Theoretical and practical aspects of the development of devices for suppressing dust streams such as "electrostatic gate" for industrial ventilation systems

Maxim S. Minkin[1], *Denis N.* Kuimov[1,*], and *Mikhail A.* Shahramanyan[2]

[1]Don State Technical University, Department of Automation of production processes, 344000 Rostov-on-Don, Russia
[2]National Center for Digital Economics of Lomonosov Moscow State University, Big Data Storage and Analysis Center, 119192 Moscow, Russia

Abstract. The main objective of this work is to study the behavior of fine dust fractions (aerosols) of different nature in a non-uniform electric field (corona discharge) under electric, gravitational, aerodynamic and other disturbances. Determination of fundamental principles, and development of methods for controlling fine-fraction particles with predetermined physical characteristics. This article also presents the results of practical application of the developed methods.

1 The method of controlling the behavior of particles of the fine fraction with different physical characteristics in the active zone of the device

To identify the optimal parameters of the corona discharge, corresponding to the ability to accurately control the movement of the dust-gas fraction, it is necessary to conduct studies of the "ionic wind" and development of a physico-mathematical model based on the obtained experimental data, which simultaneously takes into account drift, diffusion and convective transfer of ions, as well as connecting the electrical and dynamic parameters of the discharge with the physicomechanical properties of the dust-gas fraction. To solve this problem, it is necessary to study the dispersed composition of the dust-gas mixture, the velocities of the particles in the field of the corona discharge, the current-voltage characteristics, and the distribution of the potential.

Determination of the fundamental principles, and the development of methods for controlling fine-fraction particles with predetermined physical characteristics will allow the development of adequate mathematical models of the behavior of aerosols in a non-uniform electric field.

At the initial stage of research, it was revealed that when predicting the behavior of fine-fraction particles, it is necessary to describe the dynamics of charging the dust particles

---

* Corresponding author: kuimov_d@list.ru

when moving in the active zone of an electromechanical device for suppressing dust fractions. Thus, it is supposed to carry out calculations of the values of the maximum charge of a particle and the dynamics of its set. The calculations were performed taking into account the following steps:

1. Calculation of the maximum charge received by the dust particle in the active zone of the electrode system;
2. Calculation of the dynamics of the charge collection of a dust particle in the active zone of the electrode system;
3. Calculation of physical processes taking place in the active zone of the electrode system.

To predict the behavior of fine dust particles in the active zone of the electrode system, taking into account the impact of the main efforts, it is necessary to use software. In the framework of the impossibility of analytical calculations of the equations of the mathematical model, in this research work a program was developed that carries out calculations using the finite element method.

The application of the finite element method does not require direct solution of the equations of the mathematical model, including the absence of the need to search for the electric potential in the computational domain. In accordance with the idea of the finite element method, the computational domain (electrode system) is divided into separate elements. Triangular elements were chosen as finite elements to simplify calculations.

In accordance with the results described in [45], the nonlinear energy functional was chosen to connect the values of the electric potential within the finite element:

$$F\left(\varphi\right)=\int_{V}\varepsilon\left(\left(\frac{\partial\varphi}{dx}\right)^{2}\left(\frac{\partial\varphi}{dy}\right)^{2}\right)dV-2\int_{V}\rho\varphi dV \tag{1}$$
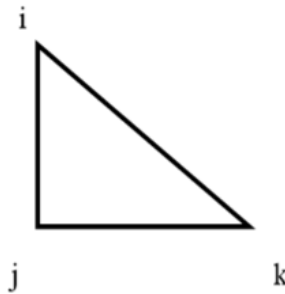

Fig. 1. The triangular finite element of the computational domain.

