting electrode, 2 – measurement fields, 3 – measurement signals

emission elements of a single electrode – *dI* and the distance between the electrodes – *H* on the electric field parameters in the chamber of precipitator.

Combustion efficiency was studied for selected best geometry and electrode configuration migration velocity and the collection of fly ash coming from industrial fuels, including the following:

– Lignite,
– Coal,
– A mixture of coal and biomass, and
– Biomass (fuel of vegetable origin).

The migration velocity is the speed at which the fly ash particles (having an electrical charge) advance in the inter-electrode space in the direction of the electrostatic precipitator-collecting electrode. Migration of the particles are the result of the following forces: the flow of the gas, gravity forces, the resistance of the gaseous medium, forces induced by the grains polarization, and especially the reaction of grain charge with the electric field. Knowing the migration velocity, the ESP efficiency can be determined using the Deutsch equation (1):

$$\eta = 1 - e^{-\frac{w_m \cdot L}{h \cdot v}} \tag{1}$$

where
η – collection efficiency,
L – the length of the electric field [m],
h – distance between different poles electrodes [m],
v – gas velocity [m/s],
m – migration velocity [m/s].

This equation takes into account the parameters of the electrical, geometrical, and aerodynamic characteristic of ESP. Although it was derived assuming a number of simplifications, it is still useful in the practice of design.

Research on the migration velocity of fly ash from coal combustion was carried out in the laboratory plate electrostatic precipitator with the following parameters:

- The active length of the chamber: 2 m;
- The height of chamber: 1 m;
- The inter-electrode pitch: 400 mm;
- Collecting electrode: flat;
- Corona electrodes: replaceable, matched to specific measurements;
- Gas flow rate: 0.1 m/s to 0.8 m/s;
- The source of fly ash: fluidized bed chamber fed from a source of compressed air; and,
- The administration of fly ash: the vertical system of nozzles in the area of the inlet of the ESP.

Because the multi-zone electrostatic precipitator concentration of fly ash in the medium is varied, testing was performed for four fly ash concentrations in the range of 2.7–7.2 g/m^3. During studying the electrostatic fly ash separation in the laboratory, it was established that a voltage supply of discharge electrodes and the parameters of movement of the medium through the chamber as for discharge electrodes of highest emissivity dust particle migration velocity did not exceed 1 m/s.

Almost all manufacturers of the currently operated electrostatic precipitators use the inter-electrode scale (the distance between the collection electrodes) H_z = 400 mm. Reducing the distance between the collecting electrodes allows for high current density in the inter-electrode space. This gives higher migration velocity of the dust, which affects the effectiveness of the fly ash collection process. However, with the reduction of H_z scale, the number of sparks in space between the electrodes is growing, consequently lowering the efficiency of the ESP. Due to the fact that the commonly used industrial electrostatic precipitator scale size H_z between collecting electrodes is strictly defined, a study of geometrical features and configurations of the corona electrodes on the combustion gases treatment was carried out for scale H_z = 400 mm.

2. Test results

2.1. The electrical parameters of discharge electrodes

The electrical parameters of mast type industrial electrodes determined on the basis current-voltage characteristics and the value of the initial corona voltage are shown in Table. 1.

Table 1. Electrical parameters and initial corona voltage of the mast electrodes

Electrode	Emissivity	Initial corona voltage U_0, [kV]
spike	high	8.0
DELTA	low	39.0
U-type	very low	44.5

Based on current density distribution *J* on the surface of the collecting electrode measurement, one can determine the electrode configurations and geometries in a way that yields high current density. At the same time, the distance between the corona electrodes should be selected in a way that the current density distribution along a collecting electrode is as uniform as possible. Such optimization is possible on the basis of the magnitude of the spectral power density *PSD* as a function of distance between electrodes *H* and between emission elements *dI* of the corona electrode. The results of the analysis are shown in Figs. 3–5.

