

**STUDY ON THE EFFECT OF FRACTIONAL COMPOSITION AND ASH PARTICLE
DIAMETER ON ASH COLLECTION EFFICIENCY AT THE ELECTROSTATIC
PRECIPITATOR**

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The goal of experimental investigations shown in this paper is to estimate operating efficiency degree of the electrostatic precipitator on a real industrial plant (at thermal power plant „Gacko“ with electric power of 310MW, Bosnia & Herzegovina) and to use obtained results as a base of periodical engineering or continual measurement and to compare them with the investigations of other investigators. Investigation of the electrostatic precipitator performance was done according to BAS ISO 9096 : 2003 .

In this paper the electrostatic precipitator efficiency during ash particle removal with wide range of particle sizes from 1 to 250 μm is evaluated. Exploitation experience points that electrostatic precipitators are efficient for the coals of different quality (coal particles diameters bigger than 1 μm) and that they could be optimized during the exploitation itself and for some following processes (e.g. flue gas desulphurization). Within the measurement plane, measurements were made on 20 points per section. It has been noticed that ash removal degrees obtained experimentally (3 investigations) have approximately equal value (95.93% to 97.78%). The best concordance with the results of experimental investigation shows the Deutsch equation, while theoretical models of Zhibin-Guoquan and Nobrega-Falaguasta-Coury do not correspondent well with the results of experimental investigations. For the ash particles with the diameters less than 17.5 μm there is no good correlation between investigated theoretical models. The highest deviation of the model for ash particles with diameters less than 17.5 μm is notable in the case of usage of the Deutsch equation.

Keywords: *Electrostatic precipitator; collection efficiency; ash particles dimensions; velocity of flue gas; migration velocity of ash particle.*

INTRODUCTION

The electrostatic removal of solid particles from the flue gases has a wide application in the range of the industrial processes. Electrostatic removal of solid particles from the flue gases operating based on the principle that the gas is allowed to pass between two electrodes, one of which is grounded (plate collecting electrode), and the other which is connected to the negative pole of high-voltage current (coronary electrode). The particles in the gas stream are electrically charged and separated from the flue gas under the influence of electric field.

Flue gas process parameters (volume flow, temperature, velocity) and the parameters of the electrostatic precipitator (length of electric field, migration velocity of the ash particle, particle size distribution, distance between plate collecting electrodes) have a big influence on the collection efficiency in an electrostatic precipitator.

Many researchers [1-7] analyze the influence of these parameters on particle collection efficiency in the electrostatic precipitators and often give contradictory conclusions. Different mathematical models were used in order to show that geometric characteristics of the electrostatic precipitators (length of collecting electrodes, distance between collecting electrodes, migration velocity) have influence on their collection efficiency.

The paper [5] demonstrates comparison between the results obtained using theoretical models of Deutsch and Zhibin-Guoquan with the results of experimental examinations of electrostatic precipitator in laboratory controlled conditions. The results obtained using model of Deutsch (equation (1)) and Zhibin-Guoquan (equation (4)) do not correspond well to the experimental results of particles with diameter less than $10\mu\text{m}$.

The newest model described in paper [5] (equation (5)) is a good approximation of the experimentally obtained results even for the particles with the diameter less than $10\mu\text{m}$.

The main goal of this paper is to compare the results obtained from the measurements of ash particle collection in an electrostatic precipitator of a real industrial plant at the thermal power plant „Gacko“ 310 MW, Bosnia & Herzegovina with the results of ash collection obtained by the available theoretical models.

A classic model of ash collection in the electrostatic precipitator is known as the equation of Deutsch, equation (1) is still used in engineering calculations [8]:

$$\eta = \left(1 - e^{-\frac{A \cdot \omega}{Q}}\right) \cdot 100 = \left(1 - e^{-\frac{L \cdot \omega}{v \cdot s}}\right) \cdot 100, \quad (1)$$

whereas:

η - grade efficiency of electrostatic precipitator, [%],

A - total area of collecting electrodes, [m²],

ω - theoretical migration velocity of ash particle, $\left[\frac{\text{m}}{\text{s}}\right]$,

Q - flue gas volumetric flow rate through the electrostatic precipitator, $\left[\frac{\text{m}^3}{\text{s}}\right]$,

L - length of the collecting electrodes (length of the electric field), [m],

v - velocity of flue gas flowing through electrostatic precipitator, $\left[\frac{\text{m}}{\text{s}}\right]$,

s - distance between the discharge and collecting electrodes, [m].

