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Reduction of PM2.5 particle emission by electrostatic precipitator

*Streszczenie. W artykule przedstawiono wyniki badań dwóch typów elektrod ulotowych różniących się zarówno konstrukcją jak i charakterystykami elektrycznymi. Wykonano pomiary charakterystyk prądowo-napięciowych, rozkładu prądu ulotu na elektrodzie zbiorczej i skuteczności odpylania dla obu elektrod ulotowych, jak również wykonano analizy składu ziarnowego i zawartości rtęci w próbkach pyłu zebranego z elektrod zbiorczych w wybranych przekrojach elektrofiltru laboratoryjnego. Uzyskane wyniki wskazują, że odpowiednio dobrana konstrukcja elektrod ulotowych może przyczynić się do wyższej skuteczności odpylania, w szczególności drobnych cząstek pyłu, a tym samym do ograniczenia emisji rtęci Hg(p) zaadsorbowanej na ich powierzchni. (**Usuwanie cząstek drobnych i rtęci przy w elektrofiltrze**).*

Abstract. Two different constructions of ESP discharge electrodes with different electric characteristics have been investigated in this paper. The electric and collection efficiency characteristics as well as analysis of collected fly ash samples from collecting electrode have been presented. The test results show that correctly chosen discharge electrode design may improve ESP collection of very fine PFA (PFA – pulverized fuel ash) particles and by that may also limit emission of mercury adsorbed on fine particles surface.

Słowa kluczowe: Elektrofiltr, Oczyszczenie gazu, Usuwanie pyłów, Usuwanie rtęci.
Keywords: Electrostatic Precipitator, Gas Cleaning, PM Removal, Hg Removal.

Introduction

According to European Union new restrictive legislation requiring farther reduction of submicron particles and mercury emission also emission of HCl, HF, NH_3 have to be limited. An enforcement term for the new BAT conclusions is expected to come in the first quarter of 2017 year. In that situation all coal firing power plants will be forced to adopt new flue gas cleaning technologies which make possible to further decrease emission of PM2.5 particles as well as of mercury.

Existing technical publications [1, 2] as well as our own studies [3, 4] points out that electrostatic precipitators (ESP) may be able to match the requirements of the new BAT conclusion. Test results had shown that ESP with proper discharge electrode design may significantly improve the ESP collection efficiency of very fine particles (submicron range; i.e. PM2.5 size range). The so called 'heavy metals'- in that also mercury- are mainly contained in the fine or ultra-fine particle range of PFA coming out from pulverized coal fired boilers (PFA – pulverized fuel ash). Hence improvement of ESP very fine particle collection (below PM2.5) enables also the reduction of mercury emission. EU countries as well as USA obtained significant reduction of mercury emission thanks to indirect benefits of ESP collection efficiency improvement; (up to 60% in the last 20 years) [5]. It is worth to mention that mercury emission from combustion processes depends on the rank of coal, its chemical composition, PFA particle properties, boiler type and flue gas cleaning installation design.

Laboratory studies

A test bench for ESP collection efficiency measurements

A diagram of horizontal flow ESP model test bench is shown in Fig. 1.
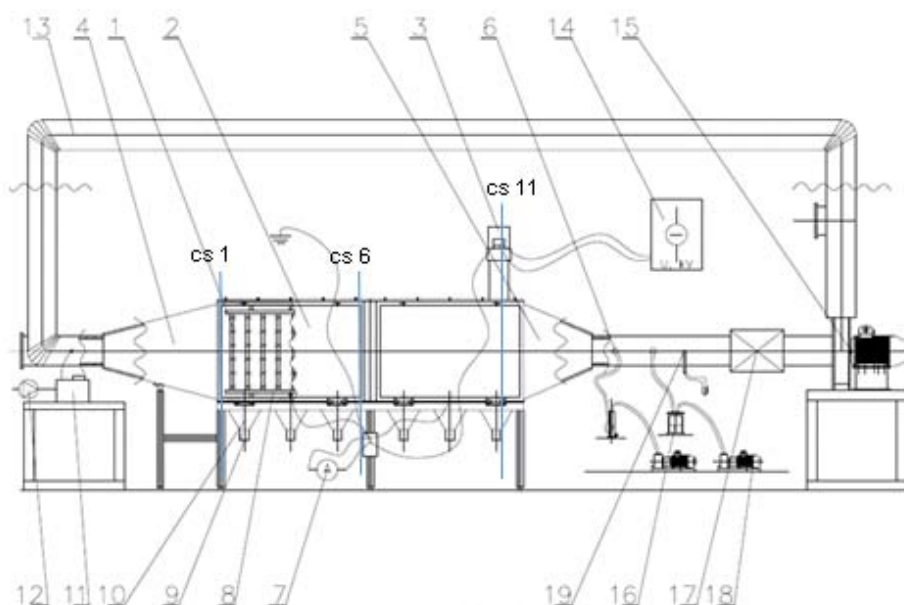

