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Mathematical Modelling and Computer Simulation Assist in Designing Non-traditional Types of Precipitators and Separators

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ABSTRACT

The article deals with the application of the method for mathematical modeling and simulation at solving some issues in the area of electrostatic technology. It focuses on the processes in electrostatic separation and precipitation. Computer simulation is highly required for equipment design and for their diagnostics in critical operating states using theoretical calculations and experimental data evaluation. The presented computer models may be applied both by project and design engineers using the most advanced computer-aided design of electrostatic technologies.

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1. INTRODUCTION

Up to present, in the study of electric separation and sorting process, as well as in the development of relevant equipment, the attention has been primarily directed towards constructional and operational aspects with empirical knowledge being the main and practically the sole source of information. Notwithstanding that ballistics of a particle (knowledge of the equation of motion and its solutions) is a keystone of the theoretical analysis of the electric separation and sorting, any comprehensive solution of the examined subject has not hitherto been found. A few attempts, trying to elucidate the issue by means of approximate methods, achieved only limited success. They could unravel the issue at the kinematic level, albeit only under conditions of not taking full account of all the factors affecting the ballistics of motion. The use of numerical methods for structuring the ballistics of particles was unfeasible, principally due to the absence of any appropriate possibilities for calculation.

The primary goal of the current research is to contribute to some extent to build a theoretical basis, inevitable for a further study of the electrostatic technology processes. The intention is not to disclose the essence of the investigated phenomena, but to identify the potential application areas for the research findings. The secondary, but not marginal goal of the research is to explore the effects of the direct and alternating (hereinafter DC and AC) electric fields on the transport of electrically charged particles. Marton [1-3] and Džmura [4-6] focused on a particular shape, given by the geometry of a particle. In their calculations, they did not take full account of all the factors affecting the motion of particles in the electric field created by high voltage. The most comprehensive experiments have been conducted by [7-14]. The research method of mathematical modelling and computer simulation has proven to become a powerful approach for understanding the complexity of a physical, biological, chemical system [15-18]. It enables to examine the system based on virtual prototyping.

2. COMPUTER MODEL OF OF ELECTRIC SEPARATOR OF CYLINDRICAL TYPE

2.1. Description of the Physical Model

The charged (e.g. by corona charging) macroscopic particles in the separator inflow jet area are carried by the flowing gas into the separation space (Figure 1).

The separation space is created by a set of coaxial cylindrical electrodes (a thin bar or a piece of wire may serve as the internal electrode) among which the direct (hereinafter DC) or the alternating (herein after AC) electric field is generated depending on the type of electrode charging. The force interaction of the electric field and the charged particles causes the separation and the sorting of these particles from the air mass to the external electrode wall. The use of inhomogeneous electric field separators or sorters (as it is in the studied case) unlike the homogeneous electric field equipment requires to take account of gradient force and its coeffects (together with some other factors) on the dynamics of a macroscopic particle. The choice of the coordinate system and the kinematic scheme is shown in Figure 1. According to Figure 1, the system of forces affects the motion of particles as shown in Figure 2.