During electrostatic precipitators design, together with the Deutsch equation (equation (1)), modified Deutsch equations are frequently used. These equations could be found in references [9,10].

For ash particles with diameters less than $1\mu\text{m}$, theoretical migrational ash velocity could be calculated by using the following equation (Stokes – Cunningham) [8]:

$$\omega = \frac{q \cdot E}{3\pi \cdot \mu \cdot d_p} \cdot \left(1 + A^* \cdot \frac{2\lambda}{d_p}\right), \quad (2)$$

whereas:

q - electrical saturation ash particles charge, [C],

E - electric field strength, $\left[\frac{\text{V}}{\text{m}}\right]$,

μ - flue gas dynamic viscosity, [Pa · s],

d_p - ash particle diameter, [m],

A^* - nondimensional parameter (its value for air is 0.86),

λ - mean free path of the molecules of the ambient gas, m.

During the practical engineering calculations for the bigger ash particles (bigger than $1\mu\text{m}$) and where the dominating field is charging, migrational ash velocity could be determined by the following equation [11]:

$$\omega = 0.345 \cdot \frac{\varepsilon_0 \cdot E^2 \cdot d_p}{\mu}, \quad (3)$$

whereas:

$$\varepsilon_0 - \text{permittivity of the vacuum } 8.85 \cdot 10^{-12} \left[\frac{\text{F}}{\text{m}} \right],$$

$$E - \text{electric field strength, } \left[\frac{\text{V}}{\text{m}} \right],$$

$$d_p - \text{ash particle diameter, [m]},$$

$$\mu - \text{gas dynamic viscosity, [Pa} \cdot \text{s]},$$

0.345 – correction factor.

The Deutsch equation assumes constant concentration profile of collection of solid particles. The paper [12] demonstrates the effect of diffusion included in the development of their analytical model of solid particles collected in an electrostatic precipitator. They suggested theoretical equation in order to define precipitator efficiency, e.g. level of solid particles efficiency [12]:

$$\eta = 1 - \left(\frac{Pe}{4 \cdot \pi \cdot De} \right)^{0.5} \cdot \int_0^1 e^{-\frac{Pe \cdot (\xi - De)^2}{4 \cdot De}} d\xi, \quad (4)$$

where:

$$Pe = \frac{\omega \cdot s}{Dp} - \text{Peclet number,}$$

$$De = \frac{\omega \cdot L}{v \cdot s} - \text{Deutsch number,}$$

$$Dp = \frac{2 \cdot 10^{-7}}{d_p}, \frac{\text{m}^2}{\text{s}}, - \text{particle diffusivity,}$$

$$d_p - \text{ash particle diameter, [m]},$$

$$\xi - \text{traverse distances.}$$

In newer investigations shown in paper [5], the authors assumed that the concentration of solid particles increased towards the plate collecting electrodes and they suggested a new equation for the collection efficiency of solid particles in the electrostatic precipitator:

$$\eta = 1 - \frac{\sqrt{\frac{Pe}{\pi}}}{De^{1.5}} \cdot \int_0^1 \xi \cdot e^{-\frac{Pe}{4 \cdot De} \cdot (\xi - De)^2} d\xi. \quad (5)$$

EXPERIMENTAL INVESTIGATIONS OF SOLID PARTICLES EFFICIENCY IN ELECTROSTATIC PRECIPITATOR

Experimental investigation of electrostatic precipitator and ash collecting in the electrostatic precipitator is performed at the thermal power plant „Gacko“, Bosnia & Herzegovina, with electric power of 310MW. Examination of electrostatic precipitator operation is performed according to the Regulation on emission limiting values into air from combustion plant (Official Gazette of the RS, No. 39/05) and according to standard methods of BAS ISO 9096:2003 [13].

The thermal power plant has one chimney 160m height and 8.4m diameter. Its furnace temperature is in the range from 1250°C to 1320°C. At the furnace entrance the excess air coefficient is in the range from 1.06 to 1.18, and at the furnace exit it is in the range from 1.35 to 1.40. Exit velocity of flue gases from the chimney is $11 \frac{\text{m}}{\text{s}}$ with temperature of 170°C. Mass fraction of sulphur in lignite is about 1.33%. For

combustion the thermal power plant uses available coal with quantity about $300000 \frac{\text{kg}}{\text{h}}$. Thermal power plant has two chimney channels, both with an electrostatic precipitator. More detailed characteristics of the plant and electrostatic precipitators are shown in the technical report [14].