Fig. 1. Drawing of horizontal flow ESP model test bench: 1 – discharge electrodes (DE); 2 – collecting electrodes (CE); 3 – DC high voltage energizing unit; 4 – diffuser; 5 – confusor; 6 – dust density meter; 7 – analog ammeter; 8 – suspension of CE; 9 - containers for PFA collection; 10 – PFA collecting hoppers; 11 – dust feeder; 12 – compressed air for feeder; 13 – inlet duct; 14 – supply voltage regulator; 15 – radial fan; 16 – scrubber; 17 – final filter; 18 – pump of dust density meter; 19 – measurement of gas velocity.

Its basic elements comprises of the ESP chamber with discharge (DE) and collecting (CE) electrode system (basic dimensions: length 2x1000 mm, height 450 mm, inter electrode space 400 mm, DE emission elements distance 170 mm).

The ESP model is energized with DC high voltage unit, with positive pole grounded. The test bench gas ducts system is of close loop type and is equipped with control and measurement devices (i.e. of temperatures, humidity, velocity, and so on). The flow of gas (in that case air flow) is forced by radial fan with controlled rotational speed. At its end, the test bench installation is equipped with a high efficiency filter.

Measurement of discharge current distribution on collecting plates

The measurement bench diagram is shown in Fig. 2a; and its photo in Fig. 2b.
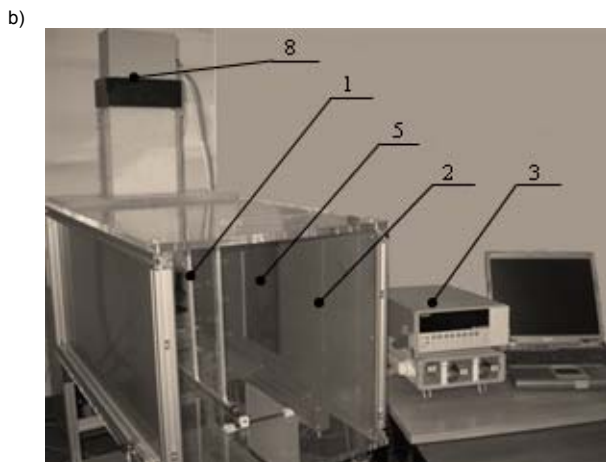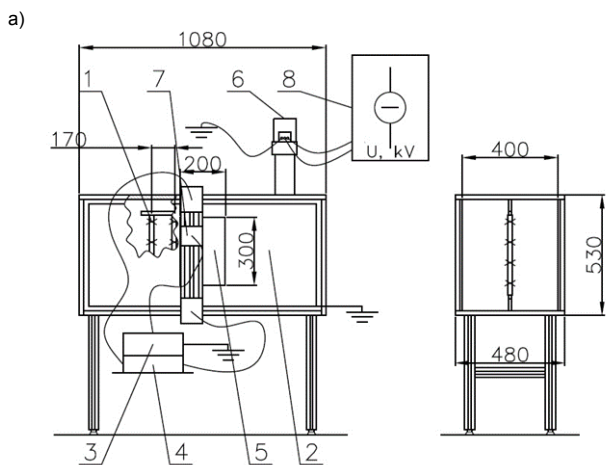
a)

b)

Fig. 2; Measurement bench for discharge current distribution: 1 – discharge electrode (DE); 2 – collecting electrode (CE); 3 – digital pico-ammeter for discharge current measurement; 4 – control panel of measuring probe; 5 – measuring field; 6 – high voltage supply unit; 7 – measuring probe; 8 – supply source of HV unit.

