Collection of low resistivity fly ash in an electrostatic precipitator

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Abstract. Due to increasing restrictions on dust emission limits (IED directive), particularly in the fine particle size range, wider application of electrostatic precipitators (ESPs) in cleaning the combustion gases from stoker boilers can be anticipated. The objective of the model studies in this paper was to select the optimal construction of the discharge electrode in ESP for obtaining high collection efficiency of fly ash leaving stoker boilers. In these studies a test bench was constructed, which comprised one-stage model ESPs with a set of discharge and collecting electrodes. The main dimensions of the precipitator chamber were as follows: length of electric field 2.0 m; active height 0.45 m and spacing between the collecting electrodes 0.4 m. Four constructions of discharge electrode were tested for fly ash of different fractional sizes and chemical compositions. The aim of the tests was to determine the current-voltage characteristics and the discharge current distribution on the collection electrode so as to find out the optimal construction and ensure the maximal collection efficiency of ESP. The results of the collection efficiency measurements in these tests were compared with those obtained from an ordinary industrial ESP. The comparison shows that it is necessary to optimise the discharge electrode construction for a specific physico-chemical property of fly ash so as to obtain the highest collection efficiency.

1. Introduction
Stoker boilers are usually equipped with mechanical dust collectors or bag filters for fly ash removal, and electrostatic precipitators (ESP) are scarcely used. More restrictive dust emission limits (under IED Directive) as well as expected requirements regarding fine particles emission (PM10 and PM2.5) will require wider application of ESPs of improved parameters for the cleaning of combustion gases after stoker boilers.

Improvement of the collection efficiency of mechanical collectors (cyclones and multi-cyclones) requires higher gas flow velocities in the collector that increases the pressure drop and shortens its lifetime. In the last years, bag filters or a combination of bag filters with cyclone were introduced after stoker boiler for exhaust gas cleaning. However, the application of such equipment for exhaust gas cleaning after stoker boiler appeared to be economically ineffective because of high cost of bag filters. For these reasons, electrostatic precipitators, which are competitive with respect to the investment and

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operational costs and can better comply with environment protection regulations, seems to be an alternative to other devices.

Fly ash leaving stoker boiler has high contents of unburned coal (8-25%). From technical literature, it is known that with an increase of unburned coal contents in fly ash, the collection efficiency of an ESP decreases. The first information about an effect of unburned coal in fly ash on ESP collection efficiency appeared in the seventieth of XX century. Hagemann and Ahland [9] have presented the results of experimental studies showing that a content of unburned coal in fly ash up to 15 % causes an increase of ESP collection efficiency, but the collection efficiency started to decrease when the coal content was higher than 20 %. Many recent studies [10, 11] also pointed out a significant influence of unburned coal on the collection efficiency of ESP. The unburned coal strongly influences the electric resistivity of fly ash, decreasing its value even below 10^9 Ω cm that has positive effect on the collection efficiency, and suppresses the back discharge. However, for too low resistivity (<10^6 Ω cm) the force of cohesion radically drops that results in particles re-entrainment and decreases the collection efficiency. It is particularly apparent for particles of diameter larger than 100 µm, for which the unburned coal content is ten times higher than in smaller particles, having diameter below 38 µm [10].

Many years of experience with industrial ESPs and proprietary studies [1-4] indicate that a proper selection of the construction of discharge electrode for a specific technological process, taking into account the physical and chemical properties of fly ash, has a significant influence on the collection efficiency of ESP.

In late ninetieth of XX century, many laboratory studies on discharge electrode constructions as well as numerical modelling of the phenomena occurring in corona discharge were carried out for different forms of the electrode spike [5-8]. The main purpose of those studies was to optimize the inter-electrode spacing, discharge electrode shape and electric supply parameters.

The aim of these studies was to determine the current-voltage characteristics and the discharge current distribution on the collection electrode so as to find the optimal discharge electrode construction, for which the collection efficiency of ESP is the highest.

2. Laboratory tests
In this section, the results of an effect of discharge electrode construction on the collection efficiency of ESP, and used for the removal of fly ash of low resistivity (due to high content of unburned coal), are presented. These studies extend and refine our earlier results presented in [1].

2.1. Current-voltage characteristics
Four discharge electrode constructions, three of which where of the RDE type (figure 1), based on results of our former studies [1-4], were proposed for the investigation.