Basic characteristics of electrostatic precipitator are:

- Collecting electrodes height is 12 m
- Electric field length (collecting electrodes length) is made of four (4) old fields (zones) $4 \cdot 2.5 = 10 \text{ m}$ long and the fifth field additionally made, 4 m long
- Collecting electrodes distance in all fields is $2s = 0.30 \text{ m}$
- In the direction of flow, flue gas is going through 49 passages (width of the passage is the distance between collecting electrodes $2s$) (Figure 1).

Figure 1 should be inserted here.

The methodology of ash concentration calculation in flue gas (in front of and behind the electrostatic precipitator, points A and B, Figure 1) is gravimetric with weighing of metal capsule (model Adventure 65g/0.0001g) before and after measurement on analytical scales. At three samples of ash particles (Examination 1, Examination 2 and Examination 3) the distribution of ash particles dimensions is determined at the sieves Coulter Counter with calibre up to $37 \mu\text{m}$. About 65% ash particles have diameter bigger than $17.5 \mu\text{m}$. The examinations have also shown much bigger mass fraction of ash particles with diameter bigger than $125 \mu\text{m}$ for Examination 3, than for examinations 1 and 2 (Table 1

and Figure 2). This could be explained by voltage change in electrostatic precipitator during examination from average 35kV , for examinations 1 and 2, to 52kV for Examination 3.

In a process in measurement plane (measured at 20 points by a section), gaseous pollutants concentrations in flue gases (O₂, CO₂, CO, NO₂, SO₂), and in second process physical characteristics of flue gas (flow, temperature, velocity) behind the electrostatic precipitator were measured (point B, Figure 1). Other measured parameters are shown in [14]. According to measured values of the specified parameters, recalculations to normed conditions (0°C i 1.013·10⁵Pa) were performed. Measured concentrations of polluting substances in flue gas were reduced to the appropriate fraction of O₂=6% (Table 2).

Dry gases were brought by pipe to the gas entrance to the analyser Dräger MSI 150 PRO 2, which was used for direct measurement of pollutant substances with error less than 5% . The device was connected to PC by cable RS 232 and in software DERAS performing processing of measurement results was done during sonda reading every two minutes. A detailed description of material and equipment used during examination of the electrostatic precipitator operation is shown in the technical report [14].

Table 1 should be inserted here.

Figure 2 should be inserted here.

The ash (solid particles) collection efficiency in the electrostatic precipitator is determined using the following equation:

$$\eta = \left(1 - \frac{C_i}{C_u}\right) \cdot 100, \quad (6)$$

whereas:

η - grade efficiency of electrostatic precipitator, [%],

C_u - mass volume ash concentration at entrance of electrostatic precipitator, $\left[\frac{\text{mg}}{\text{Nm}^3}\right]$,

C_i - mass volume ash concentration at exit of electrostatic precipitator, $\left[\frac{\text{mg}}{\text{Nm}^3}\right]$.

Dynamic viscosity of flue gas is determined using following equation [15]:

$$\mu = \sum_{i=1}^n \frac{\mu_i}{1 + \sum_{\substack{j=1 \\ j \neq i}}^n \Phi_{ij} \cdot \frac{\varphi_j}{\varphi_i}}, \quad (7)$$

whereas Φ_{ij} is a function which can be calculated using Bromley and Wilke's method of approach:

$$\Phi_{ij} = \frac{\left[1 + \sqrt{\frac{\mu_i}{\mu_j} \cdot \left(\frac{M_j}{M_i} \right)^{\frac{1}{4}}} \right]^2}{\sqrt{8 \cdot \left(1 + \frac{M_i}{M_j} \right)}}, \quad (8)$$

whereas:

μ_i, μ_j - dynamic viscosity of the components „i“ and „j“, [Pa · s],

φ_i, φ_j - volume fractions of the components „i“ and „j“ in the mixture, - ,

M_i, M_j - molar masses of the components „i“ and „j“, $\left[\frac{\text{kg}}{\text{kmol}} \right]$.

In order to include ash fractional composition during calculation of ash collecting efficiency level the following equation is used:

$$\eta = \sum_{i=1}^n \frac{\phi_i}{100} \cdot \eta_i, \quad (9)$$

whereas:

η - total degree of ash collection in electrostatic precipitator, [%],

ϕ_i - mass ratio of fraction „i“ (fractional composition), [%],

η_i - ash particles collection efficiency for fraction „i“, [%].