For this finite element:

$$\frac{\partial F\left(\varphi\right)}{\partial\varphi_{i}}=0 \tag{2}$$

$$\frac{\partial F\left(\varphi\right)}{\partial\varphi_{j}}=0 \tag{3}$$

$$\frac{\partial F(\varphi)}{\partial \varphi_k} = 0 \tag{4}$$

Electric potential function:

$$\varphi = \frac{(a_i + b_i x + c_i y)\varphi_i + (a_j + b_j x + c_j y)\varphi_j + (a_k + b_k x + c_k y)\varphi_k}{2S_\Delta} \tag{5}$$

The following expressions are proposed for the electric potential in [1, 2]:

$$\frac{\varepsilon}{4S_\Delta}((c_i^2 + b_i^2)\varphi_i + (c_i b_j + b_i b_j)\varphi_j + (c_i c_k + b_i b_k)\varphi_i) - \rho\frac{S_\Delta}{3} = 0 \tag{6}$$

$$\frac{\varepsilon}{4S_\Delta}((c_i b_j + b_i b_j)\varphi_i + (c_j^2 + b_j^2)\varphi_j + (c_j c_k + b_j b_k)\varphi_k - \rho\frac{S_\Delta}{3} = 0 \tag{7}$$

$$\frac{\varepsilon}{4S_\Delta}((c_i b_k + b_i b_k)\varphi_j + (c_j c_k + b_j b_k)\kappa_j + (c_k^2 + b_k^2)\varphi_k) - \rho\frac{S_\Delta}{3} = 0 \tag{8}$$

where S_Δ - the area of the triangular element.

$$c_i = x_k - x_j, \qquad c_i = x_i - x_k, \qquad c_i = x_j - x_i, \tag{9}$$

$$b_i = y_j - y_k, \qquad b_j = y_k - y_i, \qquad b_k = y_i - y_j, \tag{10}$$

$$S_\Delta = x_i b_i + x_j b_j + x_k b_k \tag{11}$$

The purpose of the calculations is to search values for the electric potential in all finite elements.

The paper [3] describes the method of ensembling finite elements of a computational domain. The ensemble is performed in accordance with the idea of the finite element method; according to this method, the integral over the entire domain is equal to the sum of the integrals over subdomains. Receiving ensemble allows you to reduce the order of the system of equations. As a result, when forming the equation, the calculated subdomain is allocated with all adjacent finite elements.
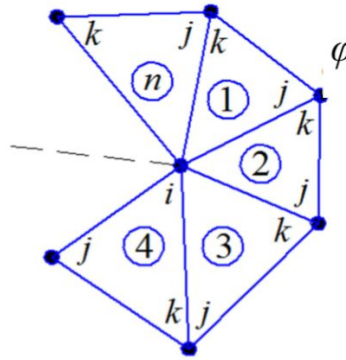
Fig.2. Calculated subdomain.

Based on the work [3], we can write the equation of the nonlinear energy potential for the one shown in Fig. 2 calculated subdomain.

$$\frac{\partial \sum\limits_{1}^{n} i}{\partial \varphi_J} = \sum\limits_{1}^{n} \frac{\partial F_i}{\partial \varphi_J} = 0 \tag{12}$$

where n - the number of finite elements in the calculated subdomain, i – finite element number of the calculated subregion, F - the value of a nonlinear energy functional of finite elements constituting a subdomain; J - node electrical potential.

Determining the equation for each node of the domain, we obtain a system of algebraic equations whose solution will give the distribution of the electric potential in the domain.

$$\varphi_i \sum\limits_{1}^{k} \left(\frac{\varepsilon_i}{4S_i} \left(c_{ji}^2 + b_{ji}^2 \right) \right) + \varphi_1 \left(\frac{\varepsilon_1}{4S_1} \left(c_{j1}c_{11} + b_{j1}b_{11} \right) + \frac{\varepsilon_2}{4S_2} \left(c_{j2}c_{12} + b_{j2}b_{12} \right) \right) + $$
$$\text{---------------------------------------} \tag{13}$$
$$\varphi_p \left(\frac{\varepsilon_n}{4S_n} \left(c_{jn}c_{pn} + b_{jn}b_{pn} \right) + \frac{\varepsilon_1}{4S_1} \left(c_{j1}c_{p1} + b_{j1}b_{p1} \right) \right) - \frac{1}{3} \sum\limits_{1}^{k} \rho S_i = 0$$

When implementing methods for predicting the behavior of fine dust particles, one of the tasks is the need to carry out a set of iterative calculations. The explanation of the iterative processes lies in the conditions where the number of unknowns exceeds the number of equations themselves.

