The Fast Model for Ionic Wind Simulation

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Abstract: The problem of computer simulating ionic wind is considered. This task is of practical importance for air filtration, ionizing, cooling facilities driven by electric force. Several generally accepted approximations obtain for computing ionic wind but each of them has significant disadvantages in respect to numerical methods application. A new simplified model is presented which is successfully realized in the "COMSOL Multiphysics" software package. The model allows of sufficient reducing computation time and used memory volume. Also the new model does not require additional input data such as experimentally measured volt-ampere characteristic. The system geometry and material parameters are required only. Comparison of full (drift-diffusion) and simplified models is presented in this work. Also comparison of computation results and experimental data for the cylinder-plane system is presented. Sufficient difference is revealed in the central jet area but integral inaccuracy is low.

Keywords: ionic wind, electrostatic precipitator, corona discharge, charged particle transport, electrohydrodynamics.

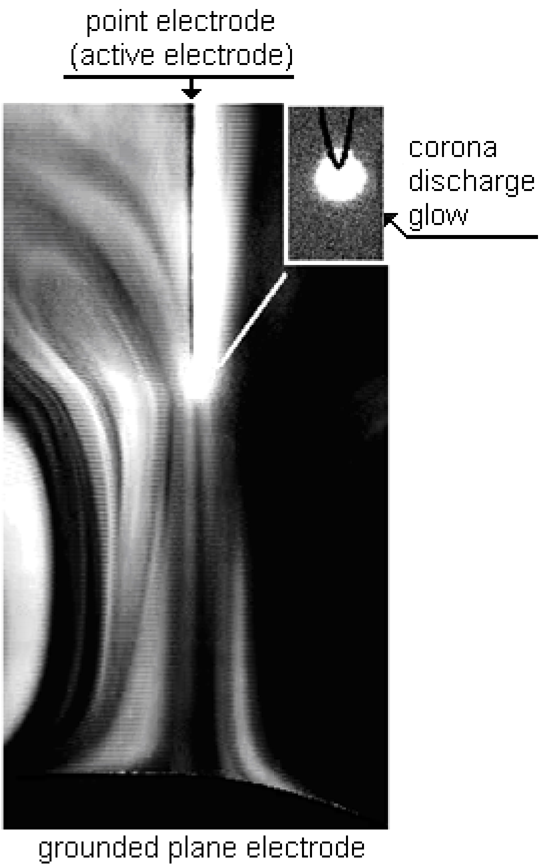

Figure 1. Ionic wind visualized by brightened smoke. The point-plane electrodes system.

1. Introduction

Non-uniform electric field appears in systems with electrodes which curvature radii differ strongly. If electric field intensity is high enough air ionizing and corona discharge obtain near the electrode of lower curvature radius. Ions produced in corona discharge are accelerated by electric field. Then due to elastic collisions momentum is passed to neutral molecules. Thus air motion emerges - "ionic wind". A typical ionic wind streamer has form of strong narrow jet which is directed from the coroning electrode to the passive opposite electrode (Fig. 1).

In the continuous media approximation one can consider that the volume force $\rho\mathbf{E}$ affects air in corona discharge. Here ρ is volume charge density and $\mathbf{E}$ is electric field intensity.

Electric energy may be transferred to kinetic energy of moving air almost directly by using ionic wind. Ionic wind is applied in electrostatic precipitators which clean air from dust particles of different size. Problems of optimization electrostatic precipitators are still actual [4-5]. Also there are applications of this phenomenon in air ionizers and air cooling systems [1-2].

The system of partial differential equations (PDE) which describes both corona discharge and gas dynamics ("drift-diffusion approximation") is resource-intensive by numerical computation. So axisymmetric problems are solved in this approximation basically. Therefore more simplified unipolar approximation is of sufficient practical interest. Consider negative polarity corona. Electrons and positive ions volume charge is neglected in the unipolar approximation. Negative ions are taken into account in bulk only. In unipolar approximation the finite elements size and the solution time step may be taken much larger than in drift-diffusion approximation. Solution time decreases sufficiently.