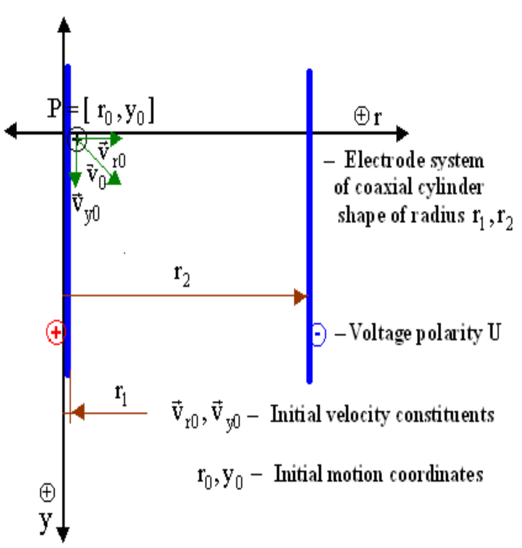

Figure 1. Kinematic scheme

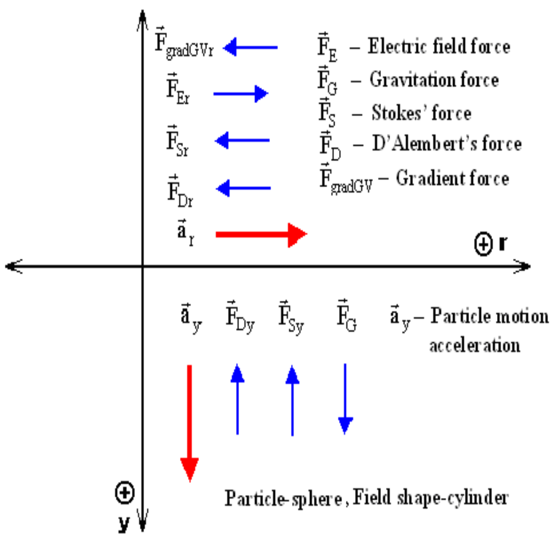

Figure 2. System of forces

2.2. Abstract Synthesis of the Mathematical model

Newton's kinematic equation (the mathematical model) for the motion of a macroscopic particle in the separator space (shown in Figure 1) charged by DC voltage takes the following form:

$$m\frac{d^2r}{dt^2}=\frac{qU}{\left(\ln\frac{r_2}{r_1}\right)r}-6\pi\eta R\frac{dr}{dt}-4\pi\varepsilon_0 R^3\frac{(\varepsilon_r-1)}{(\varepsilon_r+2)}\frac{U^2}{\ln^2\left(\frac{r_2}{r_1}\right)r^3} \tag{1}$$

$$m\frac{d^2y}{dt^2}=mg-6\pi\eta R\frac{dy}{dt} \tag{2}$$

If the separator is charged by AC voltage, the equations take the forms:

$$m\frac{d^2r}{dt^2} = \frac{qU_m \sin(\omega t + \phi_0)}{\left(\ln\frac{r_2}{r_1}\right)r} - 6\pi\eta R\frac{dr}{dt} -$$

$$-4\pi\varepsilon_0 R^3 \frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} \frac{U_m{}^2 \sin^2(\omega t + \phi_0)}{\ln^2\left(\frac{r_2}{r_1}\right)r^3} \tag{3}$$

$$m\frac{d^2y}{dt^2} = mg - 6\pi\eta R\frac{dy}{dt} \tag{4}$$

Cauchy initial conditions for the solution of the system of differential equations (constructed by us) for the chosen coordinate system the following form:

$$r(0) = r_0 \; ; \; v_r(0) = v_{r0} \; ; \; y(0) = y_0 \; ; \; v_y(0) = v_{y0} \tag{5}$$

The following relation (6) was taken from [19] where it had the form $F_{gradGVr}$

$$F_{gradGVr} = -4\pi\varepsilon_0 R^3 \frac{(\varepsilon_r - 1)}{(\varepsilon_r + 2)} \frac{U^2}{\ln^2(\frac{r_2}{r_1})r^3} \tag{6}$$

Note: The derivation of the relation results by the fact that the particle in the electric field is also charged by q_0. The particle is affected by the vector sum of forces, the gradient force affecting the dipole moment according to (7) and the force affecting the charge generated in the charging process (8).

$$\vec{F} = k\vec{E}(x)\frac{\partial \vec{E}(x)}{\partial x} \tag{7}$$

$$\vec{F}_E = q_0.\vec{E} \tag{8}$$

To simplify it, it is considered that the vector E has only the direction x. Then the resulting force is as follows:

$$\vec{F} = k\vec{E}(x)\frac{\partial \vec{E}(x)}{\partial x} + q_0\vec{E}(x) = \vec{E}(x)[q_0 + k\frac{\partial \vec{E}(x)}{\partial x}] \tag{9}$$

The research method of mathematical modelling and computer simulation has proven to become a powerful approach for understanding the complexity of a physical, biological, chemical system. It enables to examine the systems based on virtual prototyping. An original physical system is replaced by its computer-based virtual prototype to be used for various computer experiments whose results are then applied to the original physical system.

2.3. Synthesis of the Computer Model and Simulation

Based on the model of the separator (synthetized above), this work simulates the separation and sorting of the particles with varying size and weight, but with identical material parameters. In order to reflect the real technological conditions we selected the parameters of the particle 1 and the particle 2 were selected in accordance with the measurements carried out in [19], [20].

