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APPLICATION OF THE ASYMMETRIC PROFILES OF GAS VELOCITY TO AN ELECTROSTATIC PRECIPITATOR

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ZASTOSOWANIE ASYMETRYCZNYCH PROFILI PRĘDKOŚCI W ELEKTROFILTRZE

W artykule zaprezentowano badania sposobu rozdziału gazu na modelu fizycznym i symulacje komputerowe separacji pyłu w poziomym elektrofiltrze z płaskim dyfuzorem wlotowym. Badania przepływu gazu przeprowadzono metodą wizualizacji i pomiaru prędkości w przekrojach poprzecznych komory modelu. Dobierając odpowiednie sita dławiące i łopatki kierujące w dyfuzorze uzyskano skośne profile prędkości gazu (różne stopnie skośności). Otrzymane profile prędkości powinny zapewnić wyższe skuteczności działania elektrofiltru niż dotychczas stosowane profile równomierne. To założenie potwierdziły wyniki symulacji komputerowej uzyskane przy pomocy programu SYMULA-X. Wyniki badań modelowych i symulacji komputerowej przedstawiono w postaci graficznej.

Summary

The paper presents research upon the gas distribution in a physical model and the computer simulation of dust separation in a horizontal electrostatic precipitator (ESP) with a flat inlet diffuser. The research of a gas flow was carried out using the visualization method and the velocity measurement in cross sections of a model chamber. By selecting suitable choking diffusion screens and deflecting vanes in a diffuser the oblique profiles of a gas velocity were obtained for different obliqueness degree. It was assumed that the velocity profiles obtained should guarantee higher performance of an ESP than those uniform profiles as used so far. Those assumptions were proved by the results of computer simulation obtained using a program SYMULA-X. The results of experiments and computer simulation are presented in a graphical form.

INTRODUCTION

One of the most important factors, which influence the efficiency of electrostatic precipitators, is the distribution of flue gas velocity across a section of its chamber. The model of uniform gas flow through a precipitator has been assumed to be the most favourable so far. The velocity profile of such a flow across the entire cross section as well as on the entire length of the electrostatic precipitator remains unchanged. This model was a basis for the derivation of the Deutsch-Anderson equation [14] that describes the performance efficiency of an electrostatic precipitator

$$\eta = 1 - \exp\left(-\frac{Lw}{h\bar{v}}\right), \tag{1}$$

where:

- L – electrostatic field length,
- w – migration velocity of particles,
- $\bar{v}$ – average gas velocity in the chamber,
- h – inter-electrode spacing.

The above assumption is theoretical as gas flow in the electrostatic precipitator is usually non-uniform and this non-uniformity is caused by the shape and dimensions of ducts supplying flue gas to the electrostatic precipitator. White [14] was the first to modify equation (1) accounting for variability of gas velocity in the cross section of the precipitator chamber. He obtained the following relationship which defines horizontal electrostatic precipitator efficiency

$$\eta = 1 - \int_0^{v_{max}} \exp\left(-\frac{Lw}{h\bar{v}}\right) f(v)\,\mathrm{d}v, \tag{2}$$

where $f(v)$ is the function of gas velocity distribution in the cross section of the electrostatic precipitator chamber (for example Gauss' distribution).

Idelcik [6] proposed the following illustration of the impact of variable gas velocity on the efficiency of precipitation

$$\eta = 1 - \exp\left(-\frac{Lw}{h\bar{v}M_k}\right). \tag{3}$$

Boussinesq's coefficient M_k defining non-uniformity of gas velocity profile in the cross section of the chamber can be expressed as follows

$$M_k = \frac{1}{A}\int_A \left(\frac{v}{\bar{v}}\right)^2 \mathrm{d}A, \tag{4}$$

where:

- A – cross sectional area of the chamber of an electrostatic precipitator,
- v – local gas velocity in the cross section of the chamber.

So far coefficient M_k for highly efficient electrostatic precipitators has been assumed to meet the condition $M_k \leq 1.1$ [9].