To implement the methodology for predicting the behavior of dust particles in the electric field, the following steps should be observed:
1. Calculation of the charge accumulated by the dust particle while in the interelectrode space of the device;
2. The calculation of the forces acting on a single dust particle;
3. The calculation of the resulting effort.

The first step, according to the actions described above, is to simulate the dynamics of the charging process of a dust particle as it passes through the device's interelectrode space. In the process of calculations, it is necessary to calculate both the maximum charge gained by a particle and the time it takes to charge.

Like any mathematical and computer model, the following assumptions are made here to simplify calculations:

1. At any given time, only one dust particle can be found in a single finite triangular element;
2. The residence time of the dust particle in each final element is the same;
3. The particle moves only in the perpendicular direction with respect to the forming electrode.

In the process of making calculations at the initial stage, a search is carried out for the electric field intensity. In turn, the calculation of the maximum acquired charge by a dust particle is determined by the following expression:

$$q_m = Ka^2 E_{\Sigma j},$$

$$K = 4\pi\varepsilon_0 \left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2}\right).$$

Next, the calculation of the amount of charge collected in each final element as it passes the path in the interelectrode space.

Based on the data obtained on the basis of the calculations carried out above, it becomes possible to assess the performance of the electromechanical device for suppressing dust fractions at the modeling stage..

However, for a more accurate prediction of the behavior of particles in the interelectrode space of the device, it is necessary to know the degree of influence on the behavior of particles of the fine dust fraction of the physical properties of the medium and characteristics of the technological system. This fact leads to the next stage of calculations based on the study of physical processes in the interelectrode space of an electromechanical device, based on the evaluation of the acting forces on a single dust particle.

2 Development of a mathematical model of the behavior of fine particles, taking into account electromechanical processes under the action of electric, gravitational, aerodynamic and other disturbances

To solve the problem, it is proposed to use computer simulation tools based on the application of the finite element method. The computer model is based on a mathematical model describing physical processes in the core of an electromechanical device for blocking dust emissions. This mathematical model is built on the basis of the following objective laws. The following forces act on a particle that is in an inhomogeneous electric field and under the action of external disturbances:

1. Force of gravity;
2. Electric field force on a charged particle;
3. Force due to uneven distribution of electric field strength;
4. Resistance force of the environment to the movement of particles;
5. Aerodynamic force created by the "ionic wind" [4-8].

Mathematical model of electrical processes occurring in the core of an electromechanical device for suppressing dust fractions [9,10]:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = -\frac{\rho}{\varepsilon_0} \tag{15}$$

$$\rho = \frac{j}{kE} \tag{16}$$

$$\bar{E} = -grad\varphi , \tag{17}$$

$$F_1 = mg , \tag{18}$$

$$\bar{F}_2 = q(t)\,\bar{E} , \tag{19}$$

$$F_3 = pS_{сеч} , \tag{20}$$

$$F_4 = p_{ionic\;wind}\frac{\pi r^2}{4} , \tag{21}$$

$$m\frac{d\bar{V}}{dt} = \sum \bar{F} , \tag{22}$$

$$q(t) = q_m \frac{en_0 kt}{4e_0 + en_0 kt} , \tag{23}$$

$$q_m = 4\pi\varepsilon_0\left(1 + 2\frac{\varepsilon - 1}{\varepsilon + 2}\right)r^2 E . \tag{24}$$

To perform calculations according to the above mathematical model, the following assumptions should be taken into account [9,11]:
1. Particle moving velocity of dust-air mixture is equal to the speed of the stream.
2. The charge of the particle at the initial moment is zero.
3. Since the particle moves with the air flow, the resistance force for the simplification of calculations takes the value equal to zero.

The following describes the necessary comments. Under these conditions, the removal of fine particles from the tank due to their movement by air flow, the resistance force of the environment is taken to be 0. If the shutter is horizontal, the force of gravity also does not counteract the movement of the fine particle. Simulation of the electric field of an electrostatic gate (ESG) was performed using the Deutsch-Popkov technique, according to it, the electric field in the interelectrode space in the presence of the external field of the corona discharge differs from the field of the electrodes only by the scale of the electric field strength while maintaining the configuration of the power lines. Therefore, in the present work, the simulation of the electrostatic field was carried out only when the potentials of the electrodes were specified.