In the measuring field (200x300 mm) moves an electrically insulated measuring probe of specific area S_0=1 cm^2 for measurement of discharge current distribution on the area of S_0. The measurement of current is limited to a range of pA-nA. The measurement is carried out with digital pico-ammeter 6485 of Keithley. The probe movement is controlled by a joy-stick in steps of s=7.5 mm that gives a total 1080 measuring points.

Results of test bench measurements
Physico-chemical properties of PFA

For the tests has been used PFA collected in an ESP after a brown coal fired PC boiler (P-1). The particle size

distribution of fly ash was determined by optical analyser Mastersizer of Malvern Instruments Ltd. That analyser - operating on the base of laser light scattering, allows to determinate particle diameter from 0.05 to 3500 µm. The measurement results are shown in Fig. 3.
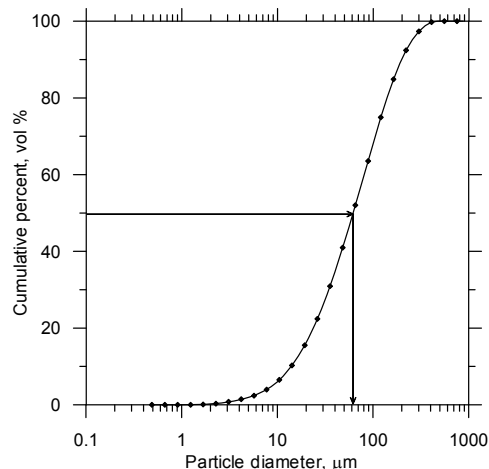

Fig. 3. Particle size distribution of tested PFA.

The tested PFA characterize a median diameter of d_{50}=63 µm and mode diameter of d_{max}=89 µm; and its physico-chemical properties are presented in Table 1.

Table 1: Physico-chemical properties of measured PFA

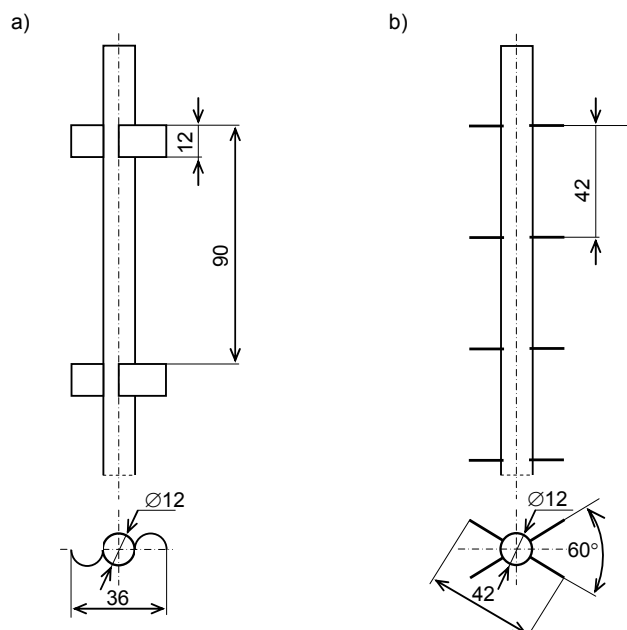| Parameter	Units	P-1
SiO_2	%	44.65
Fe_2O_3	%	4.83
Al_2O_3	%	21.5
Mn_3O_4	%	0.03
TiO_2	%	1.28
CaO	%	19.10
MgO	%	1.18
SO_3	%	3.08
P_2O_5	%	0.17
Na_2O	%	0.17
K_2O	%	0.11
BaO	%	0.04
SrO	%	0.10
LOI	%	2.99
TOC	%	2.57

a)   b)