The constructed systems of the differential equations are systems of non-linear differential equations (due to the nonlinear differential Equations (1) and (3)). Since the analytical solution of such equations has not been possible, the approximation of the methods is the only way of solving the given set of equations. The Runge-Kutta 3 method in the Matlab software were used to carry out the execution of the tasks. The system of the differential equations of motion (the mathematical model) was solved numerically in the Matlab computational environment with the following values:

a. particle 1: $q = 0{,}5 \cdot 10^{-8}$ C; $m = 1 \cdot 10^{-3}$ kg; $\varepsilon_r = 3{,}5$; $R = 2{,}5 \cdot 10^{-3}$ m ;

b. particle 1: $q = 0{,}4232 \cdot 10^{-8}$ C; $m = 0{,}807 \cdot 10^{-3}$ kg; $\varepsilon_r = 3{,}5$; $R = 2{,}3 \cdot 10^{-3}$ m;

Moreover, Matlab offers an opportunity for the computational modelling of all the relations among the state values of the modelled system. In the present research, it assists to solve the following tasks:

a. kinematics of the particle motion in the modelled physical system,
b. dynamics of the particle motion in the modelled hysical system, and,
c. values characterizing the electric field.

These values are presented in following graphs of Figure 3 to Figure 10

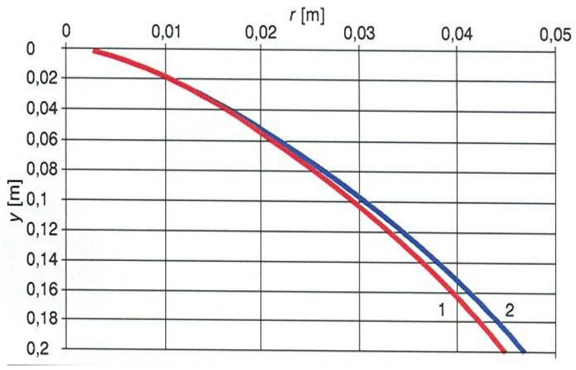

Figure 3. Graphical representation of the motion trajectory of particle 1 (red) and particle 2 (blue) moving in the space of the separator charged by DC voltage

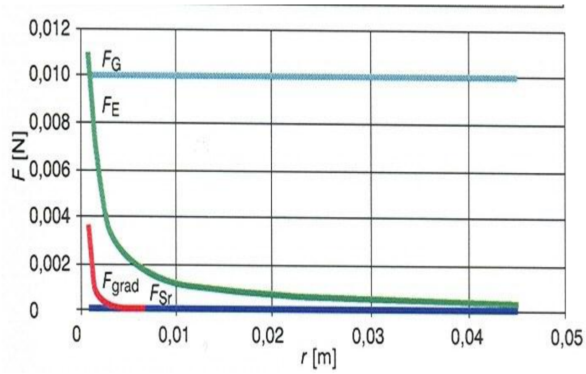

Figure 4. Graphical representation of comparison of forces affecting particle 1 in the relation F = f (r), (DC voltage), F_{grad} - red, F_{Sr} – dark blue, F_E - green, F_G - light blue

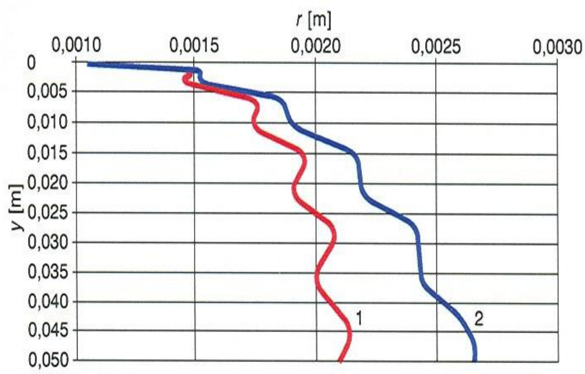

Figure 5. Graphical representation of motion trajectory of particle 1 (red) and particle 2 (blue) moving in the space of the separator charged by AC voltage