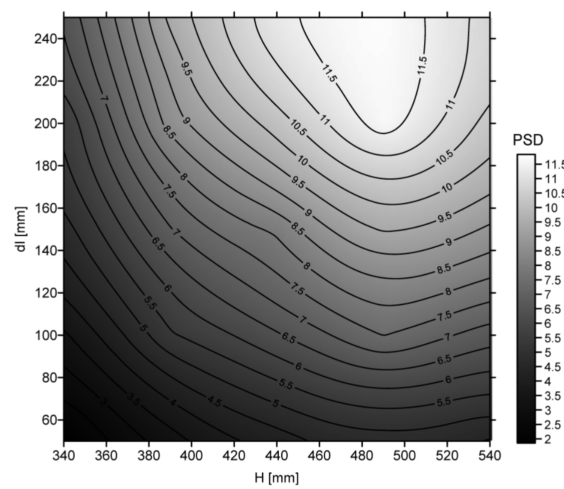

Fig. 3. The magnitude of the power spectral density *PSD* as a function of the distance between electrodes *H* and the distance between emission elements *dI* for spike type electrodes

The results of current density distribution on the surface of the collecting electrode show that, with an increasing distance between electrodes H and the distance between emission elements dI for spike type electrodes, the corona electrode maximum *PSD* value corresponds to the scale *H* = 490 mm (Fig. 3). Increasing the distance between the emission elements of the electrode affects the growth of the current density *J*. The maximum value of this current is for the inter emission elements distance *dI* = 250 mm. At the same time, an increase in the distance between the corona electrodes causes a decrease in the value of current density at the surface of the collecting electrode in the axis of corona electrodes symmetry.

In case of DELTA type electrodes, increasing the distance between the emission electrodes affects the growth of the current density *J* (Fig. 4). The maximum *PSD* value of the current density distribution at the surface of the collecting electrode corresponds to the scale H = 500 mm and *dI* = 250 mm. The increase in the distance between the corona electrodes causes a decrease in the value of current density on the surface of the collecting electrode at the axis of symmetry of the corona electrodes.

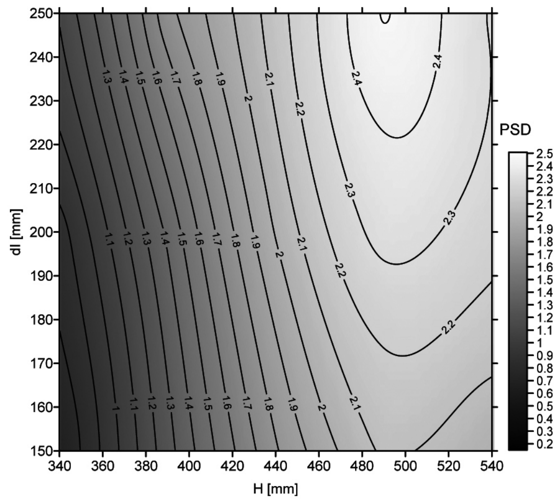

Fig. 4. The magnitude of the power spectral density *PSD* as a function of distance between electrodes *H* and distance between emission elements *dI* for a DELTA type electrode

Analysis of changes in the magnitude of power spectral density *PSD* as a function of inter electrode and inter emission elements scale of the U-type electrode indicates that the increase in the distance between the corona electrode and the distance between the emission elements cause an increase in the value of the *PSD* for the studied group of electrodes (Fig. 5). With the increase of the distance between the corona electrodes, there are increases in the current density *J*. The maximum *PSD* value of the current density distribution at the surface of the collecting electrode corresponds to the scale *H* = 540 mm and *dI* = 220 mm. The increase in distance between the corona electrodes causes a decrease in the value of current density on the surface of the collecting electrode at the axis of symmetry of the corona electrodes.

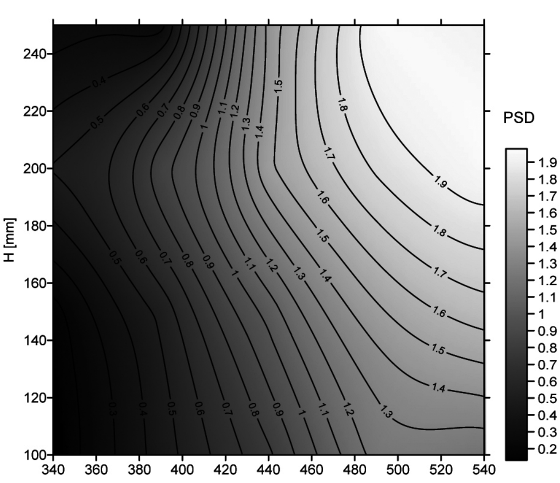

Fig. 5. The magnitude of the power spectral density *PSD* as a function of distance between electrodes *H* and distance between emission elements *dI* for a U-type electrode