Fig. 4. Construction and dimensions of discharge electrodes used for tests: (a) DE-1; (b) DE-2
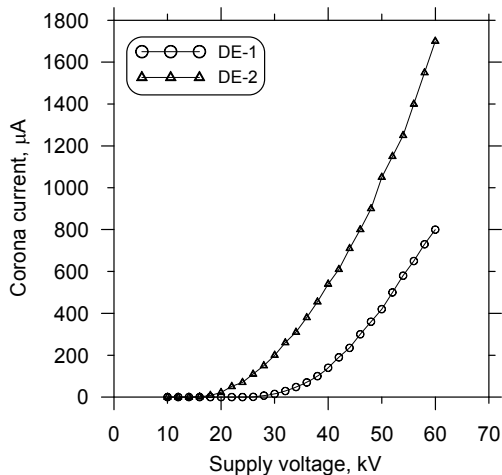
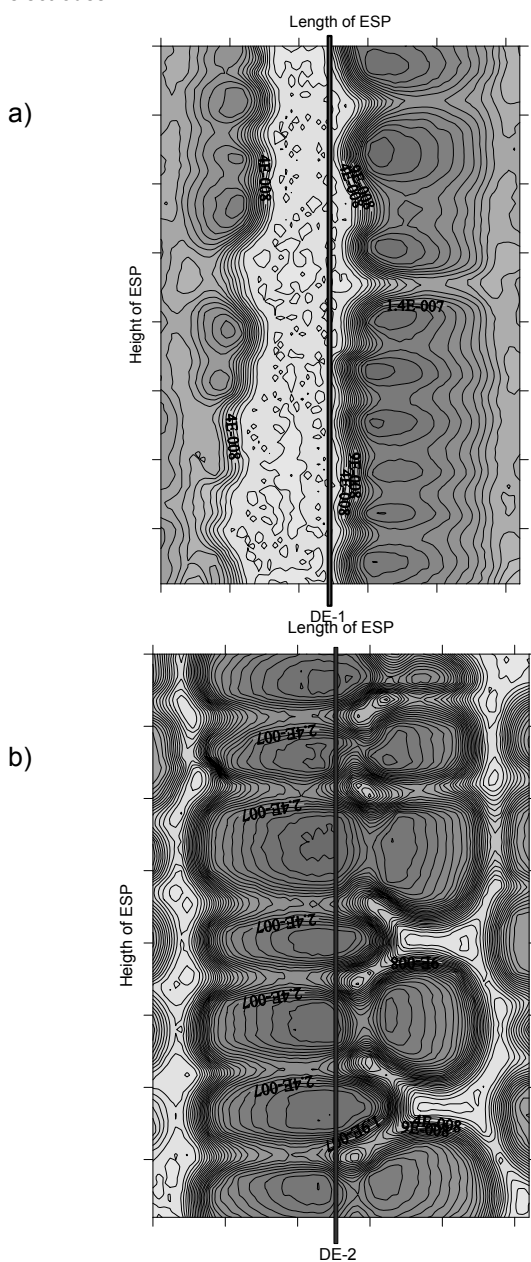Fig. 5. Current-voltage (I-V) characteristics of tested discharge electrodes.

Fig. 6. Discharge current (in amps) distribution for (a) DE-1 and (b) DE-2 on collecting plate for supply voltage of U=60 kV.

Discharge electrode current-voltage characteristics

Tests were carried out with two types of discharge electrodes (DE) in order to obtain different distribution of electric field and different discharge current distribution on collecting plate (Fig. 4).

Fig. 5 presents discharge current-voltage characteristics measured for both tested types of DE in clean environment and with clean electrodes.

Discharge electrode DE-1 is characteristic of its high voltage and low current operational parameters; where electrode DE-2 I-V characteristic shows higher values for both, current and voltage parameters. The DE-2 discharge electrode -getting higher discharge current- is recommended for electrostatic precipitators collecting PFA with high content of very fine particles, below 0.2 µm [6]. Those particles are mainly diffusionally charged, therefore high discharge current provides high space charge and high magnitude of charged particles. Whereas discharge electrode of DE-1 type - with its lower current range for high voltage - will be more suitable for ESPs collecting of moderate resistive PFA, in range of $10^{10} - 10^{11}$ Ωcm.

Discharge current distribution on collecting electrodes

Those tests were carried out on measuring test bench with a supply voltage of 60 kV for both DE types, DE-1 and DE-2. The test results are given in Fig. 6a and 6b.

The discharge current distribution for DE-1 is less uniform than for DE-2. This confirms also corresponding values of RSD parameter; defined as ratio of discharge current standard deviation to the average current value, and it get values of 68% and 59% for DE-1 and DE-2 respectively.