The calculation of the mathematical model is assumed using the finite element method. It should be considered that the common (in free use) software packages for the numerical calculation of electric fields (FEMM, MATLAB, ELCUT and etc) in our case, it is not possible to use it because of rather complex computational processes to determine the bulk charge density in the interelectrode space, the uncertainty of the space charge boundaries, and the uncertainty of the corona current. Determining the space charge boundaries of the outer corona area and the corona current requires the development of special software. In

this regard, in the framework of this work, we developed our own software for calculating the electric field in an electrostatic gate [12].

To simulate electrical processes, it must follow the sequence of actions that are necessary to obtain a solution.

This sequence includes the following actions:

1. Formation of the design scheme: determination of the geometry of the electrostatic shutter, the speed of the dust-air mixture and the force acting from the air flow on the fine fraction;
2. Formation of the computational domain for the electric field in a given section of the device (section by the OXY plane);
3. Triangulation of the computational domain (splitting into triangular finite elements);
4. Setting the boundary conditions for the scalar electric potential and setting the initial approximation of the potential values;
5. Setting the values of the scalar electric potential at the electrodes;
6. Calculation of the values of the scalar electric potential in nodes;
7. Calculation of the electric field in a given section;
8. Calculation of the acquired charge by the particle of the fine fraction during the residence time in the core of the electrostatic gate;
9. The calculation of the forces acting on the particle of the fine fraction from the electric field;
10. Comparison of the forces acting on the particle of the fine fraction from the side of the air flow and the electric field.

The calculation of the electric field in a given section of the device is carried out by the finite element method with the solution of the system of equations by the iterative method of PVR-Newton.

According to the results of the calculation of the parameters of the electric field, the maximum charge is determined for a particle of the fine fraction located in the core of an electrostatic shutter. The next step is the determination of the magnitude of the charge of the particle of the fine fraction acquired during the stay in the active zone of the electrostatic gate. The value of the force acting from the electric field on the particle is determined on the basis of the charge of the particle of the fine fraction is determined.

The process of the electrical process modeling program begins with the launch of the program module and input of the initial data from the display screen:

1) total number of nodes of the calculated area of a given section of the device;
2) estimated number of nodes in the area of a given section;
3) geometrical parameters of electrostatic shutter, shutter height, shutter width;
4) setting the nodes belonging to the corona electrode;
5) setting of the nodes belonging to the shaping electrode;
6) supply voltage;
7) accuracy of calculation.

At the end of the iterative process, the value of the electric field strength is calculated in a predetermined section.   The calculation of the charge acquired by a particle of the fine fraction is carried out on the basis of the obtained values of the electric field strength. The calculation of the forces from the electric field to the particle was carried out.

As a result of the work of the above program, both the characteristics of the electrical processes of the electrostatic gate and the characteristics of the processes affecting the behavior of the particles of the fine fraction are obtained. A characteristic distinction of this model of calculation of physical processes is the fact that, unlike all previously developed models, in the model under consideration it was possible to implement a simulation of the process of acquiring a charge by a particle of a fine fraction and a picture of the forces acting on a particle. This was made possible by introducing special subroutines into the

calculation. In all previous works, only the characteristics of the electric field were calculated, which did not give a complete picture of the processes occurring in electrostatic valves.

According to the results of modeling electrical processes using the above computer model are determined:

1) characteristics of the electric field in each final element of a given section of the device;
2) the dynamics of the acquisition of charge by the particle of the fine fraction;
3) force acting on a particle of a fine fraction from the electric field;