It is shown that the construction of discharge electrode influences the collection efficiency of ESP because of different values of the discharge current specific to the electrode type. Depending on the discharge electrode construction, for the same ESP geometry and volume, by the same supply voltage it is possible to obtain different discharge currents, which maximal magnitude is limited only by the breakdown voltage. The current-voltage characteristic I=f (U) shows the relationship between the discharge (corona) current and high voltage between the discharge and collecting electrodes.

Depending on fly ash resistivity, the optimal current-voltage characteristics, particularly the required discharge current, can vary that makes it practically almost impossible to design a ‘universal’ discharge electrode for ESP. For this reason, in order to improve the charging process and increase the collection efficiency of fly ash particles, higher values of supply voltage are, therefore, advised [12-14].

In figure 2 are presented the current-voltage characteristics of various types of discharge electrodes for the spacing between collection electrodes 2h=400 mm.

Based on the current-voltage characteristics, with respect to the discharge current, the electrodes can be characterised as follows:

- high current at high voltages (‘current aggressive’ characteristics): RDE-2 and RDE-3
• high current at medium voltage: barbed tape
• medium current at high voltage (‘soft’ characteristics): RDE-1

High content of unburned coal in fly ash from stoker boilers (from several up to several dozen percents) results in low electric resistivity of fly ash layer (the resistivity was in the range of $10^7$-$10^8 \Omega \text{cm}$, measured in laboratory conditions). By this resistivity, the electric charge on fly ash particles is easily conducted to ground after the deposition of these particles onto the collecting electrodes that leads to particles reentrainment. In this case, to keep the particles on the electrode, a high discharge current and uniform current density distribution on the collecting electrode are required. The primary task is, therefore, to design a discharge electrode, which generates high discharge current and ensures high magnitude of electric field over the collection electrode. With respect to discharge current, the ‘current aggressive’ discharge electrodes (RDE-2 and RDE-3) are recommended. However, these electrodes not always can ensure the desired uniform current distribution.

![Figure 1](image1.png)  
**Figure 1.** Tested discharge electrodes: a) RDE-1; b) RDE-2; c) barbed tape; d) RDE-3 (dimensions in mm).

2.2. Current distribution on collecting electrode

![Figure 2](image2.png)  
**Figure 2.** Current-voltage characteristics of the tested discharge electrodes.

![Figure 3](image3.png)  
**Figure 3.** Scheme of laboratory bench for measuring discharge current distribution on the collecting electrode surface: 1-collecting electrodes, 2-high voltage supply unit, 3-picoammeter, 4-moving measuring probe, 5-measuring area, 6-discharge electrodes (dimensions in mm).
Measurements of discharge current distribution on collecting electrode have been carried out on laboratory bench with a moving current-measuring probe (figure 3). Examples of the measurements are shown in figure 4 for RDE-2 and RDE-3 electrodes.

![Figure 4](image1.png)

(a)

![Figure 4](image2.png)

(b)

**Figure 4.** Discharge current distribution on the collecting electrode surface for: (a) RDE-2 electrode, (b) RDE-3 electrode, by a supply voltage of U=50 kV.

From these measurements results that the RDE-2 electrode is characterized by relatively uniform coverage of the collecting electrode by discharge current, by low relative standard deviation (RSD) of its values, and also ensures the highest average value of the discharge current as compared to the others three constructions by the same supply voltage. With this respect, the worst construction seems to be the RDE-3 electrode, providing poor uniformity of coverage of the collecting electrode with discharge current, by high RSD, and low average discharge current.
Various fly ashes from different stoker boilers have been collected for the measurements of collection efficiency of ESP. The coal burned in these boilers had the granulation of larger than 10 mm that significantly influenced the structure of fly ash and particle size distribution. In table 1 are given the physical and chemical properties of the tested fly ashes, in particular, unburned coal content, and content of alumino-silicates, iron compounds, and SO₃. Figure 5 presents cumulative size distribution curves for fly ash particles entering the ESP, determined by Mastersizer S (Malvern Instruments Ltd.), operating on a principle of laser light scattering on the measured dust particles. The presented characteristics show considerable differences in fly ash particle size distribution, depending on particle source. Usually when multi-cyclone is used as the first stage of dust control, nearly all larger fly ash fractions are precipitated in it, and only small particles enter the ESP. For example, the fly ash sample P-3 (after a multi-cyclone) has the median diameter $d_{50}=20\,\mu\text{m}$, and fly ash sample P-2 (without first-stage cleaner) $d_{50}=200\,\mu\text{m}$. Fly ashes P-1 and P-17 contain mainly larger particles, and characteristic diameters are $d_{50}=250\,\mu\text{m}$ and $d_{50}=560\,\mu\text{m}$, respectively. These fly ashes contain less unburned carbon and more silica than ash P-2 and P-3 and, furthermore, fly ash P-1 contains a minimum of unburned carbon (ca 13.8 %) and is characterized by higher resistivity ($10^8 \,\Omega\text{cm}$) than the others.