On the above shown pictures are clearly visible regions of lower and higher current densities, as brighter and darker regions (Fig. 6). Further studies confirmed that regions of lower and higher emission correspond to active and no active fields created by collected particles on collecting plates.
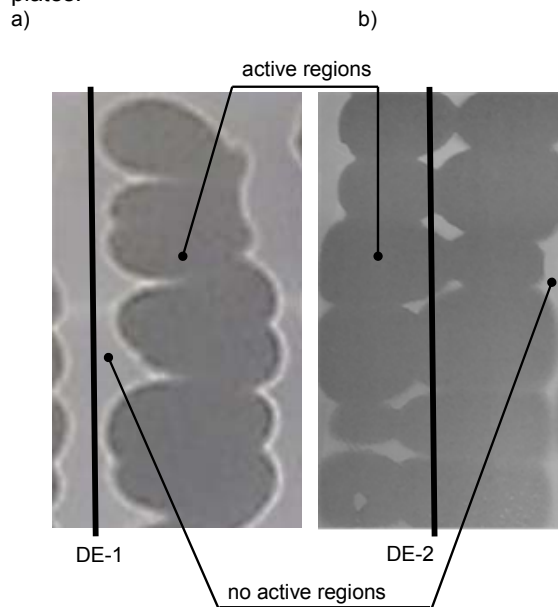

Fig. 7. Collected PFA patterns on collecting plates for both tested type of discharge electrode: (a) DE-1, (b) DE-2, supply voltage 60 kV

PFA precipitated on collecting plates – analysis of size distribution

Fig. 7 presents precipitated PFA patterns on collecting electrode plates for both types of DE electrodes. Bright

regions are regions with modest amount of participated PFA, where there is practically no discharge current (not active regions; see Fig. 6). Dark regions are the regions where a large amount of the PFA is collected and where flows a high discharge current.

The obtained collected PFA patterns get forms matched to discharge current distribution for both tested electrodes (Fig. 6a, b). The tests showed that most of the PFA has been deposited in regions of high discharge current (active regions); i.e. more than 90% of the total amount.

Fig. 8 presents PFA median diameter of dust samples taken from the active and no active regions along the ESP length, at cross sections corresponding to DE electrodes marked on Fig. 1 as: cs 1; cs 6 and cs 11. The PFA has been precipitated under a supply voltage of 60 kV.
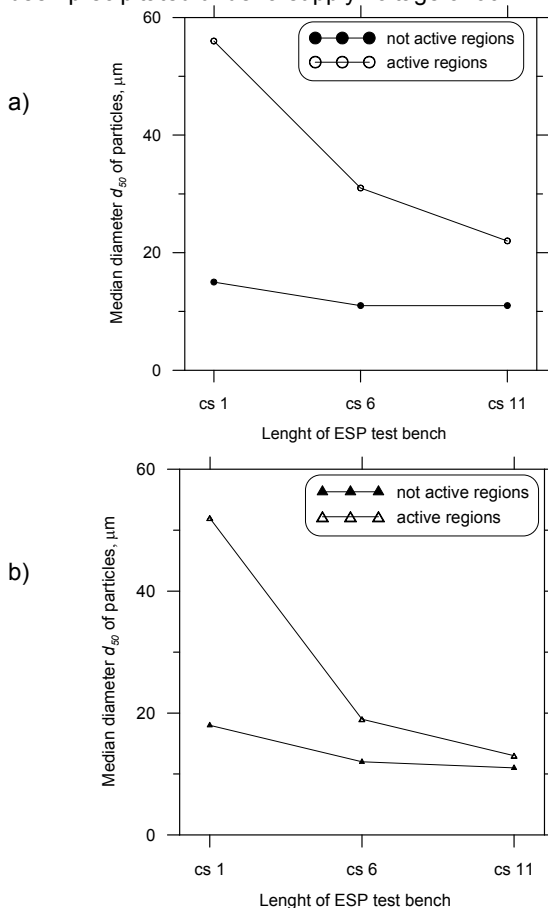

Fig. 8. Changes of median diameter of particles collected on collecting electrode plates along the ESP test bench at cross section (cs) situated at inlet (cs 1); centre (cs 6) and outlet (cs 11). Collecting process at 60 kV supply voltage; for two discharge electrode types: (a) DE-1, (b) DE-2.