The corona sheath structure is neglected in unipolar approximation. The sheath properties are described by boundary condition on the coroning electrode. Now the problem of choosing form of this boundary condition is not solved finally. There are several variants in use.

The fixed electric field intensity condition was often used in analytic models:

$$E=\text{const}$$

However preliminary selection of coroning area on the active electrode is required in this case. Also providing implementation of this condition is difficult by numerical calculations. The point is that formally restriction is applied to electric field but actually it is provided by ions concentration redistribution.

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Another approximation is often used in numerical calculations. Here ions flux density on active electrode surface is set as a function of local electric field intensity:

$$j=f(E)$$

The linear dependence is often used as a function *f(E)*. The disadvantage of this method is that one should know current-voltage characteristic of the system to define coefficients in the *f*(*E*) function. This function is not universal and depends significantly on the geometry parameters of the electrode system.

It is represented farther that boundary conditions in unipolar approximation may be formulated so that the described disadvantages are avoided.

2. Use of COMSOL Multiphysics

2.1. Governing Equations

The system of PDE is solved in air bulk:

$$\begin{cases} \varepsilon_0 \Delta\varphi = en\_ & (1) \\ \rho\left[\dfrac{\partial\vec{v}}{\partial t}+(\vec{v}\cdot\nabla)\vec{v}\right] = -\nabla P + \eta\Delta\vec{v} + en\_\nabla\varphi & (2) \\ (\nabla\cdot\vec{v}) = 0 & (3) \\ \dfrac{\partial n\_}{\partial t} + \left(\nabla\cdot\left[-D\nabla n\_ + \mu n\_\nabla\varphi\right]\right) = 0 & (4) \\ \left(\dfrac{\nabla\varphi}{|\nabla\varphi|}\cdot\nabla\right) M = \alpha\left(|\nabla\varphi|\right) & (5) \end{cases}$$

These equations were solved in the COMSOL Multiphysics software package. Several modules were used:

(1) - the Poisson's equation for electric potential *φ;* "Electrostatics" model of "AC/DC" module; *e* is the absolute value of ion charge.

(2-3) - the Navier-Stokes equations in incompressible approximation for air velocity **v** and pressure *P*; "Laminar flow" model of "Fluid flow" module. Here η is dynamic viscosity; ρ − gas density.

(4) - the transport (Nernst-Planck) equation for negative ions concentration n_-; "Drift diffusion" model of "Plasma" module. *D* is diffusivity and μ − mobility of negative ions.

(5) - integration of the ionizing collisions number *M* along electric field line. α(*E*) is the dependence of effective ionization coefficient on electric field intensity; "Coefficient form PDE interface". The dependence α(*E*) in air is measured and commonly known.

2.2. Boundary Condition on the Active Electrode

The following boundary condition on the active electrode is offered:

$$\frac{\partial j\_}{\partial t} = \frac{1}{\tau}\left(\gamma\left(\exp M - 1\right) - 1\right) j\_ \qquad (6)$$