Table 2 should be inserted here.

Results and discussion on experimental investigations

In Table 2 are shown the results of experimental examinations (Examination 1, Examination 2, Examination 3) of ash particles efficiency in electrostatic precipitator with collecting electrodes distance $2s = 0.30\text{m}$, which operates with the same specific collecting area A/Q for given examination (for

Examination 1 $A/Q=86.2742$ s/m, for Examination 2 $A/Q=84.5512$ s/m and for Examination 3 $A/Q=84.7931$ s/m). During examinations the strength of electric field in electrostatic precipitator varied and ranged from 117kV/m to 172kV/m. Ash collection degree has approximately the same value for each of the three examinations and it ranges from 95.93% to 97.78%. This could have been expected considering the approximately same value of ratio A/Q and approximately the same value of migrational velocity of about 0.04m/s.

Fractional composition of ash and ash particles diameter substantially influences the ash collection degree in electrostatic precipitator. Ash particles of which the diameters are less than $17.5\mu\text{m}$, have a lower degree of ash collection and range from 68% to 99%. For ash particles with diameters bigger than $17.5\mu\text{m}$, the ash collection degree has approximately the same value for each of the three examinations and it ranges from 99% to 100% (Figures 3).

Figure 3 should be inserted here.

COMPARISON BETWEEN THEORETICAL MODELS AND EXPERIMENTAL DATA ON ASH PARTICLES COLLECTION EFFICIENCY

Ash collection efficiency in the electrostatic precipitator, estimated by the use of theoretical models of Deutsch (equation (1)), Zhibin-Guoquan (equation (4)) and Nóbrega-Falaguasta-Coury (equation (5)), is shown in Figures 4 a, 4b, 4c.

As it can be noticed in these figures, regarding the ash particles diameters bigger than $17.5\mu\text{m}$, the correlations of theoretical models (equations (1), (4) and (5)) are in good accordance. As for the ash particles diameters less than $17.5\mu\text{m}$, there is no good accordance between investigated models. The biggest deviation between the models is noticed with the Deutsch equation (equation (1)) (Figure 4a, 4b, 4c).

Figure 4a should be inserted here.

Figure 4b should be inserted here.

Figure 4c should be inserted here.

The Figure 5 shows comparison of values of mean ash particles collection efficiency with a wide distribution of particle dimensions in the range from 1 to $250\mu\text{m}$ in the electrostatic precipitator, calculated from the experiments with foreseeing theoretical models of Deutsch (equation (1)), Zhibin-

Guoquan (equation (4)) and Nóbrega-Falaguasta-Coury (equation (5)). It is noticeable that Deutsch model (equation (1)) is the best approximation of the experimental examination of ash particles collection efficiency in the electrostatic precipitator. Other theoretical models (equations (4) and (5)) do not approximate the best results obtained through experimental examinations.

Figure 5 should be inserted here.

By comparison of the experimental results and applied theoretical models (Figures 4a, 4b, 4c and Figure 5) with the results of experimental examinations and applied theoretical models shown in [5] it can be noticed relatively good accordance for the ash particles with diameters bigger than $17.5\ \mu\text{m}$.

CONCLUSIONS

In this article the electrostatic precipitator efficiency during ash particle removal with wide range of particle sizes from 1 to $250\ \mu\text{m}$ is evaluated.

Experimental investigations were performed in the real industrial plant (at the thermal power plant „Gacko“, Bosnia & Herzegovina, with electric power of 310MW). They indicate approximately equal value of ash collecting degree for all three investigations. The values of ash particles collection are in the range from 95.93% to 97.78%.

Theoretical models of Zhibin-Guoquan and Nóbrega-Falaguasta-Coury shown in this paper do not approximate best the results of experimental examinations executed in the industrial plant (thermal power plant „Gacko“).

The best concordance with the results of experimental examinations shows the Deutsch equation (equation (1)). This could have been expected, because about 65% ash particles have diameter bigger than $17.5\ \mu\text{m}$. For ash particles with diameters less than $17.5\ \mu\text{m}$, there is no good correlation between considered theoretical models. The biggest deviation was noticed by using the Deutsch equation (equation (1)), and the smallest by using the Zhibin-Guoquan model (equation (4)) and Nóbrega-Falaguasta-Coury model (equation (5)). Considered models inconsistency could be explained by complexity of ash particles phenomenon in the electrostatic precipitator, with the particles of smaller diameter and especially diameters less than $1\ \mu\text{m}$, which was examined by Zhibin-Guoquan and Nóbrega-Falaguasta-Coury and others in a laboratory [16-18].

