Simulation of Intense Electrohydrodynamic Flow Based on Dielectric Barrier Discharge

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Abstract. This paper presents a numerical analysis of the intense EHD gas flow velocity distribution at atmospheric pressure. The system consists of a coaxial plasma emitter and a collector grid. The ion source is a dielectric barrier discharge distributed over the surface of the emitter. The computational results coincide with the experimental data which allow us to predict the maximum flow rate produced by the experimental setup.

1. Introduction
An electrohydrodynamic (EHD) flow is a physical phenomenon of a gas collective motion caused by the drift of charged particles in a high electric field. The promising atmospheric plasma technology with many potential applications in aeronautics, which allows controlling the airflow over the surface of the wing, reducing drag and impeding the transition to turbulence [1], is related to electrohydrodynamic interaction of ions and neutral particles.

The EHD flow systems are used to intensify the heat dissipation in modern high-performance computers and as an electrical pump of a gas mixture in lasers, electric filters for gas media cleaning, and surface modification applications of materials [2-4]. It is possible due to the generation of high speed gas flows without using traditional electromechanical systems, such as turbines and fans. An advantage of electric pumping is the absence of moving parts and related failures due to the rotor wear or the thermal and mechanical fatigue of fans [5-7].

2. Numerical simulation
As it was offered in [8] the high frequency barrier discharge distributed over the dielectric surface was used as an ion source for the EHD flow system for a gas mixture circulation in electric-discharge lasers. We have constructed a device with the three tubular plasma emitters (1) with optimal spacing, a grid collector (2) with transparency T, a DC high voltage supply and a high frequency high-voltage solid-state pulse generator (HFHVPG) (Figure 1). The positive polarity output pulses generated by the HFHVPG were quasirectangular with a voltage amplitude of 0 – 12 kV, a rise time of 100-200 ns, a variable duration of 500 ns –10 μs, and a repetition rate of 1 – 25 kHz [9].

Such a system has a lot of variables and to achieve maximum efficiency it requires multiparametric optimization. Since analytical solutions were obtained for the very simple cases [8], the numerical model has been constructed to design systems with a complex geometry. The intense EHD flow generated by the plasma discharge on the surface of the dielectric tube was simulated in the air at atmospheric pressure depending on the transparency of the collector grid. To achieve an acceptable computational time the model was simplified to a two-dimensional case in the X-Y plane and was solved for a single emitter.
The model based on the system of equations connects several areas of physics [10, 11].
The electric potential $U$ is determined by the Poisson equation:

$$
\nabla^2 U = -\frac{q}{\varepsilon_0},
$$

(1)

where $q$ is the space charge density and $\varepsilon_0$ is the dielectric permittivity of free space.
The electric potential associated with the electric field strength is given by:

$$
E = -\nabla U
$$

(2)

The electric current in the drift zone of charged particles is the result of the three processes: an electric drift (ion motion in the environment under the influence of an electric field), advection (movement of charged particles in the gas stream), and diffusion. Thus, considering the above, the current density can be written as:

$$
j = \mu_i E q + V q - D \nabla q
$$

(3)

where $\mu_i$ is the ion mobility in an electric field, $V$ is the fluid velocity, and $D$ is the diffusion coefficient of ions in gas. The convection term of equation is negligible as $V \ll \mu_i E$ (typical gas flow velocity is about 1-5 m/s whereas the drift velocity of ions reaches hundreds of meters per second) [12].
The continuity equation for the current is given by:

$$
\nabla j = 0
$$

(4)

The volumetric electrodynamic force in a gas with dielectric permeability $\varepsilon$, density $\rho$, and temperature $t$ is expressed by:

$$
F = qE - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[ E^2 \frac{\partial \varepsilon}{\partial \rho} \right] \rho
$$

(5)

The first term in the equation is the Coulomb force acting on a free charge in the gaseous medium, the second and the third terms are dielectrophoretic and electrostrictive forces, respectively. The second and the third terms are important in the phase transition, which is great fluctuation of permeability at the liquid-gas boundary. The permeability in air is almost constant and hence the Coulomb force [13] is the dominant term.
The model hydrodynamic part is described by the Navier-Stokes equations for a steady state incompressible gas flow:

$$
\rho (V \cdot \nabla) V = -\nabla p + \mu \nabla^2 V + F,
$$

(6)

where $\rho$ is the mass density, $p$ is the gas pressure and $\mu$ – is the viscosity.
The mass continuity equation is given by:
\[ \nabla V = 0 \]  

(7)

The system of equations (1)–(7) describes the numerical model of the EHD device in this study with the boundary conditions as follows. The DC voltage of 20 kV was applied to the emitter and the ground potential was set at the collector grid. A space charge density of \( q \) was imposed on the tubular ion emitter corresponding to ion concentration of \( 10^{10} \text{ cm}^{-3} \) \[14\]. Open boundary with no viscous stress was applied to all boundaries and wall with no-slip condition was set to the collecting grid wires and the emitter tube.

The numerical simulation was based on the finite element method. The simulation space was discretized by the inhomogeneous grid consisting of 130,000 triangular elements. The minimum size of the finite element defined on the surface of the collector electrode is 50 µm and the maximum size of 400 µm is localized in the region center.

3. Numerical results

The numerical simulations for the EHD flow circulation system are presented for a device electric field profile, a charge distribution and an output flow velocity profile. The typical intensity distribution in the X-Y plane of the amplitude of the EHD flow speed at 0.7 grid transparency is shown in Figure 2.

![Figure 2](image)

**Figure 2.** Numerical simulation results: air velocity as coloured surface map with units in m/s.

Flow velocity \( V \) was simulated depending on transparency \( T \) of the mesh collector at optimal power supply parameters \[4\] of HVHFPS and the DC supply, which are taken into account at the boundary conditions. The velocity distribution profiles along the \( Y \) coordinate, depending on the spacing of the grid is shown in Figure 3. In the figure an increase of \( V \) with increase of \( T \) is demonstrated. Transparency was varied by changing the spacing and the wire radius using a commercially available selection of grids.
The computational results show that the grid electrode has a strong deceleration of the EHD flow, so optimizing its design provides significant potential to raise the speed and the flow quantity. There is a limit to increase in $T$ which results to high field strength near the surface of the wire mesh. This field causes an opposite ion drift decelerating the main flow. Therefore, along with the influence of the geometry of the electrode gap and the space charge, the effect of grid parameters should also be taken into account.

On the basis of this simulation optimal transparency of the grid collector of 0.77 has been selected and an airflow speed up to 3 m/s was achieved. The results of computations coincide with the experimental data [4] which allow us to predict the maximum flow rate produced by the experimental setup and improve its efficiency.

4. References
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