The analysis of collected PFA size distribution has shown that median diameters of collected PFA particles in active regions are larger than of those collected in no active regions; and that parameter shows also a decreasing tendency of its values along the length of ESP. On the other hand in no active regions the PFA median diameter is nearly constant along the entire length of ESP with characteristic predominance of submicron particles. In a case of DE-2 electrode type there is visible increase of fine particles also in active regions.

Mercury content of PFA precipitated on collecting plates

A quantitative analysis results of mercury content of precipitated PFA at respective cross sections of the test

bench ESP for two types of discharge electrodes are shown in Table 2. Content of mercury in precipitated PFA had been determined with ASA selective method for Hg enriched by amalgamation.

Table 2. Mercury content in PFA precipitated on collecting plate at respective cross sections of ESP, for active and no active regions and both tested types of discharge electrode.

O.n.	Type of EU	Type of region on CE	Cross section of ESP	Hg(p) content
-	-	-	-	mg/kg
1.	DE-1	active	cs 1	0.5917
2.			cs 6	0.8434
3.			cs 11	1.0901
4.		no active	cs 1	0.8027
5.			cs 6	1.2163
6.			cs 11	1.2165
7.	DE-2	active	cs 1	0.4590
8.			cs 6	0.7955
9.			cs 11	1.0292
10.		no active	cs 1	0.6040
11.			cs 6	0.9852
12.			cs 11	1.0642

Fig. 9 presents mercury content in precipitated PFA samples, collected from respective cross sections and regions along the length of ESP bench, for two discharge electrode types.
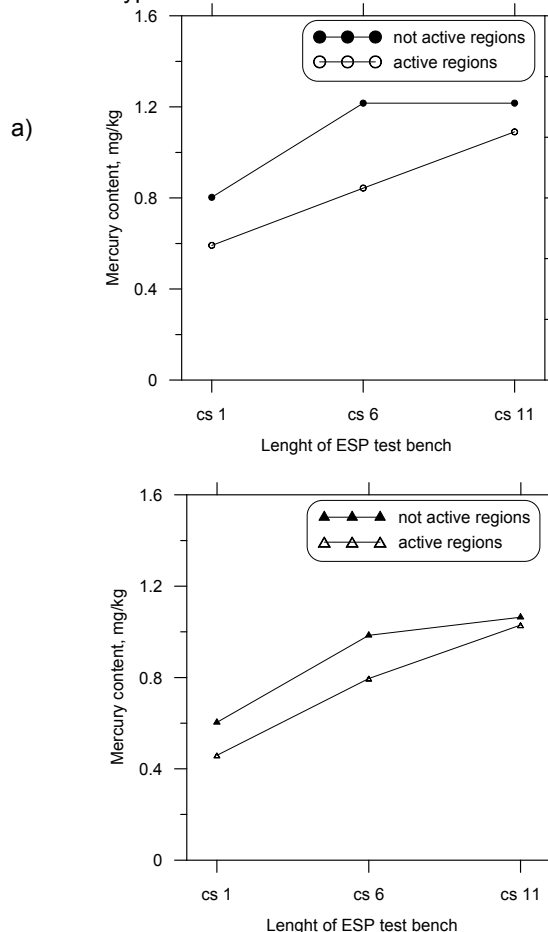

Fig. 9. Mercury content in PFA samples collected from active and no active regions, for two types of discharge electrodes: a) DE-1, b) DE-2; precipitated at supply voltage 60 kV.

The mercury content in PFA samples -taken from no active regions and from all cross sections along the ESP- is higher than in samples taken from active regions. Their characteristic pictures are related to the PFA size

distribution of tested regions, where the submicron particles are found in no active regions.

The total collection efficiency

The total collection efficiency has been determined for the ESP test bench, according to the following formula:

$$(1) \qquad \eta_c = 1 - \frac{\dot{m}_{out}}{\dot{m}_{in}} \cdot 100$$

where: $\dot{m}_{in}$ - PFA mass at the ESP inlet; $\dot{m}_{out}$ - PFA mass at the outlet of ESP.