NOMENCLATURE

A_c - Ash mass fraction in coal, [%]

A - Total collecting area of plate collecting electrodes, [m²]

A^* - Dimensionless parameter

C_i - Mass volume ash concentration at exit of electrostatic precipitator, [mg / Nm³]

C_u - Mass volume ash concentration at entrance of electrostatic precipitator, [mg / Nm³]

De - Deutsch number, dimensionless

d_p - Ash particle diameter, [μm]

D_p - Ash particle diffusivity, [m²/s]

E - Electric field strength, [V/m]

H - Length of the collecting electrode, [m]

L - Length of the collecting electrode, [m]

M_i - Molar mass of component „i“ in flue gas, [kg/kmol]

m_c - Coal mass flow (coal consumption), [kg/h]

Pe - Peclet number, dimensionless

q - Saturation charging of ash particles, [C]

Q - Flue gas volumetric flow rate, [Nm³/h]

s - Distance between the discharge and the collecting electrodes, [m]

t - Flue gas temperature, [°C]

v - Flue gas velocity, [m/s]

ω - Ash particle migration velocity, [m/s]

φ_i - Volumetric fraction of component „i“ in flue gas, [%]

Φ_i - Fraction of ash particles with mean diameter d_{pi} , [%]

η_i - Grade efficiency of ash particles fractions Φ_i with mean diameter d_{pi} , [%]

ε_0 - Permittivity of the vacuum, [F/m]

η - Total grade efficiency of ash particles (ash particle collection efficiency), [%]

λ - Mean free path of flue gas molecules, [m]

μ - Flue gas viscosity, [Pa·s]

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FIGURE CAPTIONS

Figure 1. Schematic view of electrostatic precipitator and collecting electrodes with the positions of ash particles sampling and polluting substances in flue gas

Figure 2. Fly ash size distribution in thermal power plant “Gacko”

Figure 3. Influence of ash particle diameter on ash collection efficiency

Figure 4a. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator (Examination 1)

Figure 4b. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator (Examination 2)

Figure 4c. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator(Examination 3)

Figure 5. Comparison of the ash particle mean collection efficiencies in electrostatic precipitator between theoretical models (equations (1), (4) and (5)) and experimental results

TABLES

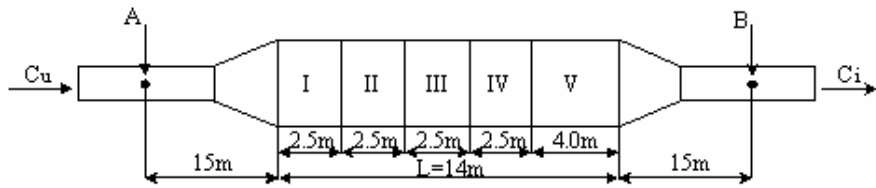
Table 1. Ash granulometry composition in thermal power plant "Gacko" [14]

Ash particle diameter d_p [μm]	Examination 1			Examination 2		Examination 3	
	Mean ash particle diameter d_p [μm]	Mass ratio of fractions [%]	Cumulative ratio mass fraction [%]	Mass ratio of fractions [%]	Cumulative ratio mass fraction [%]	Mass ratio of fractions [%]	Cumulative ratio mass fraction [%]
> 250	250	0.54	100.00	0.72	100.00	2.03	100.00
125 to 250	187.5	4.49	99.46	6.12	99.28	11.43	97.97
80 to 125	102.5	14.27	94.97	14.46	93.16	16.92	86.54
37 to 80	58.5	11.73	80.70	16.44	78.70	15.69	69.62
30 to 37	33.5	11.72	68.97	6.04	62.26	4.42	53.93
20 to 30	25.0	22.28	57.25	17.06	56.22	15.86	49.51
15 to 20	17.5	12.21	34.97	14.44	39.16	11.38	33.65
10 to 15	12.5	10.90	22.76	14.82	24.72	10.62	22.27
8 to 10	9.0	4.07	11.86	4.20	9.90	3.94	11.65
1 to 8	4.5	7.79	7.79	5.70	5.70	7.71	7.71
Entrance	100.00			100.00		100,00	

