Journal of Electrostatics 93 (2018) 118–124

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

A double-vortex EHD flow pattern generated by negative corona discharge in point-plane geometry

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ARTICLE INFO

Keywords:
Electrohydrodynamics
Corona discharge
Flow pattern
Numerical simulation

ABSTRACT

The paper presents the results of numerical simulation of the electrohydrodynamic flow in the point-plane configuration in air at atmospheric pressure and room temperature. A stationary corona discharge model considering three ionic species (electrons, negative and positive ions) includes four reactions in the ionization layer and doesn't use an assumption that the electric field on the corona electrode surface remains constant. The distributions of electric field and ionic species were used to calculate the electric body force and EHD flow. In addition to the well-known flow vortex in the drift zone, calculations predict the existence of an additional small vortex in the ionization layer. The effect of the voltage level on the flow pattern was also investigated.

1. Introduction

In a non-uniform configuration consisting of two, or more, electrodes, a stable electric discharge, called corona discharge, is produced when a high voltage is connected between a sharp electrode and the other, much flatter, electrode. In a high-field region, called the ionization zone, positive ions and electrons are produced and their movement depends on the polarity of the sharp electrode. In a low field region, called the drift zone, electrons don't have enough energy to further ionize neutral molecules and just drift towards the ground electrode. In electronegative gases, like air, these electrons can attach to neutral molecules, forming negative ions.

Non-thermal plasma created by the corona discharge is used in numerous applications due to its high chemical activity. Ions produced in the discharge are also often used to electrically charge small particles and surfaces of larger objects. There is also one more effect of the corona discharge – secondary electrohydrodynamic flow (EHD) or ionic wind. Ions and electrons, drifting in the electric field, collide with neutral molecules, what leads to the momentum transfer, so the ambient gas starts to move.

The EHD flow was first observed long time ago [1]. Also, relatively early the mechanism responsible for the movement has also been explained, as reported in Ref. [2]. However, for long time this phenomenon was treated as just curiosity without any practical implications.

The first area when the EHD flow has had to be considered was electrostatic precipitation and numerous researchers have been discussing the effect of this flow on the particles collection efficiency. Without any doubts the corona discharge increases flow turbulence [3]. However, there are still contradictory opinions whether the net effect of EHD flow on the overall precipitator characteristics is beneficial or detrimental [4,5].

More recently, the EHD flow has found many useful applications. One of them is an ionic wind-driven bulk air blower or an EHD pump. These pumps may have several configurations, where different flow patterns can be observed [6,7]. The most popular are the EHD pumps using sliding discharge [8] and needle-ring-metal pumps [9]. During the last 20 years many works have been also published in the area of discharge actuators for controlling flow boundary layer [10]. Very promising are applications in heat transfer enhancement, for example, to improve cooling of electronic devices [11]. More recently, the EHD flows have been considered to accelerate drying, which can be a very economical option since the process requires a small pressure difference and a relatively low thermal energy [12,13].

Ionic wind generated by the corona discharge has been investigated both experimentally and theoretically, and different models have been considered. In one of the first published numerical studies, Batina et al. considered the dynamic models for the EHD flow in point-plane geometry considering streamers, although only for a very simplified discharge model [14]. Because unipolar ions in the drift discharge zone play the main role in formation of the EHD flows, a very simplistic monopolar discharge model coupled with Navier-Stokes equation was adopted in Ref. [15]. A staggered multiphysics algorithm for simulating a strongly coupled system of non-linear partial differential equations, governing ionized electric field, gas flow and temperature was proposed in Ref. [16], although again this was done for a single-species discharge model. Another simplified discharge model neglecting processes in the

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https://doi.org/10.1016/j.elstat.2018.04.010
Received 21 March 2018; Received in revised form 19 April 2018; Accepted 22 April 2018

ionization layer [17] showed a substantial difference in generating ionic wind by ac and dc corona discharges. The first fully dynamic model of corona discharge based on three ionic species and including the ionization layer was presented in Ref. [18]. This paper focused mainly on the flow fluctuation caused by the pulse nature of the discharge (Trichel pulses). Different aspects of the EHD flows generated by corona discharge in various configuration of electrodes were also studied in Refs. [19–21].

The objective of this paper is to investigate a full air flow pattern in the air gap between a sharp needle and a flat ground plate, generated when a simplified stationary discharge model with three ionic species (electrons, positive ions and negative ions) is considered. A numerical algorithm based on the Finite Element Method was implemented using the commercial software COMSOL 5.3. The distributions of electrical (the space charge density and the electric potential) and mechanical parameters (the airflow streamlines, the pressure and the velocity distribution) were determined.

2. Mathematical model and numerical algorithm

2.1. Corona discharge

The investigated corona discharge model consists of two electrodes: the first one is an infinitely large grounded metal plate and the second one is a sharp needle, perpendicular to the ground electrode and supplied with a high dc negative voltage. This needle has a shape of a cylinder ended up with a hemisphere. The system geometry is defined by the needle tip radius of curvature R, the needle body length L and the distance between the ground electrode and the tip of the needle d. As the system geometry is axisymmetric, the simulation was performed in the two-dimensional cylindrical coordinates.

