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The Influence of Shape and Dimension of Dust Particle on Electrostatic Precipitator Operation

***Abstract**. The efficiency of electrostatic filters depends mainly on the value of the supply voltage and the distribution of the electric field. This paper presents an analysis of organic dust. The dust was used during testing of a bifilar electrostatic precipitator. Information about the shape and size of dust particles allows to simulate the influence of particle size and shape on the operation of the filter.*

***Streszczenie.** Skuteczność filtrów elektrostatycznych zależy głównie od wartości napięcia zasilającego oraz rozkładu pola elektrycznego. W artykule zamieszczono analizę pyłu wykorzystywanego w badaniach skuteczności bifilarnego filtru elektrostatycznego. Informacje na temat kształtu i rozmiaru cząstek pyłu pozwoliły na przeprowadzenie symulacji wpływu kształtu i rozmiaru cząstek na funkcjonowanie filtru. (**Wpływ kształtu i rozmiaru cząstek pyłu na działanie odpylacza elektrostatycznego**)*

Keywords: precipitator, electrofilter, bifilar filter.
Słowa kluczowe: odpylacz, elektrofiltr, filtr bifilarny.

Introduction

The problem associated with air pollution removal has been known for many years. Numerous types of filters with diversified structure have been created during this period. The range of filters encompasses mechanical filters (e.g. cyclones, fabric and bag filters), dry and wet filters as well as electrofilters [1, 2, 3, 4]. Electrostatic precipitators (ESP) are extensively used by industry. In connection with the long period of their practical use, ESPs are the subject to continuous improvements. The changes can be observed in the following scope [4, 5, 6]:

- preliminary charging of dust particles,
- modification of shapes (flat or cylindrical) and number of electrodes,
- modification of electrodes material,
- several cleaning stages,
- agglomeration of small particles of impurities,
- filter chamber structure (rectangular or cylindrical layout),
- introduction of different improving methods for electrostatic precipitation process (e.g. cyclones).

Regardless of applied modifications, the working principle of an electrofilter is always the same. The particles of impurities are charged in the system consisting of emission electrode and collecting electrode. In the next stage, charged particles are attracted to collecting electrode. The presence of corona effects with current density of the order of 0.1-1.0 mA·m^{-2} [4]. After atomization, some types of dusts form explosive mixtures (e.g. coal, flour) impeding or preventing the use of typical electrofilters dedicated for the removal of this type of impurities [6, 7, 8, 9].

However, the structure of electrofilter described in the present paper is different. Bifilar winding plays the role of working element. This winding can be wound onto a flat as well as cylindrical frame. The working winding is wound in a manner ensuring the opposite electric potential of the adjacent conductors in winding [10, 11]. The conductors are insulated from each other. There is no working current of particles charging. The current flowing in the system depends on the value of insulation resistance. The winding of bifilar filter can be provided with DC and AC power supply. The practical tests demonstrated that DC power supply is a better solution due to significant electrical capacity [10]. Due to the lack of the corona effect current, it is possible to apply a bifilar filter for explosive mixtures. There are several typical methods of electrofilters functioning analysis. The first method consists in the determination of global efficiency of the filtration process. It is possible to apply Eq. (1) for all types of the filters. This method is based on the measurement of the mass of impurities at the inlet and outlet of the filter [4, 8, 10]:

$$\eta = 1 - \frac{m_{out}}{m_{in}}, \tag{1}$$

where: η – efficiency of electrofilter, -; m_{out} - particle mass concentrations at the outlet of the device, kg; m_{in} - particle mass concentrations at the inlet of the ESP, kg.

With regard to analysis of the method of functioning and designing of discharge filters, Deutsch theory is applied [2, 12, 13]. The equation (2) introduces the issues associated with particle movements in the filter electrodes electric field into the analysis.

$$\eta = 1 - e^{-N_{De}} = 1 - e^{-\frac{w \cdot A}{Q}}, \tag{2}$$

where: η – theoretical efficiency of ideal electrofilter, -; N_{De} – Deutsch number, -; A - surface area of the collection electrode, m^2; w - particle migration velocity; m·s^{-1}; Q – air flow rate; m^3·s^{-1}.