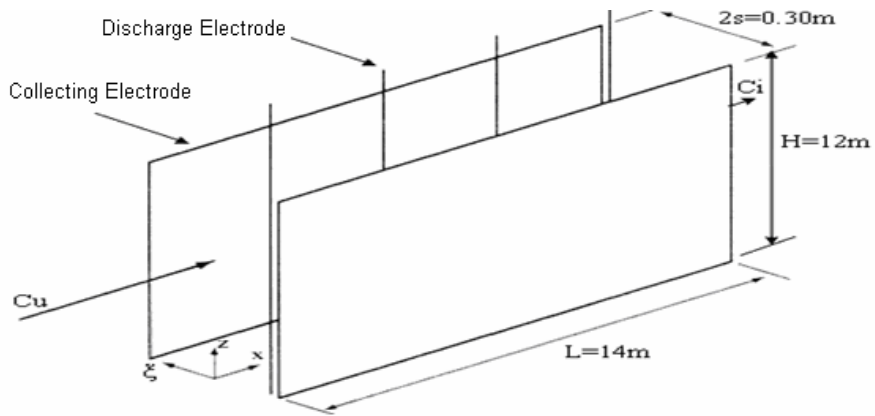
Table 2. Mean measured and calculated values needed for electrostatic precipitator analysis in thermal power plant "Gacko" [14]

Characteristic dimensions	Examination 1	Examination 2	Examination 3
Coal consumption m_c , [kg/h]	300000	300000	300000
Mass fraction of ash in coal A_c , [%]	11.76	17.55	21.76
Volume fraction of wet in flue gas W , [%]	17.2 ± 0.5	16.8 ± 0.5	16.9 ± 0.59
Volume fraction of O ₂ in flue gas, [%]	7.0 ± 0.3	8.3 ± 0.3	8.3 ± 0.3
Volume fraction of CO ₂ in flue gas, [%]	13.6 ± 0.3	12.0 ± 0.3	12.0 ± 0.3
Volumetric flow rate of wet flue gas Q , [Nm ³ /h]	687000	701000	699000
Volumetric flow rate of dry flue gas Q , [Nm ³ /h]	568836	583232	580869
Flue gas temperature t , [°C]	204 ± 2	196 ± 2	199 ± 2
Mean velocity of flue gas through the electrostatic precipitator v , [m/s]	1.1	1.1	1.1
Flue gas dynamic viscosity μ , [Pa·s]	$14.288 \cdot 10^{-6}$	$14.511 \cdot 10^{-6}$	$14.506 \cdot 10^{-6}$
Mean electric field strength E , [kV/m]	117	138	172
Collecting electrodes effective area A , [m ²]	16464	16464	16464
Length of collecting electrodes L , [m]	14	14	14
Height of collecting electrodes H , [m]	12	12	12
Distance between collecting electrodes $2s$, [m]	0.30	0.30	0.30
Ash particle migration velocity ω , [m/s]	0.0377	0.0449	0.0440
Specific collecting area A/Q , [s/m]	86.2742	84.5512	84.7931
Mean value of ash particles collection in electrostatic precipitator (equations (1) and (9)), η , [%]	96.43	97.91	99.22
Mean value of ash particles collection in electrostatic precipitator (equations (4) and (9)), η , [%]	97.15	98.08	98.92
Mean values of ash particles collection in electrostatic precipitator (equations (5) and (9)), η , [%]	98.97	99.40	99.72
Ash volumetric mass concentration at electrostatic precipitator entrance C_u (dry flue gas, 6% O ₂), [mg/Nm ³]	29926	47928	59622
Ash volumetric mass concentration at electrostatic precipitator exit C_i (dry flue gas, 6% O ₂), [mg/Nm ³]	1218	1064	1419
Ash collecting efficiency in the electrostatic precipitator (equation (6)) η , [%]	95.93	97.78	97.62

FIGURES



a)



b)

Figure 1 a) Schematic diagram of electrostatic precipitator with ash particles and polluting substances in flue gas sampling positions, b) schematic diagram of collecting and discharge electrodes of electrostatic precipitator

(C_u - mass ash particle concentration at the entrance, $[mg / Nm^3]$, C_i - mass ash particle concentration at the exit, $[mg / Nm^3]$, H - height of collecting electrodes [m], L - length of collecting electrodes, [m], $2s$ - distance between collecting electrodes, I,II,III,IV,V – electric fields (zones), A,B – positions of ash particles sampling)