The most important stage of modeling in this case is the study of the dynamics of the process of charging a dust particle during its movement in the interelectrode space.
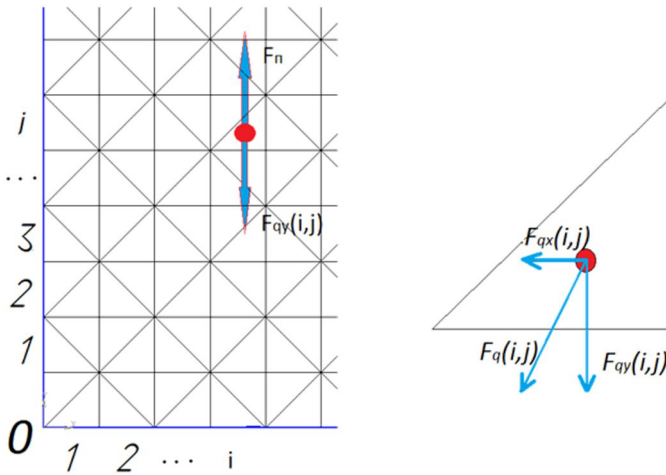

Fig.3. To the calculation of the magnitude of the forces affecting on the particle in the electrode system, from the side of the electric field.

The calculation of the magnitude of the force acting on a particle in the interelectrode space of an electromechanical device for suppressing dust fractions is carried out for particles moving from the entry point to exiting the core in a straight line perpendicular to the plane of the shaping electrode.

The following forces are active in the active part of the ESG:

$$F_1 = mg \,, \tag{18}$$

$$\overline{F}_2 = q(t)\ \overline{E} \,, \tag{19}$$

$$F_3 = pS_{сеч} \,, \tag{20}$$

$$F_4 = \frac{I_{corona} \times h_{m.electrodes}}{k_{ions}} \tag{21}$$

Only the tangential component of the electric field is used to calculate:

$$F_{qy}(i,j) = q(t)_{i,j} \cdot E_y(i,j) \tag{22}$$

To check the effectiveness of the ESG, each balance element is used to calculate the balance of forces:

$$F_{rez}(i,j) = F_{qy}(i,j) + F_{mg} - F_n \qquad (23)$$

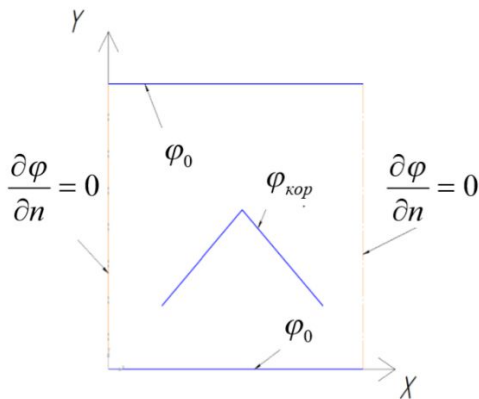In case, $F_{rez}(i,j) > 0$, the electrostatic shutter will be considered fulfilled.

Fig. 4. Calculated interelectrode space and boundary conditions.

In accordance with Fig. 4, the boundary conditions for a given design of the electrode system of an electromechanical device for suppressing dust fractions consist of the following positions:
1. At the boundary of the domain, the electric potential is always zero;
2. The potential is set on the corona electrode;
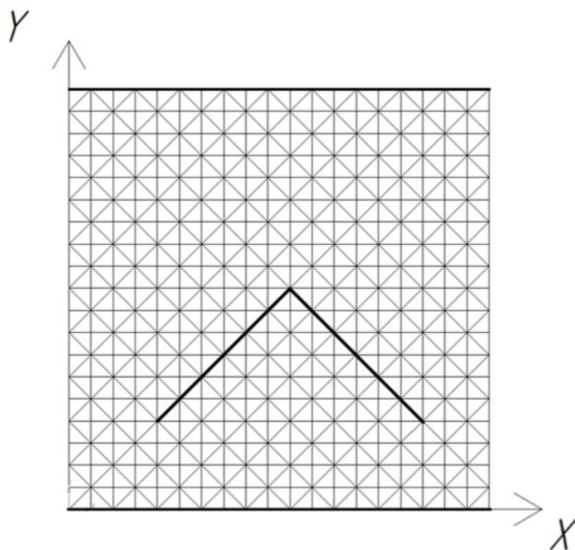3. A boundary value problem with Dirichlet boundary conditions.

Fig.5. Triangulation of the computational domain.