2.2. The migration velocity of fly ash and ESP efficiency

The migration velocity is conditioned by the distribution and intensity of the electric field in the ESP chamber, and, based on its value, one can determine the future operating parameters of the ESP. The migration velocity is due to the properties of the electric field in the inter-electrode space and the physicochemical properties of the medium gas-dust. Therefore, the migration velocity of the fly ash in the direction of the collecting electrode of the precipitator was adopted as a criterion for selecting the type of the discharge electrode. The values of the migration velocity are presented in Tables 2 and 3. In Tables 2–5, the fly ash samples are marked as follows: *FA1* – lignite, *FA2* – coal, *FA3* – a mixture of coal and biomass, and *FA4* – biomass.

Table 2. The migration velocity of fly ash particles in the laboratory ESP for fly ash concentrations s < 5 g/m³

Electrode type	The migration velocity [m/s], fly ash particles concentrations s<5 g/m³			
	Symbol of the fly ash sample			
	FA1	*FA2*	*FA3*	*FA4*
spike	0.65	0.79	0.62	0.73
DELTA	0.49	0.57	0.45	0.38
U-type	0.43	0.56	0.49	0.38

Table 3. The migration velocity of fly ash particles in the laboratory ESP for fly ash concentrations s > 5 g/m³

Electrode type	The migration velocity [m/s], fly ash particles concentrations s<5 g/m³			
	Symbol of the fly ash sample			
	FA1	*FA2*	*FA3*	*FA4*
spike	0.64	0.59	0.64	0.53
DELTA	0.35	0.53	0.35	0.53
U-type	0.35	0.53	0.38	0.36

The results of the relative efficiency of the laboratory ESP calculated using the equation (1) are given in Tables 4 and 5.

Table 4. The laboratory ESP efficiency for fly ash concentrations s < 5g/m³

Electrode type	Collection efficiency [%], fly ash concentrations s <5 g/m³			
	Symbol of the fly ash sample			
	FA1	*FA2*	*FA3*	*FA4*
spike	99.56	99.86	99.43	99.77
DELTA	98.31	99.13	97.65	95.78
U-type	97.22	99.06	98.31	95.78

Table 5. The laboratory ESP efficiency for fly ash concentrations s > 5 g/m³

Electrode type	Collection efficiency [%],fly ash concentrations s >5 g/m³			
	Symbol of the fly ash sample			
	FA1	*FA2*	*FA3*	*FA4*
spike	99.52	99.27	93.61	98.79
DELTA	94.59	99.65	94.59	98.79
U-type	94.59	98.79	96.72	95.02

Studying the dust separation in the laboratory ESP, the voltage supply of discharge electrodes and the parameters of movement of the medium through the chamber was set on such a level that for the discharge electrodes had the highest emissivity, and the migration velocity of fly ash particles did not exceed 1 m/s. To the values of migration velocity, w_m was assigned weight n in the range of 1 to 10, taking as $n = 1$ for migration velocity $w_m = 0.1$ m/s and n = 10 for migration velocity of $w_m = 1$ m/s. This allowed for easy assessment of the impact of discharge electrode geometry on the efficiency of the deposition process on the surface of collecting electrode. The sum of the weights calculated for each type of electrode and types of fly ash, providing evidence for universal application, was determined from the following equation (2):

$$\sum n_p = n_{p1} + n_{p2} + n_{p3} + n_{p4} \qquad (2)$$

where
$n_{p1} - n_{p4}$ – weights for particular fly ash.

The sum of the weights was calculated from equation (3)

$$\sum n_{pp} = \frac{\sum n_p}{40} \cdot 100 \qquad (3)$$

where
n_{pp} – the sum of the weight in percentage.

Because, in a multi-zone ESP, the concentration of fly ash is varied, testing was performed for four fly ash concentrations in the range of 2.7–7.2 g/m³.