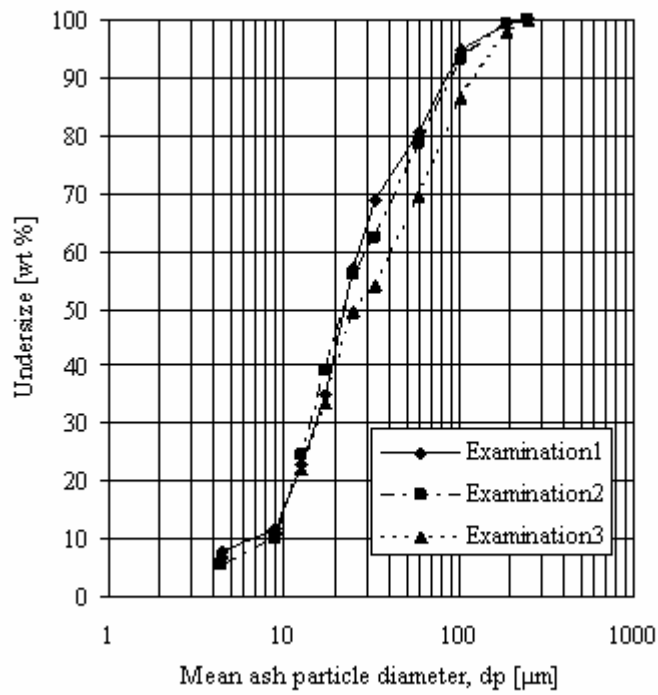


Figure 2. Fly ash size distribution in thermal power plant "Gacko"

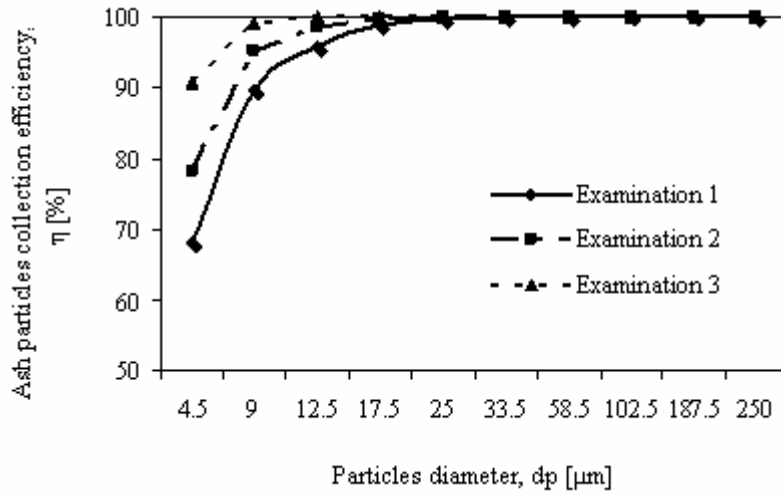


Figure 3. Influence of ash particle diameter on ash collection efficiency

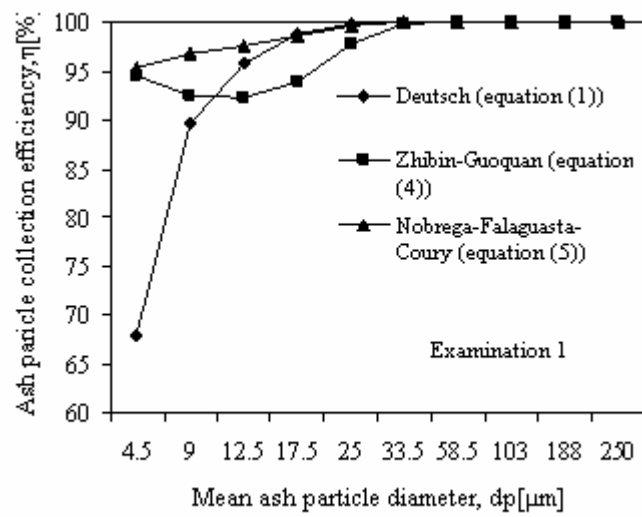


Figure 4a. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator (Examination 1)