3 Development of the geometry of the location of the corona electrodes of a prototype of an electromechanical device for suppressing dust fractions with improved characteristics

A disadvantage of previously developed and using a corona discharge to block dust fractions of many devices is the insufficient area of the corona electrodes and the short residence time of the particle in the zone of the corona electrode.

The technical objective of the proposed device is to increase the effectiveness of the suppression of dust emissions for protection against dust of various technological objects, while reducing power consumption and mass and size parameters of the device.

The technical objective is achieved due to the fact that the electromechanical device for suppressing dust fractions contains a corona electrode consisting of a series of metal plates bent at an angle, spaced at equal distance from each other and parallel to the precipitation electrode. This design is very effective due to the fact that there is an increase in the area of the discharge electrode, an increase in the residence time of the particle in the area of the discharge electrode, as well as partial mechanical removal of the dust fraction. Dust particles falling inside the interelectrode space adsorb an electric charge and are removed due to Coulomb forces.

Due to the fact that the corona electrode is made of separate plates bent at an angle and connected to the negative electrode of the power source, the bulk density of charge in the interelectrode space increases due to additional streamer streams and, thereby, the time required for dust particles to get corona discharge, and also increases the force acting on the dust particle from the electrostatic field.

In turn, the forming electrode is made in the form of a grid of non-magnetic material stretched perpendicularly to the gas-air mixture flow and connected to the positive pole of the high-voltage source.

The fine particle moves in the interelectrode space due to excessive air pressure. Then the force acting on the particle from the air side is defined as the product of the excess air pressure inside the bunker or container and the cross-section of the particle. This effort is counteracted by a complex of forces that act on it from the electric field in the interelectrode space. Moreover, as the particle moves to the outlet, its charge increases and the braking force increases, while the force from the air flow can be considered constant. The gate will be considered to have fulfilled its functions if the path traveled by the particle to a stop is less than the distance from the point of entry of the particle into the outer area of the corona discharge to the outlet of the bunker.

The main physical processes that ensure the functioning of the gate are:

1) creation of a drift region of electric charges in the space between the corona-forming and shaping electrodes;

2) adsorption by fine particles of electric charges;

3) deceleration of charged particles in an electric field;

4) redirection of the movement of charged dust particles. Thus, in the working area of the device, three stages can be distinguished (Fig. 2): 1) particle charge region; 2) braking area; 3) area of particle removal from the working area.

On parallelly arranged precipitating-2 and corona-1 electrodes, the difference of electric potentials is supplied, and around the corona-1 electrode an area of bulk electrical charge is formed. Particles of dust, getting into this area, are polarized and begin to experience two types of electrostatic forces: one directed towards the corona-1 electrode, and the second directed axially, due to the configuration and arrangement of the electrodes. The predominance of the axial component of the electric forces leads to the ejection of dust particles from the gap between the two parallel-arranged collecting electrodes, which are connected to the positive pole of the high voltage source. Due to the fact that the corona-1

electrode consists of plates 3, the residence time of dust particles in the zone of the corona discharge increases, which leads to an increase in the efficiency of the gate.

Thus, the device acquires the function of a shutter located in the path of moving dust streams and blocking their movement with a free exit of the purified gas, which prevents dust from spreading and keeps dust particles in the area of the dusting source.

According to the results of the mathematical and computer simulation carried out as part of the research work, two applications for security documents were prepared, describing two configurations of electromechanical devices for suppressing dust fractions. In addition to the design of the electrode system considered above, an installation with sawtooth corona plates was developed. The use of plates with sawtooth edges allows you to increase the intensity of the corona discharge and increase the area of impact.

In the framework of this work, the modeling of physical processes was carried out for a new design of an electromechanical device for suppressing dust fractions of a louvre type, the research results were used in the development of valves for specific working conditions. Below are the results of calculations of the dynamics of charging of particles and forces acting in this electrode system when changing:

1) the inter-electrode space of the corona electrodes relative to each other;

2) particle size of the fine fraction.