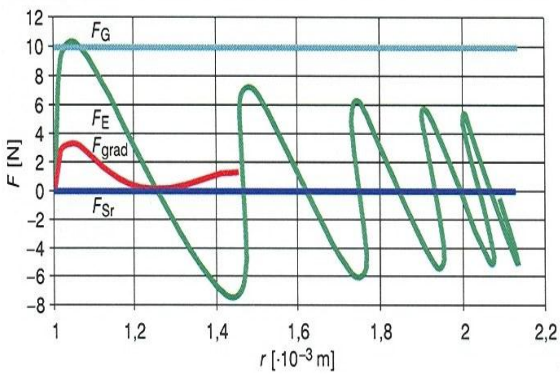

Figure 6. Graphical representation of comparison of forces affecting particle 1 in the relation F = f (r), (AC voltage), F_{grad} - red, F_{Sr} - dark blue, F_E - green, F_G - light blue

2.3. Analysis and Discussion on the Simulation Results

A proper control over the separation technological process is guaranteed by achieving a high degree of control over the kinematics and dynamics of the particles motion in the separator space. This is not workable without recognizing and identifying the effects of the individual quality and quantity factors on this motion. This is exactly what the current research is aimed at. The key finding that resulted from the present computer simulation may be drawn as follows: when analyzing dynamics of the charged macroscopic particle motion in the separator, it is necessary that also gradient force will be taken into account because gradient force is comparable with the other force interactions (see Figure 4 and Figure 6).

Another important accomplishment is the revealing of the possible occurrence of critical operating states of the separator provided that it is charged by AC voltage (see Figure 8.). The blue curve in Figure 8 illustrates the relation v_r (t) for t = (0;0,01s) provided that φ_0= 0°. The red curve in Figure 8 illustrates the same relation provided that φ_0 = 180°. The conducted investigation showed that under the condition of φ_0 = 180°, the operation of the separator may become critical. If this is the case, the velocity of the motion v_r (t) takes the opposite direction in comparison to the one stated as the positive one. If the velocity of the motion reached a negative value during the time t close to zero, the particles would adhere to the wall of the separator. It would then depend upon nothing but the value v_r (0) and the adhesive conditions. It is essential that this observation will be taken into consideration in the process of designing and constructing an AC voltage separator.

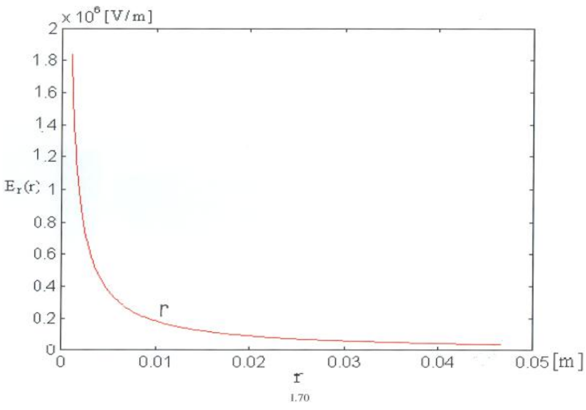

Figure 7. Dependence E_r = f (r) on the trajectory of the particle motion in the space of the separator charged by DC voltage

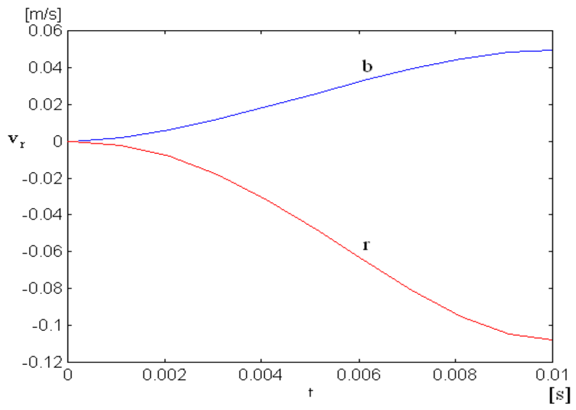

Figure 8. Graphical representation of velocity of particle 1 motion in the space of the separator (shown in Figure 1) charged by AC voltage. The relation v_r = f(t)) in the case of ϕ_0 = 0° (blue), in the case of ϕ_0 = 180° (red)