Indicators for the selection of the geometry of the discharge electrode depending on the physicochemical properties and concentrations of the fly ash are shown in Tables 6 and 7.

In these tables, ashes are marked as follows: *FA1* – lignite, *FA2* – coal, *FA3* – a mixture of coal and biomass, and *FA4* – biomass.

Table 6. The indicators for the selection of the geometry of the discharge electrode at the supply voltage 65 kV, for the fly ash at the different physicochemical properties and concentrations s < 5 g/m³

Electrode	Symbol of the fly ash sample				The sum of weights $\sum n_p$	The sum of weights in % $\sum n_{pp}$
	FA1	*FA2*	*FA3*	*FA4*		
Spike type	7	8	7	8	30	75.0%
DELTA	5	6	5	4	20	50.0%
U-type	5	6	5	4	20	50.0%

Table 7. The indicators for the selection of the geometry of the discharge electrode at the supply voltage 65 kV, for the fly ash at the different physicochemical properties and concentrations s > 5 g/m³

Electrode	Symbol of the fly ash sample				The sum of weights $\sum n_p$	The sum of weights in % $\sum n_{pp}$
	FA1	*FA2*	*FA3*	*FA4*		
Spike type	7	6	7	6	26	65.0%
DELTA	4	6	4	6	20	50.0%
U-type	4	6	4	4	18	45.0%

Conclusions

Research on the influence of the geometry and configuration of the corona electrodes on the effectiveness of ESP were targeted for industrial applications. The data obtained by measuring electrical parameters of selected corona electrodes used on an industrial scale were aimed to help design industrial ESPs used for combustion gases purification resulting in energy production.

The study showed that the parameters of the electric field in the precipitator's chamber are strongly dependent on the distance between the corona electrodes *H*. Based on the distance *H*, ranges to which the current density distribution at the surface of the collecting electrodes is most favourable were defined.

The results show that, depending on the type of the discharge electrode, the preferred distances between corona electrode *H* and emission elements *dI* are as follows:

- Spike type: 460–500 mm, 200–250 mm;
- DELTA: 480–540 mm, 190–250 mm; and,
- U-type: 500–540 mm, 220–250 mm.

In the process of designing an electrostatic precipitator, according to the adopted type of discharge electrodes, the top value of *H* should be applied. The final selection of this value, however, is dependent on the planned width of the elements constituting the collecting electrode. In addition to the selection of the voltage supplying corona electrodes in each zone of an electrostatic precipitator, the predicted mode of power suppliers and the frequency of cleaning of the collecting and corona electrode are also important.

Analysis of the results expressed as a percentage of sum weights for different types of electrodes and all types of studied dusts indicates that the established evaluation criteria is best met by spike type electrodes. The U-type electrode meets the established evaluation criteria below 50% for dust concentrations above 5 g/m^3; therefore, it does not qualify for extraction processes at these concentrations of dust in the exhaust gas. In case of the fly ash from the burning of coal at concentrations above 5 g/m^3, a change in the shape of the electrode does not change the criterion. Designated indicators for the studied types of corona electrodes and types of dust do not allow an unambiguous choice of electrodes for all kinds of dust in the full range of their concentrations. The expression using the percentage of the sum of the weights for different types of electrodes and tested dusts indicates that, at the supply voltage of 65 kV, high deposition rates are found only in mast type spike electrodes. For other types of electrodes, migration velocity in the precipitator's chamber is lower than that of the spike electrode. This particularly concerns the dust from the burning of lignite.

DELTA and U-type electrodes can be used in the last zones of the ESP. In these zones, the concentration of dust is low, and their diameters are small (≤ 10 um). The separation of fly ash with such grain sizes requires a higher supply voltage of corona electrodes. Low emissions of these types of electrodes allow increasing their power supply without disturbing the extraction process (increasing the number of sparkles in the chamber of electrostatic precipitator).

Presented results do not cover the whole issue of the selection of the corona electrodes used in electrostatic precipitators but represent only a fraction of extensive and complicated problems of electrostatic fly ash removal systems. The research results may contribute to such changes in of the mast type corona electrode design that will increase their operational advantages, while lowering their manufacturing costs.

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