In practice it turned out that ideally uniform gas velocity distribution would be the most favourable if at the same time the concentration of particles across the electrostatic field was constant. In reality gas concentration values in the lower part of the chamber are higher while in the upper part-lower. The values are also higher in the inlet and lower in the outlet of the electrostatic precipitator.

In the mid 80s the concept of applying the principle of uniform gas velocity distribution in the electrostatic precipitator inlet as well as along the entire chamber was thoroughly changed. Hein [4] proposed linear velocity profile in the cross section of the chamber which was higher at the bottom of the chamber at the entrance of the precipitator and higher at the top of the chamber at the exit of the chamber.

Frank [1], on the other hand, introduced a velocity profile which was identical at the inlet and outlet, rising from bottom to the top of the electrostatic precipitator chamber.

GAS VELOCITY PROFILES

Research on the impact of asymmetry (askewness) of flue gas velocity in the horizontal electrostatic precipitator on its efficiency is carried out worldwide [1, 3–5, 10–13]. Thus it is necessary to classify the types of asymmetry of profiles which can occur in the vertical cross section of an electrostatic precipitator. It has been assumed that gas velocity profiles in the horizontal cross sections of the chamber are uniform.

A linear equation in its non-dimensional form has been applied to describe the shape of flue gas velocity in the cross section of the chamber

$$v^* = az^* + b, \tag{5}$$

where:

$v^* = v/v_n$ – non-dimensional gas velocity,

$z^* = z/H$ – non-dimensional vertical co-ordinate,

a – the gradient of a straight line,

b – constant,

v – gas velocity in the electrostatic precipitator chamber,

H – the height of the electrostatic precipitator chamber,

$v_n = 1$ m/s – accepted (nominal) velocity in the electrostatic precipitator.

Depending on the slope of the line towards the axis three types of profiles can be distinguished:

a) growing linear ($a > 0$),

b) constant ($a = 0$),

c) falling linear ($a < 0$).

In reality the velocity profiles of the flow of flue gas in the chamber of an electrostatic precipitator often differ significantly from the linear profiles listed above. That is why each of the listed linear profiles should be supplemented with concave and convex profiles. In total 9 basic shapes of velocity profiles are obtained.

To define the type of an asymmetric non-linear profile an additional non-dimensional parameter φ has been introduced and described as follows

$$\varphi = \frac{v_s - v_c}{v_n}, \tag{6}$$

where:

$v_c = (v_d + v_g)/2$ – the gas velocity half way up the vertical section of the precipitator calculated using equation (5),

v_d, v_g – the real gas velocity at the bottom and the top of the precipitator respectively (Fig. 1),

v_s – the real gas velocity half way up the vertical section of the precipitator.