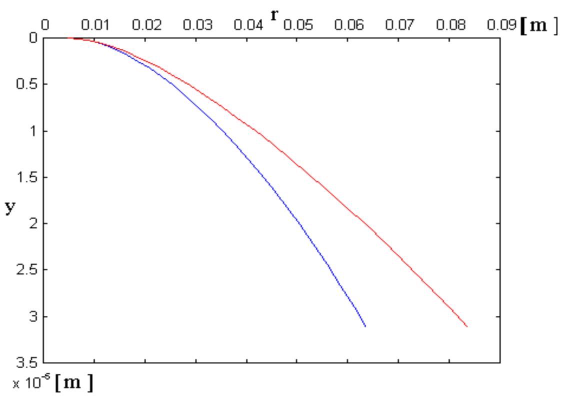

Figure 9. Graphical representation of the motion trajectory of a particle moving in the inter-electrode space specified according to Figure 1 (dependency y = f(r)). (Red color represents the trajectory in the case of motion in the field of space charge, blue color is used for the non-existence of space charge)

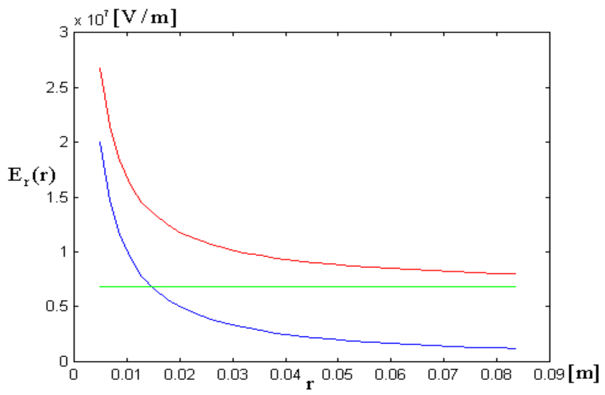

Figure 10. Graphical representation of the intensity course of the electric field (dependency E_r = f(r) - red) in the interelectrode space according Figure 1. (Blue color shows the course in the case of non-existence of space charge, green is for “deformation contribution”)

The most important research contributions are:

a. The improvement of the existing research methods in the technology of separation and sorting (the emphasis has been so far put on constructional and operational aspects with empirical knowledge being the main and practically the sole source of information),
b. The parallel solution of the aspects of the kinematics, the dynamics, and of the electric field of a moving

macroscopic particles (in the real environment of electrostatic technologies).

Unlike the past, the proposed method offers a more complex solution to the issue. It solves the issue not only from the viewpoint of kinematics but also from the viewpoint of dynamics and of the theory of the electromagnetic field taking into account all the major factors affecting the ballistics of a particle. According to it, the then used empirical methods were capable of solving only the kinematics of a particle but not its dynamics, therefore the method proposed seems to be at the moment the only complex solution. The overall result of the present computer simulation is the knowledge that the operation of the examined type of a separator is also basically possible when it is charged by AC voltage (it is necessary to consider the possible occurrence of critical operating states).

Analogically, it is possible to synthetize a computer model of the separator with the electric field of spatial charge distribution (the model is even more identical to the real model) and to use it for the simulation of particle separation and sorting (including programming equipment as well as programming technology). This problem is dealt with in details in [19], where the following issue was selected and discussed: The motion of a particle of macroscopic size in the electric field of a space charge (the density of the space charge is $\rho = k/r$) as shown in the Figure 1.
The solution of the electric field are:

$$\Delta V = -\frac{\rho(r)}{\varepsilon_0} = -\frac{k}{\varepsilon_0} \tag{10}$$

$$\frac{1}{r}.\frac{d}{dr}\left(r\frac{dV}{dr}\right) = -\frac{\rho(r)}{\varepsilon_0} = -\frac{k}{\varepsilon_0 r} \tag{11}$$

For boundary conditions:

$$r = r_1; V(r_1) = U; r = r_2, V(r_2) = 0 \tag{12}$$

$$V = -\frac{k}{\varepsilon_0}r + C_1 \ln r + C_2 \tag{13}$$

$$E_r(r) = -\frac{\partial V}{\partial x} = \frac{k}{\varepsilon_0} - \frac{C_1}{r} \tag{14}$$