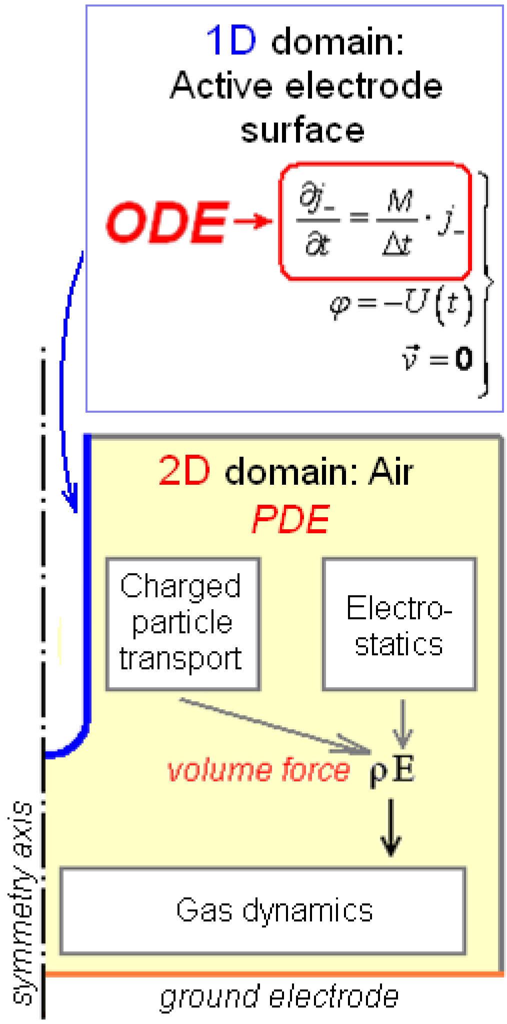

Figure 2. The COMSOL Multiphysics model scheme for computation ionic wind.

The rate of ions flux density change is set as a function of ionizing collision number *M* which is computed in the equation (5).

In (6) γ is the secondary ion-electron emission coefficient. τ is the character time of avalance development.

The boundary condition (6) is an ordinary differential equation (ODE). Thus one should solve equations (1-5) as PDE in bulk 2D domain and simultaneously solve equation (6) as ODE in boundary 1D domain. The COMSOL Multiphysics software package gives an opportunity to solve such non-standard systems of coupled equations (Fig. 2).

2.3 Derivation of the Boundary Condition (6)

The following short explanation grounds choosing form of the statement (6). More accurate analysis may be implemented to reveal conditions of applicability but here these issues are omitted.

Let us assume that N_k electrons where emitted from the active electrode surface in time moment t_k. The avalanche formed from these electrons spread along the electric field line. If ionizing collisions number is *M* on this line the avalanche is growing and electrons number reaches in the end of avalanche stage the number P_k:

$$P_k = N_k e^M$$

Then these P_k electrons turn to negative ions and begin slow drift to the opposite electrodes. The avalanche ceases to exist. However not only P_k-N_k electrons emerge in avalanche but also the same number of positive ions. Ions are much slower than electrons and positive ions return to the active electrode surface time-lagged: in moment $t_{k+1}=t_k+\tau$.

The positive ions are falling on the active electrode surface and cause emerging of N_{k+1} electrons due to secondary emission. If γ is the secondary emission coefficient the number of emitted electrons N_{k+1} is:

$$N_{k+1} = \gamma\left(P_k - N_k\right) = \gamma N_k\left(e^M - 1\right)$$

The following statement estimates the electron number change rate:

$$\frac{dN_e}{dt} = \frac{N_{k+1} - N_k}{\tau} = \frac{1}{\tau}\gamma N_k\left(e^M - 1\right) \quad (7)$$

The statement (7) is similar to the offered boundary condition (6).

3. Results Analysis

3.1. Comparison of Full and Fast Models

The axisymmetric model of the point-plane electrodes system was built to compare the offered model with the more complete drift-diffusion model.

There are significant (up to 50%) distinctions in velocity field between the full and unipolar models in the central part of jet. It is related with the fact that unipolar model does not describe the corona charge sheath structure which influence sufficiently on this area (Fig. 3).

However the area of distinction is very thin. Integral parameters of the flow and discharge (pressure on the opposite electrode, flow bulk rate, summary current) differ in the full and the unipolar models by less than 10% (Fig. 3-4).

Voltage-current characteristics in the both models fit the experimental data well.

3.2. Comparison of Fast Model and Experimental Data

There are experimental data about the velocity field of ionic wind in the wire-plane electrodes system [3]. The parameters of this system is close to some electrostatic precipitators parameters so it is of certain practical interest.

The boundary and volume conditions are similar to the model of the point-plane system (Fig. 1) but the active electrode is not a point but a cylinder; also the symmetry of this model is plane instead of axial in the previous model.

Velocity in simulation results is more than the experimental data on the symmetry axis. Maybe it is due to the small radius of the central jet and its velocity profile was not measured accurately in the experiment (Fig. 6). In other areas difference is less.