The studies had also proved that the content of unburned coal in fly ash changes with the particle diameter and gets the highest value for fractions above 126 $\mu\text{m}$. For example, for fly ash sample P-2 the content of unburned coal was: $d<32\,\mu\text{m}–23\%$, $d=32–80\,\mu\text{m}–22\%$, $d=80–125\,\mu\text{m}–18\%$, $d>125\,\mu\text{m}–37\%$, respectively.

![Figure 5. Cumulative size distribution of fly ash particles at ESP inlet.](image)

**Figure 5.** Cumulative size distribution of fly ash particles at ESP inlet.

![Figure 6. Scanning electron microscope micrographs of fly ash particles: (a) sample P-2: particles of irregular shapes and dimensions. (b) sample P-1: in the central area is visible irregular particle of high coal contents (magnification 230x).](image)

**Figure 6.** Scanning electron microscope micrographs of fly ash particles: (a) sample P-2: particles of irregular shapes and dimensions. (b) sample P-1: in the central area is visible irregular particle of high coal contents (magnification 230x).
The fractional particle size distribution analysis determines only one geometric parameter of fly ash – its equivalent diameter, regardless of the method of measurement used. The actual shape of fly ash particles is rarely spherical (figure 6), which also affects the process of their separation in ESP. For the analysis of collection efficiency of ESP it is essential to take into account the content of fly ash particles of irregular shape and porous large unburned coal particles, which favor the particle re-entrainment from the collecting electrode [15].

**Table 1.** Analysis of physical and chemical properties of fly ashes from selected stoker boilers.

| Parameter         | Unit | P-1    | P-2    | P-3    | P-17   |
|-------------------|------|--------|--------|--------|--------|
| SiO₂%             | %    | 47,44  | 28,99  | 28,64  | 40,39  |
| Fe₂O₃%            | %    | 6,91   | 3,67   | 8,62   | 10,01  |
| Al₂O₃%            | %    | 19,65  | 17,14  | 18,06  | 18,09  |
| TiO₂%             | %    | 0,99   | 0,86   | 1,09   | 0,96   |
| CaO%              | %    | 3,98   | 2,82   | 2,84   | 5,44   |
| MgO%              | %    | 1,41   | 1,01   | 0,98   | 1,47   |
| SO₃%              | %    | 0,73   | 2,26   | 6,48   | 1,27   |
| K₂O%              | %    | 3,03   | 2,68   | 2,48   | 2,08   |
| P₂O₅%             | %    | 0,01   | 0,01   | 0,01   | -      |
| Na₂O%             | %    | 1,33   | 1,14   | 1,17   | 1,47   |
| Unburned carbon   | %    | 13,77  | 28,60  | 27,72  | 17,92  |
| Density           | kg m⁻³| 1850   | 2090   | 2350   | 1760   |
| Resistivity       | Ω⋅cm | 5,1×10⁸ | 5,0×10⁷ | 6,4×10⁷ | 5,0×10⁷ |

2.4. Collection efficiency measured in laboratory conditions

The test bench (figure 7) comprises of model ESP with discharge and collecting electrode system, fly ash feeding system, exhaust gas fan, supplying and drain-off gas ducts, high voltage supply unit and outlet filter. The main dimensions of the model ESP are: length of electric field L=2000 mm, height of the field H=450 mm, collecting electrode spacing 2h=400 mm and distance between the discharge electrodes s=170 mm.