Table 1. Dynamics of charge set by a particle of fine dust fraction depending on the size of the interelectrode window

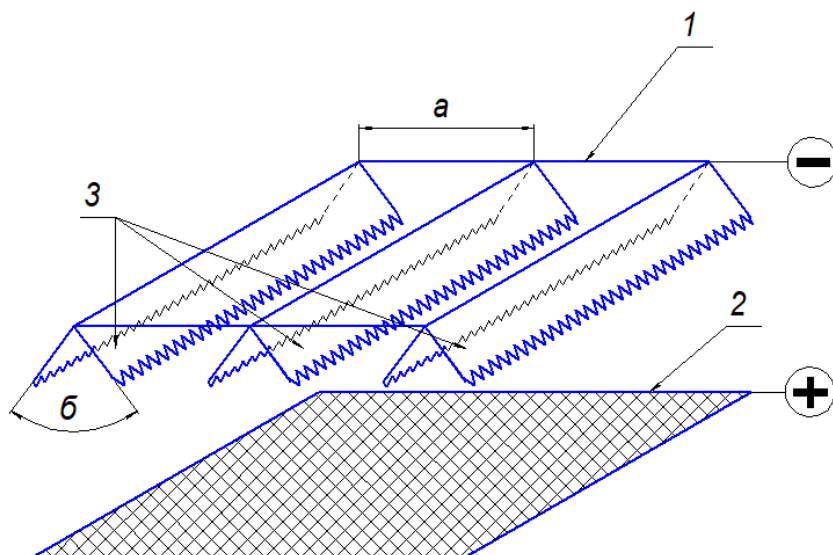|	interelectrode window 150 mm	interelectrode window 200 mm	interelectrode window 120 mm
entrance to the active zone	0	0	0
50 mm	3,57752E-13	3,08703E-13	3,11245E-13
100 mm	7,11909E-13	6,11325E-13	6,19361E-13
150 mm	1,057E-12	9,02139E-13	9,1959E-13
guaranteed stop line	1,3818E-12	1,17343E-12	1,20216E-12

Fig.6. Electrode system of an electromechanical device for suppressing dust emissions.

Conclusion

The study of the fundamental principles of control of the fine fraction with different physical properties, and the development of methods for controlling the behavior of particles in the core of an electromechanical device for suppressing the dust fraction, open up new possibilities for the use of devices of this type. Also an important advantage of this work is that the behavioral models will be valid for all devices related to the field of electron-ion technology.

An example of a promising high-performance device - an electrostatic gate designed to block dust emissions in domestic and industrial ventilation systems, should undoubtedly become a more energy efficient system designed to replace existing air aspiration systems.

References

1. T. Ward, E. Bromgead *FORTRAN and the art of programming personal computers* (Radio and communication, Moscow, 1993)
2. E.S. Kolechitsky, I.P. Dloedow, V.N. Shulgin, Electrical Engineering, 11, 6 (1987)
3. K.S. Demirchyan, Yu. V. Rakitskiy, P.A. Butyrin, Energy and transport, 2, 21 (1982)
4. L.Dascalescu, D.Rafiroiu, A.Samuila, and R.Tobazeon, IEEE Trans, on Ind. Appl, 34, 35 (1998)
5. L. Daskalescu, R. Morar, AL. Iuga, V. Neamtu, I.Suarasan, Magn. and Electrical Separ., 4, 16 (1993)
6. J. Stahe, P-M. Beier, Proc.20 Int.Mmer.Congr., 5, 7 (1997)
7. Komptner, O. Mientkewitz, Schubert G. Proc.20 Int.Miner.Congr. 5, 11 (1997)
8. J.J. Lowke, R. Morrow, Pure and Appl. Chem, 66, 8 (1994)
9. M.S. Minkin, D.N. Kuimov, MATEC Web of Conferences, 226, 6 (2018)
10. M.S. Minkin, D.N. Kuimov, A.V. Mozgovoj, MATEC Web of Conferences, 132, 6 (2017)
11. M.S. Minkin, D.N. Kuimov, A.D. Lukyanov, Procedia Engineering, 150, 6 (2016)
12. M.S. Minkin, D.N. Kuimov, A.D. Lukyanov, Materials Science Forum, 870, 5 (2016)