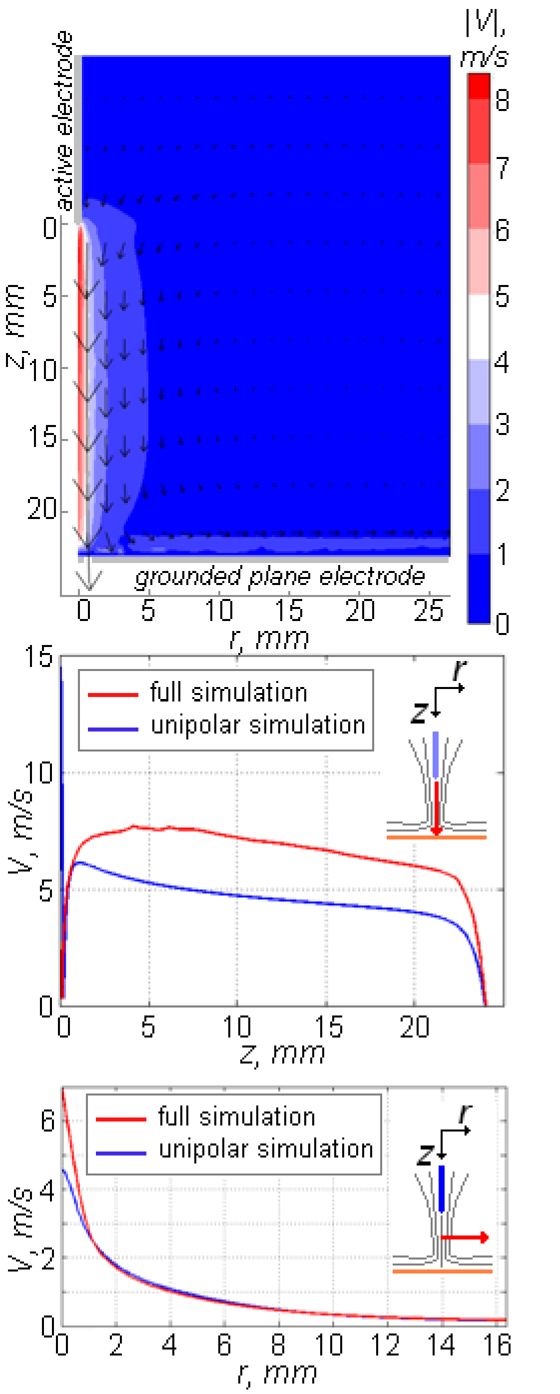

Figure 3. Ionic wind in the point-plane electrodes system. Velocity distribution. Comparison of the full (drift-diffusion) and the unipolar model.

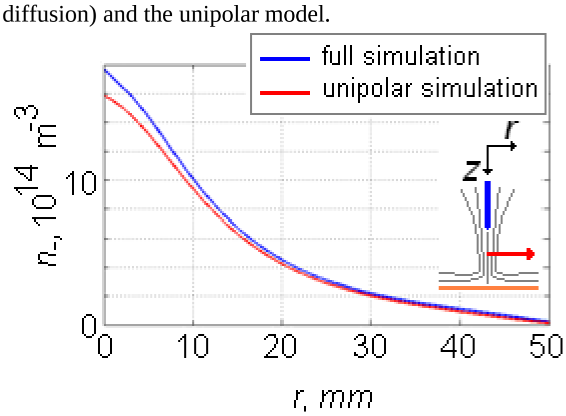

Figure 4. Ionic wind in the point-plane electrodes system. Negative ions concentration. Comparison of the full (drift-diffusion) and the unipolar model.

The common flow pattern is restored correctly. Dependence of basic parameters on voltage is in good accordance with experiment (Fig. 5).

4. Conclusions

The offered simplified unipolar model of ionic wind gives results which are close to the full (drift-diffusion) model results. However the simplified models reduces solution time and used memory volume up to 10 times in comparison with the full model. This advantage is significant for 3D simulations. The offered new boundary condition on the active electrodes makes the model more universal: information about voltage-current characteristic or corona area is not needed to implement the simulation. The simulation results are in good correspondence with experimental data.