The major difficulty in simulating corona discharge is caused by complicated chemistry of the process, which involves a large number of different species and reactions, and irregular dynamics of the process (Trichel pulses and streamers). Any realistic model needs substantial idealization. The model considered in this paper assumes a stationary discharge, and takes into account just three ionic species (electrons, positive and negative ions) and four chemical reactions (the electron avalanche ionization, the recombination of the electrons and the positive ions, recombination of the positive and negative ions, and the electron attachment to neutral molecules) [22].

$$e + O_2 \rightarrow 2\,e + O_2^+ \tag{1}$$

$$e + O_2^+ \rightarrow O_2 \tag{2}$$

$$O_2^- + O_2^+ \rightarrow 2O_2 \tag{3}$$

$$e + O_2 \rightarrow O_2^- \tag{4}$$

As a result, the mathematical model consists of three drift-diffusion equations governing generation, dissipation and movement of the ionic species and Poisson's equation for the electric potential distribution:

$$\nabla(-\mu_e \mathbf{E} n_e - D_e \nabla n_e) = R_e \tag{5}$$

$$\nabla(\mu_p \mathbf{E} n_p - D_p \nabla n_p) = R_p \tag{6}$$

$$\nabla(-\mu_n \mathbf{E} n_n - D_n \nabla n_n) = R_n \tag{7}$$

$$\nabla^2 V = -\frac{e(n_p - n_e - n_n)}{\varepsilon} \tag{8}$$

where n_e, n_p, n_n are the densities (1/m^3), D_e, D_p, D_n are the diffusion coefficients (m^2/s), μ_e, μ_p, μ_n are the mobilities (m^2/V·s), R_e, R_p, R_n are the source terms (1/m^3·s) of electrons, positive ions and negative ions, respectively, and E is the electric field intensity (V/m). The ionization reaction rate coefficients are expressed using the local electrical field approximation:

Table 1
Swarm parameters for the ionic reactions in air.

Parameter	Value	Unit
Electron mobility (μ_e)	$1.9163 \cdot E^{-0.25}$	[m^2/V·s]
Positive ion mobility (μ_p)	$2.24 \cdot 10^{-4}$	[m^2/V·s]
Negative ion mobility (μ_n)	$2.16 \cdot 10^{-4}$	[m^2/V·s]
Electron diffusivity (D_e)	0.18	[m^2/s]
Positive ion diffusivity (D_p)	$0.028 \cdot 10^{-4}$	[m^2/s]
Negative ion diffusivity (D_n)	$0.043 \cdot 10^{-4}$	[m^2/s]
Recombination coefficient of positive and negative ions (β_{np})	$2 \cdot 10^{-13}$	[m^3/s]
Recombination coefficient of electrons and positive ions (β_{ep})	$2 \cdot 10^{-13}$	[m^3/s]
Ionization coefficient (α)	$3.5 \cdot 10^5 \cdot \exp(-1.65 \cdot 10^7/E)$	[1/m]
Attachment coefficient (η)	$1.5 \cdot 10^3 \cdot \exp(-2.5 \cdot 10^6/E)$	[1/m]

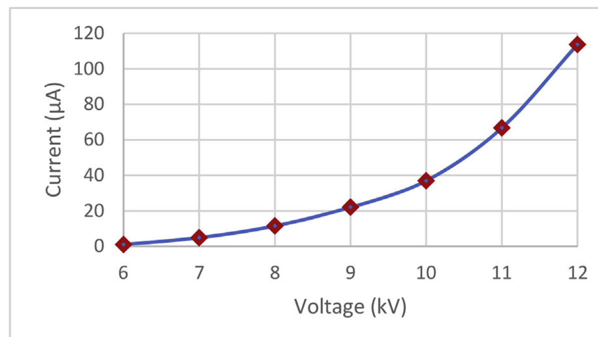

Fig. 1. V-I characteristics of the investigated corona system.

$$R_e = \alpha\, n_e\, \mu_e\, \mathbf{E} - \eta\, n_e\, \mu_e\, \mathbf{E} - \beta_{ep}\, n_e\, n_p \tag{9}$$

$$R_p = \alpha\, n_e\, \mu_e\, \mathbf{E} - \beta_{ep}\, n_e\, n_p \tag{10}$$

$$R_n = \eta\, n_e\, \mu_e\, \mathbf{E} - \beta_{np}\, n_n\, n_p \tag{11}$$

The values of these parameters have been studied experimentally by many authors and different analytical approximations have been proposed. The values used in this paper given in Table 1 are compilation of data found in a few previously published papers [22–26].

To solve the above equations, appropriate boundary conditions must be specified. The corona and ground electrodes satisfy Dirichlet boundary conditions for the electric potential: $V = 0$ on the ground, and $V = V_c$ on the corona electrode.

In order to have a self-sustained corona discharge model, some mechanism for generating seed electrons must be implemented. The most important source of these electrons is the secondary emission from the discharge electrode. When the positive ions collide with the negative corona electrode, the secondary electrons are ejected. The concentration of the secondary electrons is given by the following equation [27]:

$$n_e = \gamma \cdot n_p \cdot \frac{\mu_p}{\mu_e} \tag{12}$$

where n_e is the concentration of the electrons and n_p is the concentration of positive ions on the corona wire surface (1/m^3). The secondary emission coefficient γ is typically taken to be equal to 0.01.

2.2. EHD flow

EHD flow is generated when ions, drifting in electric field, collide with neutral molecules. There is a momentum transfer, which causes gas motion. When this EHD flow is simulated, in addition to solving the Poisson's equation for electric field and the drift-diffusion equations for