In case of discharge filters, dust particles can have electric charge and additionally are charged in course of corona effect discharge. Attraction of dust particles to electrodes is based on the opposite charges of a dust particle and collecting electrode. In case of analysis of bifilar filters functioning method, it is important to indicate the source of F force affecting dust particles. In case of pre-charged particle (e.g. in a result of friction), particle attraction force caused by free charges Fe participates in the attraction. Unless a particle is charged, attraction force caused by polarization F_p is the principal factor of the impact [10, 14, 15]. The value of electric field intensity or its change is of key importance for the value of force in the both cases.

$$F = F_e + F_p = \int_V \rho E \, dV - \frac{1}{2}\varepsilon_p \int_V grad \; E^2 \, dV, \tag{3}$$

where: F – particle attraction force, N; F_e – dielectric particle attraction force caused by free charges, N; F_p – dielectric particle attraction force caused by polarization, N; ρ – volumetric charge density, C·m^{-3}; ε_p – permittivity of dust particle, F·m^{-1}; E – electric field intensity inside dust particle, V·m^{-1}.

Three approaches conforming to the three equations presented above are applied in the studies concerning the filters functioning i.e.:

- estimation of global efficiency of filtration process. Less emphasis is put on phenomena occurring in the filtering system (Eq. 1) [3, 8, 16];

- examination of filter functioning in terms of the area of electric field impact on air stream as well as estimation of the manner of working electrodes shaping (Eq. 2) [7, 17];

- determination of the impact of electric field parameters (voltage, electric field intensity) (Eq. 3) [3, 9].

In parallel, experimental works and the works modelling the electrofilters functioning are carried out [4, 7, 13, 18]. In previously published papers concerning bifilar filters, prevails the presentation of filter efficiency results in various applications [10, 11].

The present paper is focused on the manner of bifilar winding electric field impact on dust particles in the surrounding of such winding. Dust material used in course of filter efficiency examination has been examined repeatedly in terms of granulation. Information about dust parameters has been used for execution of simulation of electric field variations in dust particles. This information is important for determination of “particles – to – electrodes” attraction force.

Test stand and apparatus

The practical tests in the scope of bifilar filter operation efficiency have been carried out at the stand presented on Fig. 1. Air pumping to filters system is provided by means of inlet fan. Controlled mass of dust is added in the first segment of test stand. Air pollutions are captured by means of three segments of the filter with bifilar winding in centrally nstalled filtration chamber. The chamber is closed by means of fabric filter with exhaust fan. Air parameters (humidity, temperature), humidity of dust material and bifilar windings power supply parameters (voltage, corona current) are controlled in course of tests. Two methods of filtration efficiency determination were used. The first method consisted in comparison of mass of dust introduced into filtration system with the mass of dust accumulated on bifilar filter segments, in precipitation chamber and on fabric filter. The measurements of the mass of dust made it possible to determine the global efficiency of filtering system. Another examination method consisted in the measurement of dust concentration at the inlet and outlet of precipitation chamber. The measurements have been carried out by means of Portable Dust Monitor model 1.108 (manufacturer: Grimm Aerosol Technik GmbH & Co. KG). The measurements of the mass of dust made it possible to determine the efficiency of impurities capturing in relation to the selected granulometric fraction of dust.

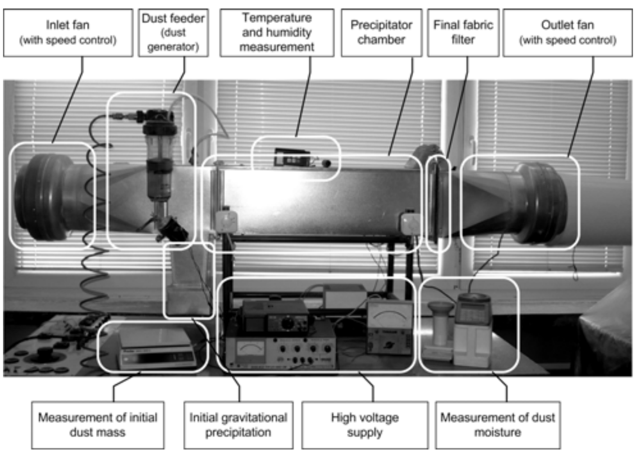

Fig. 1. View of bifilar filtration system

The earlier tests on the overall filter efficiency were carried out on dust samples obtained from “flour and pasta factory”. The samples are picked from the following places in the factory line: a porridge line (sample A); a pasta line (sample B), a flour line (sample C). The fourth sample (sample D) is dust on the basis a wheat flour (type 500).The relative moisture content of dust material is 11.4 %÷19.3 % at relative humidity 31÷51 %. The temperature of air on the inlet of the chamber is 24.1÷27.1°C at air pressure 995-998 hPa. The air velocity is 0.18 $m \cdot s^{-1}$. The voltage of bifilar windings achieves value of 13 kV (maximal value for working without electric discharges in this configuration).