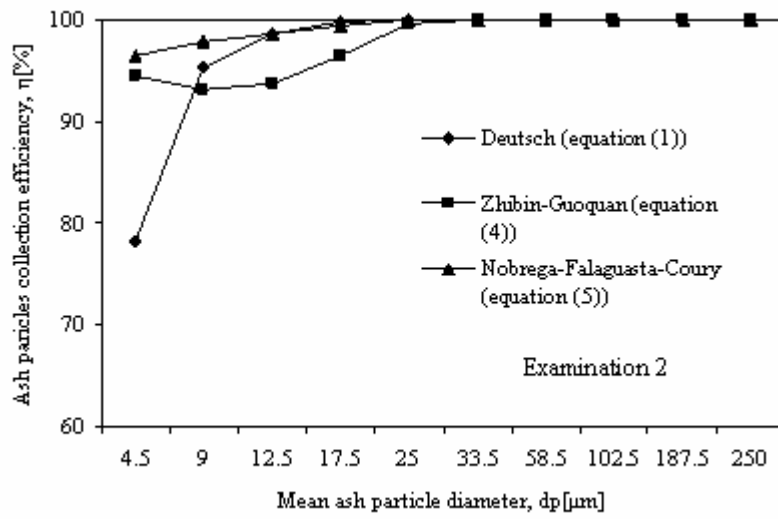


Figure 4b. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator (Examination 2)

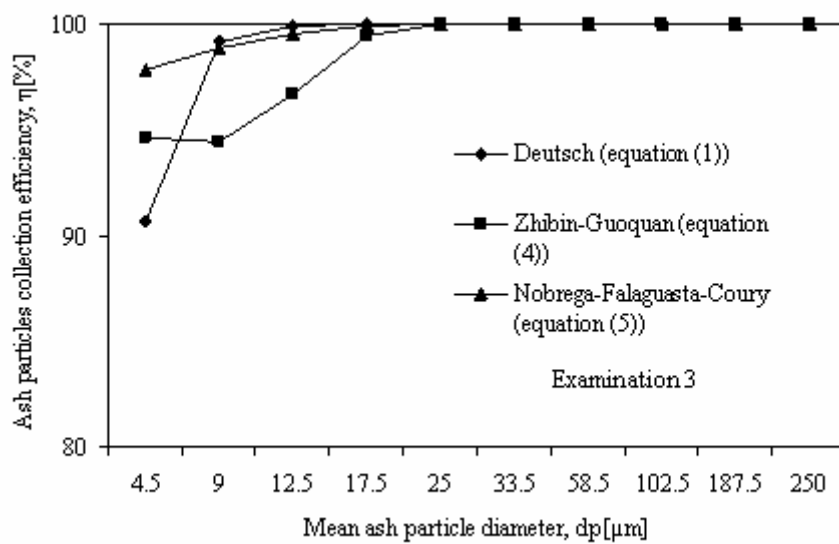


Figure 4c. Ash collection efficiency comparison by use of different theoretical models in electrostatic precipitator (Examination 3)

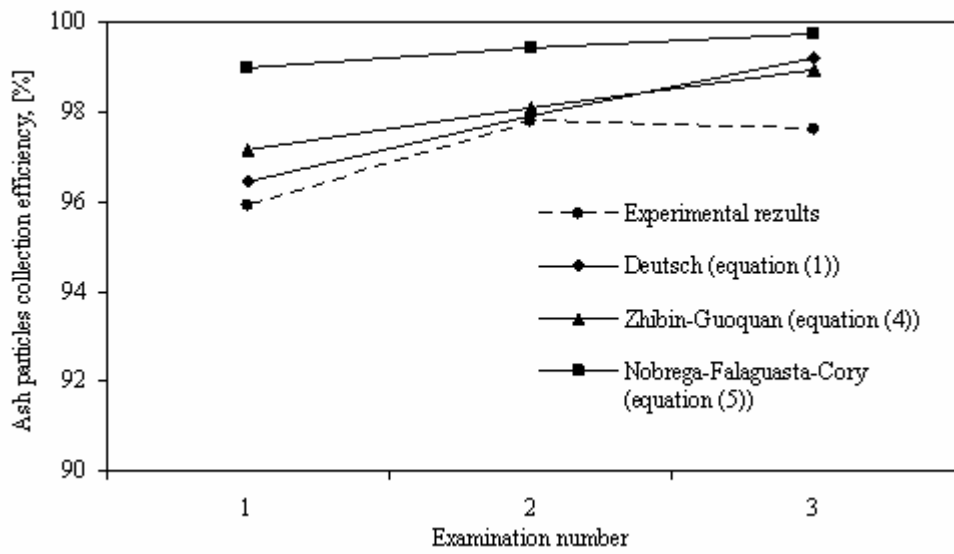


Figure 5. Comparison of the ash particle mean collection efficiencies in electrostatic precipitator between theoretical models (equations (1), (4) and (5)) and experimental results