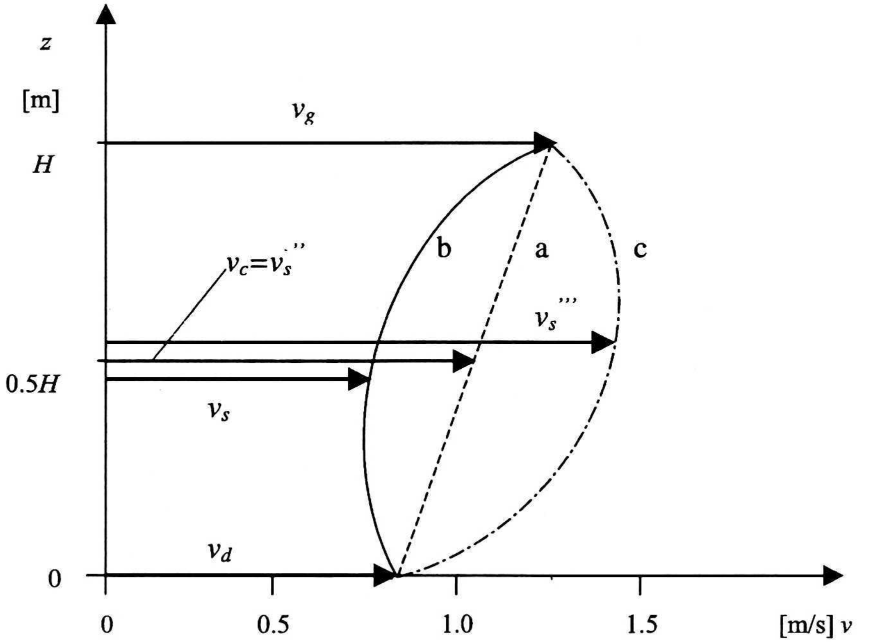


Fig. 1. Examples of velocity profiles of flue gas in the vertical cross section of the chamber of an electrostatic precipitator where the flow is dominant in the upper part of the chamber: a – linear profile, b – concave profile, c – convex profile

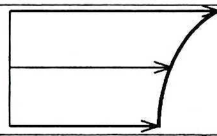
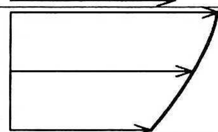
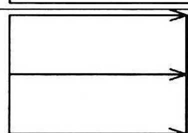
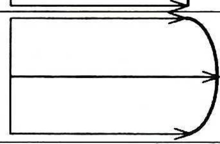
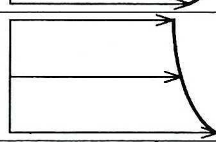
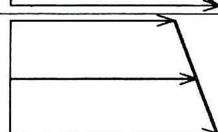
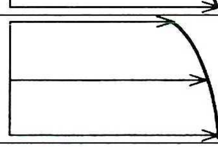
All types of velocity profiles together with parameters which characterize them have been presented in Table 1. Parameter φ assumes the following values:

- for linear profiles $\varphi = 0$,
- for convex profiles $\varphi > 0$,
- for concave profiles $\varphi < 0$.

Certainly, these velocity profiles do not constitute all possibilities of profile combinations which allow to achieve high efficiency values for precipitation of flue gases of defined parameters and for specific design parameters of the electrostatic precipitator. In practice, the real shape of the gas velocity profile in the chamber of an electrostatic recipitator is substituted with a profile from Table 1 which is most similar to the real shape.

To achieve a defined gas velocity profile in the chamber of an electrostatic precipitator it is necessary to apply appropriate elements shaping and moderating the flow in the diffuser. These elements can be selected by carrying out research on a physical model of the electrostatic precipitator where the flow of flue gas is substituted with a stream of clear air.

Table 1. Types of flue gas velocity profiles in the vertical cross section of the electrostatic precipitator

No.	a	φ	Shape of the velocity profile	Description of velocity profile
1.		$\varphi < 0$		Growing concave
2.	$a > 0$	$\varphi = 0$		Growing linear
3.		$\varphi > 0$		Growing convex
4.		$\varphi < 0$		Concave
5.	$a = 0$	$\varphi = 0$		Even
6.		$\varphi > 0$		Convex
7.		$\varphi < 0$		Falling concave
8.	$a < 0$	$\varphi = 0$		Falling linear
9.		$\varphi > 0$		Falling convex

The results of research carried out on the model of the electrostatic precipitator can easily be transferred to the real object. In practice, in most cases the real velocity profiles are similar to those in the model [12].

In the case of untypical diffuser channels, both in laboratories and in industrial conditions, it is often easier to achieve asymmetric rather than ideally uniform shapes of gas velocity profile. On the basis of the results, as obtained during model tests, one can design proper shaping and moderating elements at the inlet of an electrostatic precipitator. For some asymmetric profiles of the gas velocity, as determined during the model tests, the numerical computations of the efficiency of an electrostatic precipitator were made.