In case of naked eye observation of samples, there are no visible grounds for determination of granulation or even for coarse determination of the material consisting of grains with larger diameter. In order to determine the granulometric distribution, Mastersizer 3000 analyzer has been used (manufacturer: Malvern Instruments Ltd.). The Mastersizer 3000 uses the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data is then analyzed to calculate the size of the particles that created the scattering pattern. Analyzer can recognize particle sizes in scope 0.01-3500 μm (dependent on sample preparation). The results of granulation distribution are presented on Fig. 2a-c. All the dust samples are characterized by similar distribution. There are samples with sizes of about 0.6 up to 806 μm. The content of particles with diameter of about 100 μm is the highest in the samples. Their volume fraction varies between about 6 and 8 %.

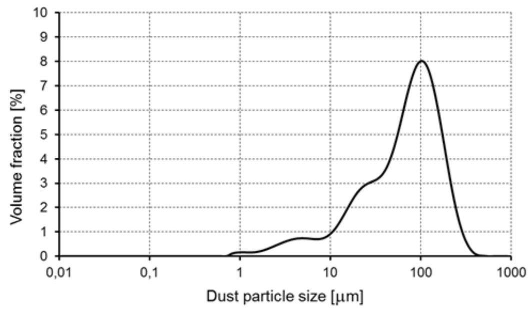

Fig. 2a. Volume distribution of dust particle size for A type dust

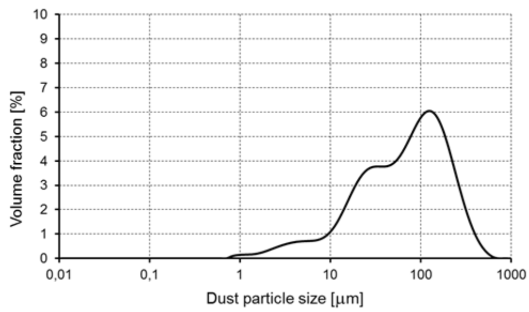

Fig. 2b. Volume distribution of dust particle size for B type dust

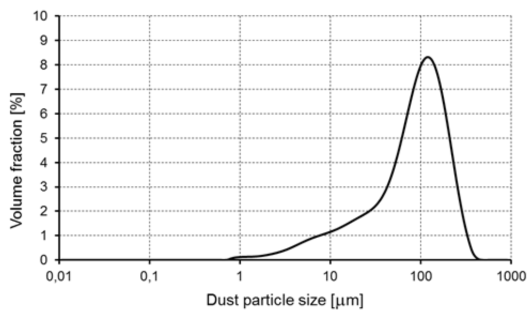

Fig. 2c. Volume distribution of dust particle size for C type dust

The knowledge of granulometric distribution does not provide any information about the shape of dust particles. Examined dust was subjected to observation by means of electron microscope. i.e. by means of scanning electron microscope Quanta FEG 250 (manufacturer: FEI Company). It accommodates the widest range of samples of any SEM system, capable of characterizing traditional samples from metals, fractures and polished sections, to non-conductive soft materials. The microscope achieves a resolution of 1 nanometer in high vacuum mode. The samples have been observed in the scope of magnifications between 10 and 4000. In case of particles with the largest dimensions, the dust particles with elongated shape up to 500 μm were prevailing (Fig. 3a).