**Figure 7.** Scheme of laboratory ESP test bench: 1–fly ash feeder, 2–model chamber, 3–collecting electrodes, 4–discharge electrodes, 5–gravimetric dust-meter, 6–thermo anemometer, 7–exhaust gas fan with controlled rotational speed, 8–outlet filter, 9–high voltage supply (of negative polarity).
A fly ash collection efficiency tests were carried out at the stand shown in figure 7 in order to determine the effect of physico-chemical properties of fly ash, in particular, its resistivity, and fractional size distribution on the ESP collection efficiency. The collection efficiency has been measured for four different fly ash samples, collected from stoker boilers, and also for four constructions of discharge electrode. For each magnitude of supply voltage, three test of the collection efficiency have been carried out.

The total collection efficiency was estimated from the measured fly ash mass at the inlet and the outlet of ESP and calculated from the following formula:

$$\eta_c = 1 - \frac{\dot{m}_{out}}{\dot{m}_{in}}$$  \hspace{1cm} (1)

where: $\dot{m}_{in}$ – mass flow rate of fly ash at the inlet of ESP, g s\(^{-1}\); $\dot{m}_{out}$ – mass flow rate of fly ash at the outlet of ESP, g s\(^{-1}\).

Figure 8. The effect of supply voltage on average collection efficiency of ESP for four constructions of discharge electrodes, and four samples of fly ash: (a) P-1, (b) P-2, (c) P-3, (d) P-17 (air flow velocity in the ESP v=0.8 m s\(^{-1}\)).

The fly ash particles concentration at model ESP outlet was measured by means of gravimetric dust meter, after isokinetic sampling with a multi-hole probe. The sampled dust was collected on a highly efficient absorbent paper of a measuring filter. The ash was injected by the vibration feeder with
concentration of 0.2 g m\(^{-3}\). All tests were carried out in laboratory in ambient conditions: air temperature of 293 K and relative humidity of \(\varphi=60\%\). The gas flow velocity inside model ESP was measured with thermo-anemometer. Power supply Sörensen HV Supply 1121 (0-100 kV) was used for the excitation of discharge electrodes with rectified and smoothed DC current.

Test results have shown that fly ashes with high content of large particles (about 90 \% above 100 \(\mu\)m; samples P-1 and P-17) and having resistivity in a range of \(10^7-10^8\) \(\Omega\)cm are difficult to collect by ESP as compared to fine fly ash (sample P-3) and fly ash with low silica content (sample P-2), regardless of low content of unburned coal. Furthermore, in the case of fly ash with high content of large particles, the collection efficiency is less sensitive to supply voltage than in a case of fine fly ash (P-3). Most probably it is because of high content of unburned coal (more than 20 \%) in particles having diameter above \(d>100\ \mu\text{m}\) [10].

For fly ash samples taken from ESP without a cyclone as the first stage, the highest collection efficiency was obtained when RDE-2 type of discharge electrodes was used, however, for fly ash sample P-3 (from a boiler with an initial mechanical collector stage) the best collection efficiency was obtained for barbed-tape discharge electrode.

On the other hand, an optimal value of high voltage supply was about 50 kV. Further increase in supply voltage does not improve the collection efficiency, and even sometimes makes it worse. This result indicates that the optimal supply voltage has to be determined for specific fly ash parameters, which are related to a boiler type and the fired coal parameters.

3. Industrial tests

The primary aim of the experiments was to estimate the influence of operational parameters of boiler (boiler capacity) and ESP (average values of discharge current, secondary voltage, method of ESP energizing: conventional DC, semi-pulsed) on the ESP collection efficiency.

For these experiments, an industrial ESP with two sections in series and having inter-electrode spacing of 400 mm was selected. Each section has been energized with H.V. supply unit with nominal secondary parameters of 250 mA/ 106 kV. The ESP has been equipped with the collecting electrodes of SIGMA VI type, and discharge electrodes made of spiked pipes. The source of raw gas has been stoker boiler with capacity of 32 MW. The fly ash fractional size analysis of sample P-2, as well as its chemical analysis are presented in Table 1.

![Figure 9](image-url)

**Figure 9.** Collection efficiency characteristics of ESP after stoker boiler as a function of: (a) average electric power supplied to the ESP, (b) operational capacity of the boiler.
In order to estimate the ESP collection efficiency a gravimetric measurements of dust concentration were carried out at the ESP inlet and outlet \[16\]. It is worth noting that experimental tests carried out on industrial ESPs have many limitations, and the measurement results cannot be statistically processed because of uniqueness of operational conditions. Nevertheless, from the collected measuring results some trends, graphically presented in figure 9, can be noticed.