MODELLING GAS FLOW THROUGH THE ELECTROSTATIC PRECIPITATOR BASICS FOR MODELLING THE AERODYNAMICS OF ELECTROSTATIC PRECIPITATORS

In order to model the electrostatic precipitator physically, it is necessary to meet the requirement of geometric similarity by means of applying an appropriate linear scale of the model. Each model should be copied only with respect to elements which have an essential influence on forming gas velocity field in the diffuser and the chamber of the electrostatic precipitator. Then, it is necessary to meet the requirement of dynamic similarity where Reynolds Re and Euler Eu figures are the most important criteria for gas flow in the electrostatic precipitator.

In real electrostatic precipitators the Reynolds' numbers calculated for the flow of flue gas in the channels, diffuser and chamber are usually in the range $10^5 \div 10^6$ flow is therefore turbulent. Precise physical modelling requires Reynolds' numbers being equal in the model and the object. This is, however, a condition difficult to meet. Thus approximated modelling is applied which is based on the existence of the range of self-modelling. Such a range exists with turbulent flow for a range of Reynolds' numbers for which the following condition is met

$$\mathrm{Eu} = \mathrm{f}(\mathrm{Re}) = \mathrm{const}. \tag{7}$$

This means that the results of measurement of velocity distribution and pressure losses in the model can be transferred to the real object reliably. In modelling research $Re = 10^4$, which usually meets condition (7), is assumed to be the lower limit of the self-modelling range. This assumption is the basis for defining the linear scale of the electrostatic precipitator model [2].

In modelling research it is also important to meet the requirement of dynamic similarity – Euler's number. This criterion allows hydraulic resistance to be transferred from the object to the model and vice versa [8].

METHOD OF MODELLING RESEARCH

Modelling research of gas flow in the electrostatic precipitator is carried out on physical models which use air as a substitute of flue gases. This allows the velocity distribution, flow direction and pressure losses to be determined. Geometric models of examined objects are transparent and are made of organic glass (plexi). This way flow can easily be visualized and the quality of the different elements shaping and moderating the stream can be assessed [7, 8].

In modelling research local gas velocity is measured using the hot-wire anemometer. In order to assess the quality of flow (location of swirls, areas of recirculation, the assessment of the degree of fill of the precipitator) the flow is visualized using the "glowing spark technique". Using this method, selected solid particles are introduced to the stream of air. In the research described burning saw dust was used. Steady burning and constant dosage was achieved using a circulative gas burner with tangential application of air under pressure. Glowing particles of saw-dust carried by the stream of air enable the visualization of flow and recording of the flow using a camera or a VHS camera. It should be noted that due to the relatively small size and low density of the burning particles the effect of their momentum on the trajectories of flow is negligible. Both quality (visualization) and quantity measurements (using the hot wire anemometer) are carried out in identical conditions.

DESCRIPTION OF RESEARCH
DESCRIPTION OF THE MODEL

The object under research was a horizontal four-field, three stream electrostatic precipitator used in precipitation of flue gas from a 200 MW steam boiler.

The aerodynamic model of one of the streams of the electrostatic precipitator together with ducts was built from plexi in the scale of 1:16 (Fig. 2a). Due to the complexity of the shape of the diffuser (Fig. 2b) as well as the asymmetry of the inlet and outlet of the electrostatic precipitator, non-uniform gas velocity profiles were used.

A non-uniform gas flow profile at the inlet of the electrostatic precipitator chamber was established by means of shaping elements installed in the diffuser. In the first part of the modelling research, shaping and moderating elements (two diffusion gas-distribution screens and a layer of guide vanes) were designed and installed in order to form the flow at the inlet of the electrostatic precipitator (Fig. 2b).

The parameter characterizing diffusion screen is the quotient of the surface area of the perforations to the surface area of the whole screen

$$f = A_o / A, \tag{8}$$

where:

A_o – surface area of diffusion screen apertures,

A – surface area of the whole screen.

The first and the third diffusion screens consisted of horizontal C-profiles with parameters $f_1 = 37\ \%$ and $f_3 = 55\ \%$ respectively. The second element was a set of guide vanes with flat blades of $270\times15\times3$ mm. The angle of inclination of blades towards vertical axis amounted to 40°.