Equations of motion (mathematical model) are:

$$m\frac{d^2r}{dt^2} = q.E_r(r) - 6\pi\eta R\frac{dr}{dt} \tag{15}$$

$$m\frac{d^2y}{dt^2} = mg - 6\pi\eta R\frac{dy}{dt} \tag{16}$$

The solution is for the values:
p.p : r(0) = 0,005 m ; v_r (0) = 15 m/s ; y(0) = 0 m ; v_y (0) particle: q = 1.10^{-8}C ; m = $5,5.10^{-8}$ kg; R = $0,5.10^{-3}$ m r : U = 15000 V; r_l = 0,005 m ; r_2 = 0,5 m, k = 6.10 -5 ; C_l = 1.105 ; s_0 = 8,854.10-12 F/m dynamic viscosity of the environment: η = 18,1.10-6 kg/ms.

3. COMPUTER MODEL OF OF ELECTRIC SEPARATOR OF CYLINDRICAL

Macroscopic particles diffused in the surroundings of coronary electrode, which is connected to alternating high voltage, are not charged by hypothesis. For this reason it is necessary to create an electro-physical condition for the creation of monopolar electrical charges in the area of feeder embouchure. One possibility is to utilize the physical phenomena in metal-dielectric-gas boundary. During the conducted experiments a coaxial precipitator with four various coronary electrodes has been constructed. The PVC tube serving as collecting electrode is the basic part of precipitator.

Thin aluminum electrode is attached on the outside of the tube and it creates the ground electrode. Within the tube there is fixed a thin cooper wire serving as coronary electrode. The experiment used four types of coronary electrode. One of them is a linear electrode and the others are spiral electrodes with various rises (Figure 11). The function of coronary electrode is the creation of strong inhomogeneous electric field. This field can be created by electrodes with a small radius of bend. If the coronary electrode is positive, the new electrons are created as consequence of bombing a point by electrons. If the coronary electrode is negative, it is analogical, but the difference is that the avalanches emitted by the negative point are moved to more homogeneous field, and as a consequence the mobility and ability to ionize decrease.

In the electrical precipitator supplied by alternating voltage by using the metal coronary electrode the insulating barrier is used as a collecting electrode. For maximal efficiency it is necessary to choose insulating materials with great value of resistance and permittivity. The choice of materials depends on another non electrical quantity as for example the temperature of flying gas, enough mechanical solidity and etc. Insulating barriers must not change their mechanical and dielectric attributes under the influence of temperature.

For finding the efficiency of precipitator model three types of dust from thermal power plant with different values of resistance were used. The model of precipitator with length 30cm has an efficiency in the range of 60 % to 97 % for each of the dust type. Provide a statement that what is expected, as stated in the "Introduction" chapter can ultimately result in "Results and Discussion" chapter, so there is compatibility. Moreover, it can also be added the prospect of the development of research results and application prospects of further studies into the next (based on result and discussion).

Figure 11. Sections configuration of cascade tubular precipitator supplied by alternating high voltage

Table I. Average values of efficiency for each of sections of cascade tube-type precipitator supplied by alternating voltage

	Efficiency [%]		
	Dust with $\rho_e = 3\ \Omega\cdot m$	Dust With $\rho_e = 13\ \Omega\cdot m$	Dust with $\rho_e = 800\ \Omega\cdot m$
Linear electrode	77.77	58.77	98.51
2,5 cm spiral electrode	87.10	65.42	90.99
4 cm spiral electrode	75.21	61.06	93.07
7 cm spiral electrode	72.20	58.79	94.32

4. CONCLUSION

Computer simulation is becoming a useful tool in the implementation of the research findings into a manufacturing process. It can assist in the process of designing and constructing a new type of an AC separator. It can also help to get it into practice and thus move research findings into the real conditions. The presented computer models may be applied both by project and design engineers using more advanced computer-aided design of electrostatic technologies, e.g. in the areas where computer simulation is highly required such as prognosing and diagnosing critical operating states. In conclusion, it is important to draw attention to the following: in the case of the existence of a great number of the particles (the more identical model to the real model) and their interactions (due to which they influence each other) it is recommended to use a statistical approach and stochastic computer modelling of the above-mentioned processes (the creation of the stochastic computer model is described in the dissertation thesis [19], [20]).

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