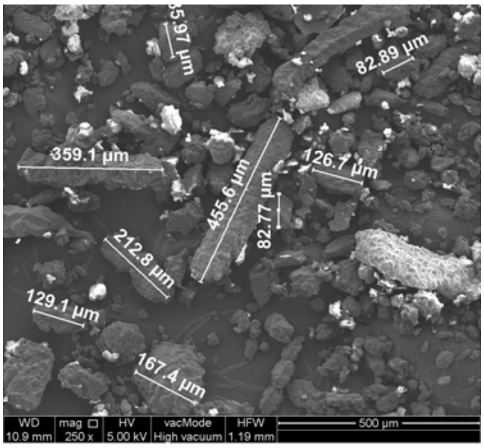

Fig. 3a. View of dust particles at 250x magnification

Fig. 3b. View of dust particles at 4000x magnification

The particles with dimensions close to 100 μm were characterized by the shape which can be described as an intermediate condition between a sphere and cuboid. Dust particles with the lowest granulation were characterized by spheroidal shape (Fig. 3b). The shape became more spheroidal with reduction of dimensions. The particles are characterized by compact structure without any sharp edges. No layered structure has been observed. The application of 4 models of particles (Fig. 5) has been declared in course of the simulation of electrical field impact:

- ellipsoidal (in cross-section ellipse 10x20 μm),
- spherical (in cross-section circle 10x10 μm)
- cuboidal (in cross-section rectangle 80x120 μm),
- cubical (in cross-section square 80x80 μm).

Results

Practical tests of bifilar filter system efficiency were carried out for 4 types of dusts. Applied windings were characterized by conductors with cross – section of 0.5; 1.0; 1.5; 2.5 i 4 mm^2 in PVC insulation. DC power supply with the voltage of 0, 5, 7, 10, 13 kV.

For the recognition of electric field intensity distribution inside a dust particle, free available software package FEMM 4.2 (ver. 2016) is used. This non commercial product is widely used in magnetic and electric field simulation. Simulated configuration incorporated a copper conductor with cross – section of 1 mm^2 in PVC insulation, with DC power supply – voltage of 10 kV. The winding was wound onto frame made of ebonite. On the basis of data from literature, assumed value of ε_p (dielectric permittivity of dust particle) was equal to 2 [10]. The distribution of field intensity is illustrated on Fig. 4.

The following features are specific for the electric field intensity distribution:

- presence of maximum values in the gap between winding conductors;
- rapid exponential decrease of electric field intensity vs. departure from the winding. The values on conductor insulation surface reach almost $4{\cdot}10^6$ V$\cdot$m^{-1}. On the distance of about 1 mm from insulation, the value of electric field intensity is less than $1{\cdot}10^6$ V$\cdot$m^{-1}.

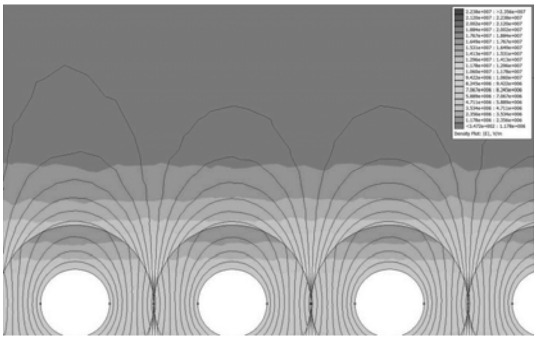

Fig. 4. Distribution of electric field intensity in bifilar winding with a solid chassis (voltage 10 kV, wire cross-section 1.0 mm^2)

Nine points have been declared in order to locate dust particles models. Points 1-5 are situated above the contact point of the conductors. Points 6-9 are located in the winding conductor axis. The points spacing in vertical axis is equal to 5 mm.

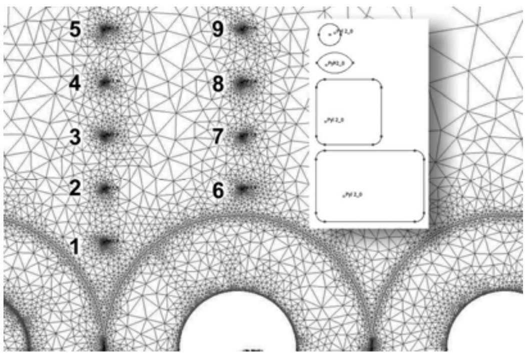

Fig. 5. Placement of dust particles around the bifilar winding during simulation

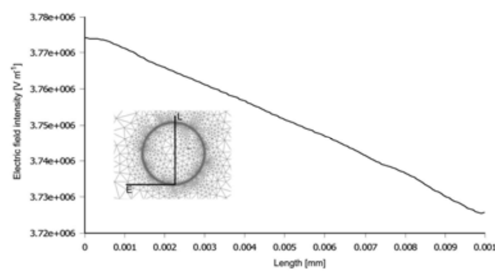

Fig. 6. Distribution of the electric field intensity along the vertical axis of the circular cross-section sample (point 1)