During the basic research the only parameter changed was the number of blades in the set of guide vanes.

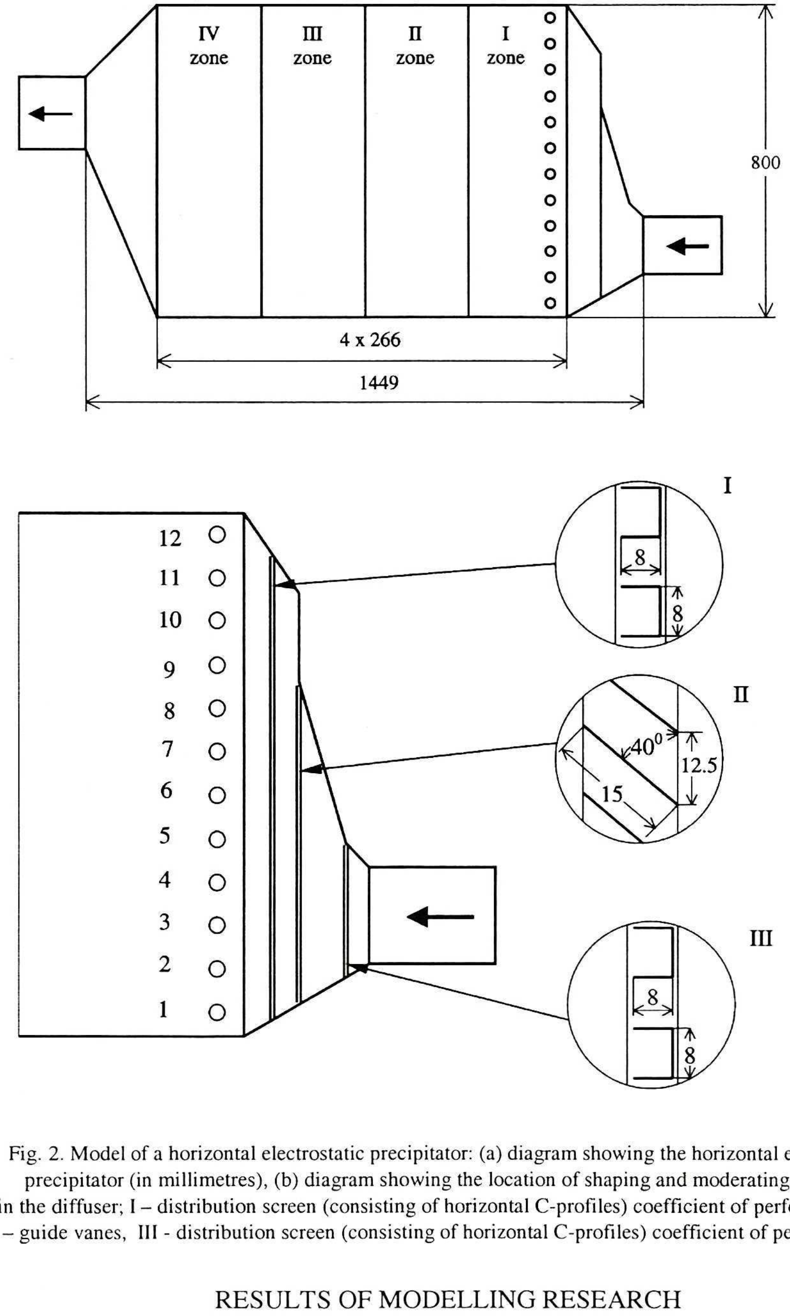


Fig. 2. Model of a horizontal electrostatic precipitator: (a) diagram showing the horizontal electrostatic precipitator (in millimetres), (b) diagram showing the location of shaping and moderating elements in the diffuser; I – distribution screen (consisting of horizontal C-profiles) coefficient of perforation 55%, II – guide vanes, III - distribution screen (consisting of horizontal C-profiles) coefficient of perforation 37%

RESULTS OF MODELLING RESEARCH

An example of one of asymmetric profiles applied to the inlet of the chamber of the model was a concave profile shown in Fig. 3. It resulted from non-uniform placement of blades in the set of guide vanes (in the lower part of the inlet the blades of the guide vanes were placed at $s' = 12.5$ mm apart, at the top part of the inlet the blades of the guide vanes were positioned $s'' = 25.0$ mm apart).