and: $\dot{m}_{in}$ - has been manually controlled; $\dot{m}_{out}$ - has been measured with gravimetric dust meter. The total efficiency measurements are presented in Fig. 10.
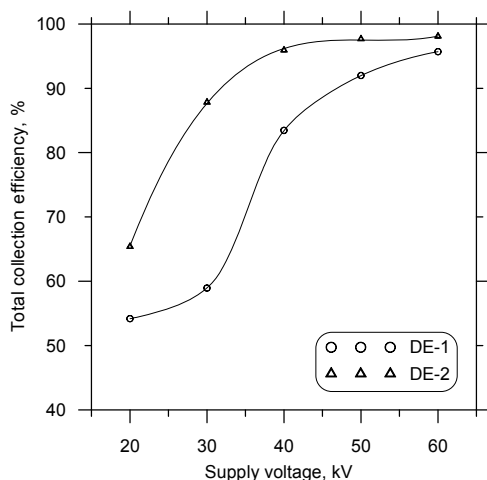

Fig. 10. Total collection efficiency of test ESP bench as a function of supply voltages; for discharge electrodes DE-1 and DE-2; the average gas (air) flow velocity v_g=0.8 m/s.
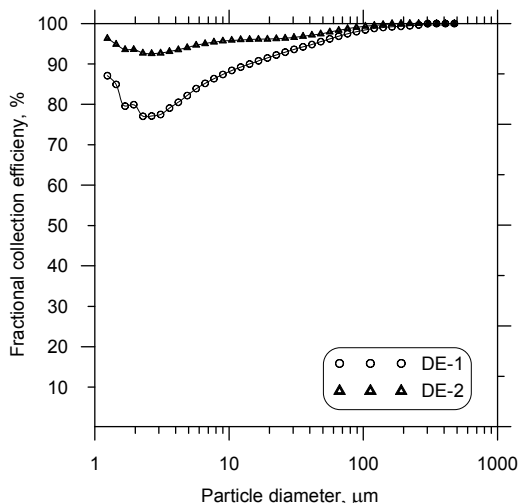

Fig. 11. Fractional collection efficiency of the model ESP with electrodes DE-1 and DE-2; supply voltage of 60 kV.

Test results had shown that the ESP total collection efficiency for DE-2 electrode is higher with supply voltages below 60 kV than for DE-1. When supply voltage is at 60 kV the collection efficiency for both DE electrodes are comparable; the difference is about 2% points.

Fractional collection efficiency of ESP

Estimation of ESP fractional collection efficiency has been done by comparison of PFA particle size distribution at the model ESP inlet and outlet for a specific total collection efficiency of the ESP model, accordingly to the following equation:

$$(2) \qquad \eta_{f_i} = \frac{q_{3inlet,\,i} - 1(1 - \eta_c) \cdot q_{3outlet,\,i}}{q_{3inlet,\,i}}$$

where: $q_{3inlet,\,i}$ − percentage of particle in the i-th class of volume basis at the ESP inlet, $q_{3outlet,\,i}$ − percentage of particle in the i-th class of volume basis at the ESP outlet.

The ESP fractional collection efficiency for both tested DE has been determined from PFA size distribution, measured with particle size analyzer Malvern Ltd. The results obtained for supply voltage of 60 kV are presented on Fig. 11.

From the above presented results appears that fractional collection efficiency of ESP for electrode DE-2 is higher, especially for the very fine particles in the range of PM2.5 and PM10.

Summary

The above presented studies refer to different constructions of ESP discharge electrodes with different electric characteristics. Performed tests and measurements of the model ESP fractional and total collection efficiency as well as analysis of collected PFA samples from electrodes confirmed a thesis that discharge electrode characterized with uniform discharge current distribution at collecting electrode and higher average current provides higher ESP collection efficiency, and by that also improve collection of submicron particles.

As theoretically expected, there has been increased percentage of submicron particles in samples taken from electrode plates at successive cross sections along the ESP length. Additionally, there has also been confirmed an increase of mercury content in PFA with decreasing size of particles.

The test results show that correctly chosen discharge electrode design may improve ESP collection of very fine PFA particles and by that also collection of mercury adsorbed on its surface. It is likely that the premises maybe exploited in industrial ESP designing by providing outlet sections of ESP (with low dust particle concentrations) with discharge electrodes characterized for its high and uniform distribution of current values. Additional actions managed in combustion process – i.e. maintaining of percentage of unburned carbon in ash on properly high level, or installing additional flue gas cleaning systems (catalysts, injection of mercury oxidants) which enhance the share of mercury oxides Hg^{2+} in flue gases may also be utilized to reduce mercury emission in combustion processes.

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