Results presented in figure 9(a) show, that there exists a limit of power supplied to ESP, above which the collection efficiency no further increases that was also shown by the measurements carried out during laboratory tests. However, a decrease in the collection efficiency with an increase of boiler load, shown in figure 9(b), results from an increase of dust concentration in flue gas and an increase of gas flow velocity in ESP.

In order to determine the influence of the method of ESP energization on the collection efficiency, two energizing methods have been tested: semi-pulse energization (with periodically switched-off supply voltage) and conventional DC supply. Characteristic supply voltage waveforms are shown in figure 10.

![Figure 10. High voltage waveforms of ESP supply units: (a) conventional DC energization with ripples, (b) semi-pulse energizing with each seventh supply voltage half-cycle ON, superimposed on DC voltage, and six half-cycles OFF.]

The results shown that in order to get the same collection efficiency of 98.2 % for both energizing methods it is necessary to deliver 5 kW of discharge power to ESP with semi-pulsed method of energization, and 3.9 kW for conventional method. It seems that the semi-pulse energizing option is not justifiable from the point of view of energy efficiency. However, this method is successfully applied in large industrial ESPs as a means of energy-efficient energizing or even as a method of increasing collection efficiency of ESP for collecting high-resistivity dust.

4. Discussion and conclusion

Fly ash leaving stoker boiler has its characteristic particle morphology (chemical composition, unburned coal contents, particle size distribution and particle shape) which can cause significant differences in electrostatic precipitation process in comparison with operation of ESP after PC or fluidal boilers.

The results obtained from the tests carried out in laboratory-scale ESP and in industrial conditions have shown that special construction of ESP discharge electrode has to be used as well as the optimization of electric supply parameters and energizing method (taking into consideration the physical characteristics and chemical composition of fly ash) has to be carried out for the efficient collection of low-resistivity fly ash coming from coal fired stoker boilers.

Analysis of the collection efficiency measured in laboratory scale ESP for various fly ashes has shown that:
An increase of the number of particles larger than 100 μm (samples P-1 and P-17 in this specific case) in fly ash decreases the maximal obtainable level of collection efficiency. Particles of this size are easy to charge and its collection is possible even at low supply voltage levels. An increase of supply voltage does not improve significantly the collection efficiency, and sometimes, at certain conditions can even decrease the efficiency. The most probably it is caused by a large percentage of larger porous particles having well developed surface, light weight, and great content of coal (figure 6), which in contact with collection electrode can easily lose its charge and are re-entrained to the flow.

For fine particles, the collection efficiency can be increased via increasing supply voltage, however, some measurements indicate that the optimal voltage (for example about 50 kV for the sample P-2) can exist, for which the collection efficiency is the maximal. There was also noted that a relatively high content of unburned coal (comparing to fly ash with large particles) does not worsen the collection process. This effect may suggest that more important in the precipitation process is the size of individual particles than their chemical composition, mainly because fine particles are not easily re-entrained from the collecting electrode.

The optimal construction of discharge electrode for the tested fly ash samples was that of type RDE-2, for which the current-voltage characteristics can be approximated by the following equation: $I = 101 - 13.2 \cdot U + 0.44 \cdot U^2$. This type of electrode generates high discharge current, which is uniformly distributed on the collection electrode. It may be concluded that this type of discharge electrode, of current-voltage characteristics described with this equation, can be applied in ESPs for the collection of fly ash particles of similar physical and chemical properties to those given in table 1.

Finally, it may be said that it is possible to electrostatically precipitate fly ash from exhaust gases after stoker boilers with high collection efficiency. But in order to obtain the best results for actual physical and chemical properties of fly ash, a careful selection of discharge electrode construction and electric energization parameters will be required. The proposed discharge electrode of type RDE-2 may be an alternative solution to typical electrodes with barbed tape or similar constructions generating non-uniform current distribution on the collection electrode. This alternative should be considered during ESP modernization or retrofitting via replacement of existing electrodes without a need of changing HV supply unit.

**Acknowledgments**

These studies were carried out as a part of project no. N R06 0014 06/2009 funded by the Polish National Centre for Research and Development (NCBiR)

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