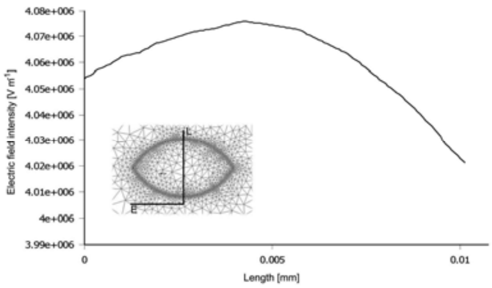

Fig. 7. Distribution of the electric field intensity along the vertical axis of the ellipsoidal cross-section sample (point 1)

The simulation of electric field intensity changes has been carried out along vertical axis for each of 4 models of dust particles. The simulations were carried out for each of nine points. The readings of electric field intensity changes have been taken as from the examples of diagrams shown on Fig. 6 and 7 for ellipsoidal and spherical particle placed in point 1 of bifilar filter system. The summary of values for all the cases is included in Tab. 1 and on Fig 8.

Table 1. Change of electric field intensity ($\cdot 10^3$ V$\cdot$m^{-1}) inside particle for selected particle location in the dedusting system (value converted to 1 μm of the sample model)

Point	Shape of dust particles			
	Ellipsoidal (ellipse)	Spherical (circle)	Cuboidal (rectangle)	Cubical (square)
1	7.90	5.00	5.78	7.00
2	3.70	2.60	1.99	3.38
3	2.00	1.30	1.25	1.46
4	1.01	0.55	0.70	0.92
5	0.59	0.29	0.38	0.50
6	3.20	2.10	2.13	2.16
7	1.94	1.20	1.00	1.29
8	0.99	0.78	0.56	0.94
9	0.55	0.43	0.29	0.44

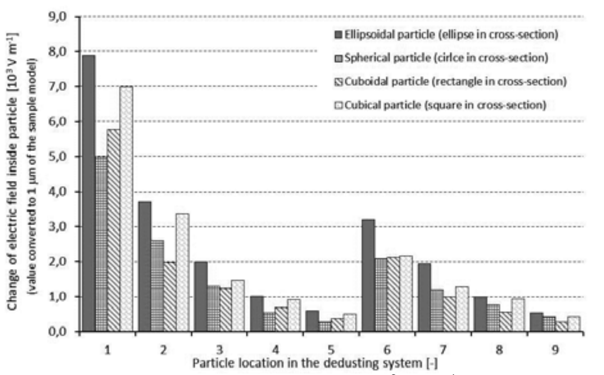

Fig. 8. Change of electric field intensity ($\cdot 10^3$ V$\cdot$m^{-1}) inside particle for placement in the dedusting system converted to 1 μm of the sample model

Conclusions

The following conclusions can be drawn on the basis of data obtained for four models of dust particles of plant origin located in 9 points of bifilar filter system:

1. In accordance with expectations, the influence of field is the highest in the nearest surrounding of winding conductors and its maximum values are achieved in the gap between the conductors (Fig. 5).

2. The maximum change of electric field intensity within the length of dust sample has been recorded for an ellipsoidal sample 10x20 μm. Achieved average value was equal to $7{,}9\cdot 10^3$ V$\cdot$m^{-1} per each μm of the cross-section length at point 1.

3. The irregularity of dust particle shape does not imply any higher change of electric field intensity. The values obtained for "regular" square samples are each time higher than in case of rectangular cross-section (e.g. in point 1 - 7.00>5.78; in point 9 - 0.44>0.29).

4. High values of changes of electric field intensity obtained in the course of simulation for the small (about 10 μm) models of dust particles are confirmed by practically better values of precipitation efficiency for fractions under 20 μm [10]. This indirectly confirms the thesis from Eq. 3 concerning the influence of field intensity changes on the filter influence.

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