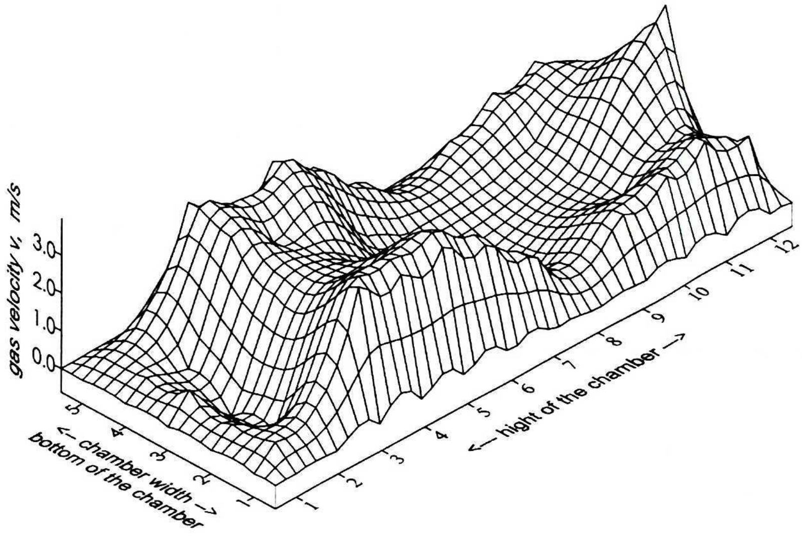


Fig. 3. Velocity distribution at the inlet of the chamber of the electrostatic precipitator for a concave profile

Fig. 4 shows the visualization of air flow in the model of the electrostatic precipitator examined.

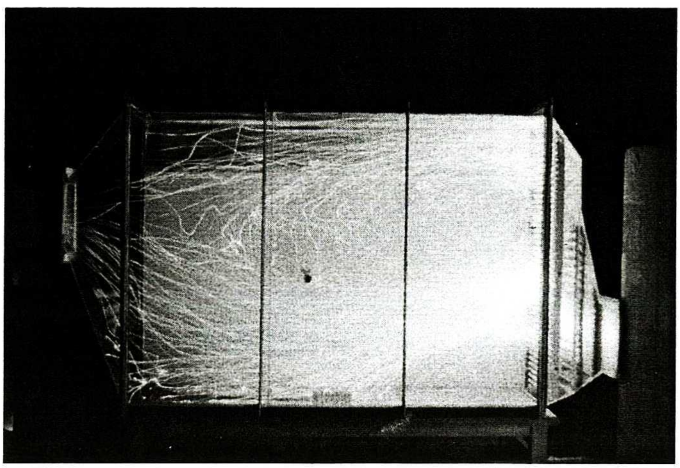


Fig. 4. Visualization of gas flow in the chamber of the model of the examined electrostatic precipitator

NUMERICAL MODEL
DESCRIPTION OF THE CALCULATION METHOD

In theoretical research of the flow of flue gas through the electrostatic precipitator Hein [4] and Lind [10] introduced a discrete model. Numerical calculations carried out for such a model for various gas velocity profiles in the electrostatic fields of the precipitator also indicated the increase in its efficiency in some cases of non-uniform velocity field [1, 3, 5, 11]. Theoretical and experimental analysis has shown that uniform gas velocity does not always give the highest precipitation efficiency. In some cases non-uniform velocity profiles which are easier to achieve turned out to give better results.