5. References

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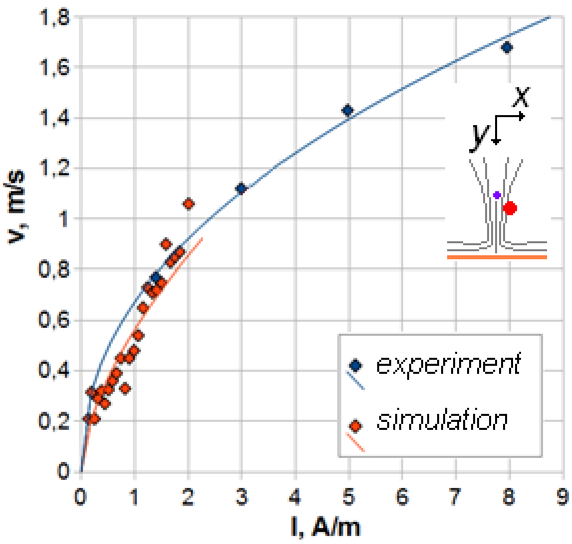

Figure 5. Ionic wind in the wire-plane electrodes system. Dependence of air velocity on current. x=10 mm, y=10 mm. Comparison of calculation results (unipolar model) and experimental data.

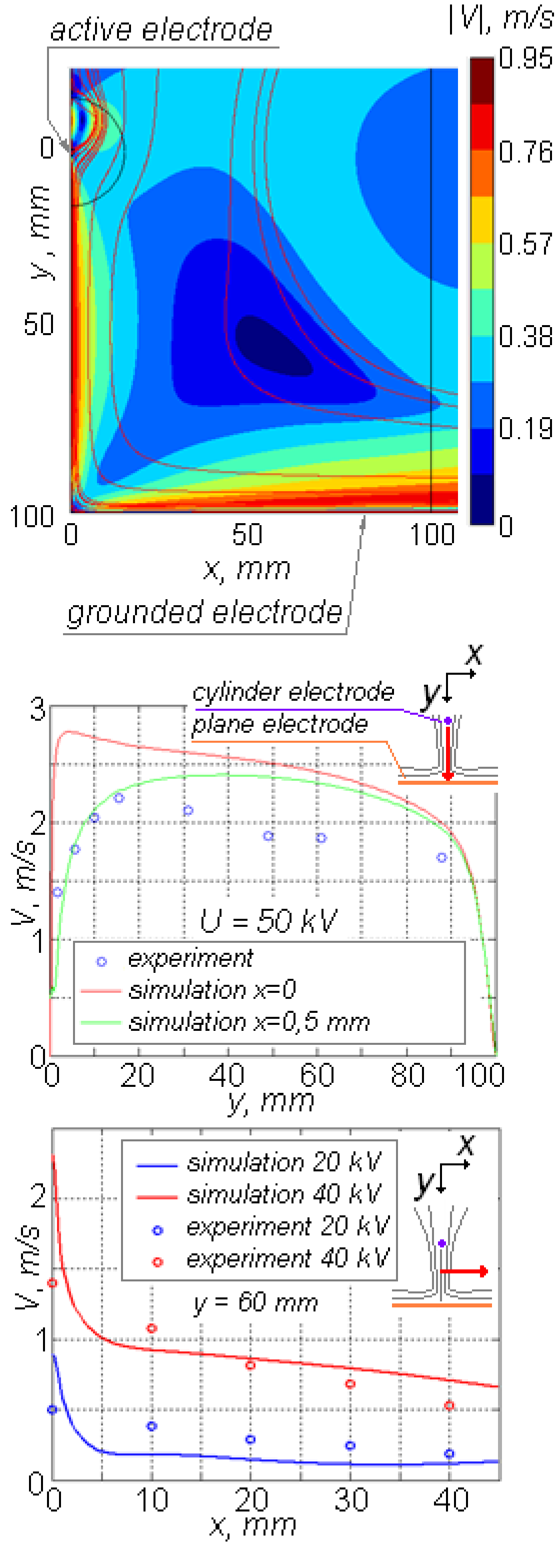

Figure 6. Ionic wind in the wire-plane electrodes system. Air velocity distribution. Comparison of simulation results (unipolar model) and experimental data. h=100mm, U=50kV.