The calculation model used in the research consists of cells (discrete separated elements) which are used to divide the entire electrically active part of the electrostatic precipitator. Each cell is a miniature electrostatic precipitator where flue gas of defined dust concentration enters. It has been assumed that the gas velocity in such a cell is uniform. In each cell dust is precipitated in accordance with the Deutsch-Anderson (1) formula. A small amount of precipitated dust is reentrained again by the gas stream and added to dust which has not been precipitated in the preceding cell [13].

In order to define the mass of reentrained dust a coefficient of dust reentrainment has been introduced to the calculation which can be expressed by the following formula

$$\kappa = m_w / m_o \,, \tag{9}$$

where:

m_w – mass of reentrained dust,

m_o – mass of dust settling in dust hopper.

RESULTS OF CALCULATIONS

Numerical calculations of diffuser efficiency were carried out for selected asymmetric velocity profiles by means of SYMULA-X [13] software. In the computations, two gas velocity profiles at the inlet of the chamber of an electrostatic precipitator (zone I, Table 2) were taken:

- uniform ($a = 0$, $\varphi = 0$),
- concave ($a = 1.23$, $\varphi = -0.48$)

In the middle part of the chamber (zone II and III) the uniform profiles were assumed. At the outlet from an ESP (zone IV), for a concave profile two outlet profiles apiece were taken:

- uniform ($a = 0$, $\varphi = 0$)
- linear-slanting ($a = 0.9$, $\varphi = 0$).

In the procedure the dust reentrainment was taken into account, and the calculation was made for three values of the dust reentrainment coefficient: $\kappa = 0.00$, $\kappa = 0.08$, $\kappa = 0.15$.

It was assumed that the mean dust concentration at the inlet to the ESP chamber was 22 g/m^3 under standard conditions. Particle size distribution is described by the normal distribution of an arithmetic mean of 12 μm and of a standard deviation of 2 μm.

The data and the results of the computation of the performance efficiency of an electrostatic precipitator are presented in Table 2.

Table 2. Efficiency and dust concentration versus the shape of gas velocity profile and the coefficient of reentrainment

No.	Shape of velocity profile in the inlet	The value of parameters a and φ in zone			$\kappa = 0.00$		$\kappa = 0.08$		$\kappa = 0.15$	
		I	II i III	IV	η %	S mg/m^3	η %	S mg/m^3	η %	S mg/m^3
1.	Uniform	$a = 0$ $\varphi = 0$	$a = 0$ $\varphi = 0$	$a = 0$ $\varphi = 0$	99.545	100	99.313	151	99.019	215
2.	Growing concave	$a = 1.23$ $\varphi = -0.18$	$a = 0$ $\varphi = 0$	$a = 0$ $\varphi = 0$	99.596	88	99.390	134	99.136	190
3.	Growing concave	$a = 1.23$ $\varphi = -0.18$	$a = 0$ $\varphi = 0$	$a = 0.9$ $\varphi = 0$	99.621	83	99.440	123	99.215	172

On the basis of the results of the numerical computations, as shown in Table 2, one can state that for a given coefficient of the dust reentrainment κ the values of the efficiency of dust collection η are higher for nonuniform velocity profiles every time.

The dust concentration S in flue gas after the ESP for a given κ is lower for the slanting flows. The decrease in the dust concentration with respect to a uniform flow is considerable and is:

- 17% for $\kappa = 0$,
- 18% for $\kappa = 0.08$,
- 20% for $\kappa = 0.15$.

The above results are a presentation of a fragment of research upon the improvement of the ESP performance efficiency carried out by our research team.

SUMMARY

1. The application of a non-uniform (growing concave) flue gas velocity profile in an electrostatic precipitator can facilitate a permanent increase in precipitation efficiency.
2. The simulation computations, as made for nonuniform flows, showed the increase in the efficiency by 0.1% on average for the asymmetric flows at the inlet to the ESP compared to the efficiency for uniform flows. This increase brings about a decrease of the dust concentration after the ESP by 15%.
3. Physical modelling permits one to obtain a desired velocity profile thanks to the selection of type and geometry of the shaping and moderating elements and to enable their simple reproduction in a real object.

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