Journal of Electrostatics 92 (2018) 54–65

Contents lists available at ScienceDirect

Journal of Electrostatics

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

A simplified formulation of wire-plate corona discharge in air: Application to the ion wind simulation

M.R. Bouazza[a], K. Yanallah[a,*], F. Pontiga[b], J.H. Chen[c]

[a] Laboratoire de Génie Electrique et des Plasmas, Université de Tiaret, Algeria
[b] Departamento de Física Aplicada II, Universidad de Sevilla, Spain
[c] Department of Mechanical Engineering, University of Wisconsin-Milwaukee, Milwaukee, WI 53211, USA

ARTICLE INFO

Keywords:
Corona discharge
Electric wind
Semi-analytical approach
Wire-to-plane electrode geometry
Fluid model

ABSTRACT

The spatial distribution of charged particles (electrons, negative ions and positive ions) and electric field have been evaluated using a semi-analytical approach of the positive and negative corona discharge for a wire-to-plate electrode system. Thus, approximate formulas useful for the characterization and control of corona discharge devices are provided, which helps to significantly reduce computational costs. Based on the obtained results, the electro-hydrodynamic (EHD) force generated by the corona discharge has been determined, and it has been used in the Navier-Stokes equations to compute the spatial distribution of the gas velocity. As a result, the influence of the corona plasma region in the flow pattern, particularly in the vicinity of the corona electrode, has been brought to light, which helps to understand the different flow velocities observed in positive and negative coronas. Moreover, the influence of voltage, wire radius, and inter-electrode separation on the electric wind velocity has been investigated.

1. Introduction

Corona discharge occurs when high voltage is applied between two electrodes, and at least one of them has a sharp curvature. A strong electric field is then created around the sharp electrode, causing a local breakdown and the flow of electric current between the two electrodes. When charged carriers (electrons and ions) traversing the inter-electrode space collide with neutral gas particles, they transmit a part of their momentum to them, which sets the gas in motion. The flow thus generated is generally referred to as electric wind, ion wind or EHD flow. This phenomenon has been known for a long time [1], but it still remains under study due to its complexity. The electric wind can be generated in corona discharges as well as in other types of electric discharges [2], and its mechanism depends on the nature of the discharge itself.

Electric wind has many growing industrial and research applications, such as heat transfer enhancement [3,4], EHD pumps and micropumps [5,6], EHD flow control [7] and ionic loudspeakers [8]. Moreover, practical devices exploiting electric wind usually have additional advantages over other technologies, including a simple design, small weight and size, no need for moving parts, low cost, and a long lifetime.

In the last decades many theoretical and experimental efforts have been conducted to increase our understanding on the EHD flow produced by corona discharges. For instance, the pioneer model of Robinson [9] related the velocity of the ionic wind to the current intensity of the electric discharge, which was confirmed in his experiments. Béquin et al. [10] investigated the velocity flow distribution in negative point-to-plane corona in air. They developed a one-dimensional model of neutral particle velocity along the corona discharge axis, and they measured the velocity profiles using Laser Doppler Anemometry (LDA). The discrepancy between the modeling and the measurements were attributed to the omission of the ring vortex formation in the model, and to the perturbation that tracing particles may have on the corona discharge. For the case of positive DC corona discharge, Lacoste et al. [11] were able to estimate the gas velocity using a simplified model, and they compared the model predictions with the measurements obtained using LDA. The measured velocity profile was reasonably fitted by the model, but the radius of the corona plasma region was an adjustable parameter in their model.

More recently, a wide variety of numerical techniques and modeling approaches have been applied to investigate and characterize the generation of ion wind in electric coronas. For example, Zhao and Adamiak [12,13] used a hybrid numerical algorithm to solve both the Gauss and charge transport equations. Once the EHD force was determined, Navier-Stokes equations were integrated using the finite-volume method in order to evaluate the gas flow. The authors followed an iterative

---

[*] Corresponding author.
E-mail address: yanallahkh@yahoo.fr (K. Yanallah).

https://doi.org/10.1016/j.elstat.2018.02.001
Received 14 October 2017; Received in revised form 19 January 2018; Accepted 12 February 2018
0304-3886/

procedure to ensure the consistency between the corona simulation and the fluid flow programs. Ahmedou and Havet [14] have simulated the airflow in a flat duct, in which corona discharge is generated by a single or multiple fine-wire electrodes. The electrical problem (Gauss and charge conservation equations) was coupled to the fluid dynamics problem (mass, momentum and energy conservation equations) and they were solved in the drift region using the finite element method. Since the ionization layer at the vicinity of the wire was not modeled, the authors have to formulate a proper boundary condition for the space charge density on the corona wire. In order to reduce the computational costs, Seimandi et al. [15] have proposed an asymptotic model for steady wire-to-wire corona discharges, in which the inter-electrode space is divided in three regions: two thin ionization regions around the electrodes and one larger ion-drift region. A simplified kinetic model was considered for each region, which allowed the establishment of quasi-analytical solutions for the electric field and the particle fluxes, and to estimate the velocity of the ionic wind from Euler equations. Cagnoni et al. [16] have carried out a numerical study with the aim of modeling the EHD cooling of a condensation radiator. They have applied a staggered solution algorithm to solve the strongly coupled set of partial differential equations that governs the problem. Very recently, Chen et al. [17] have studied numerically and experimentally the ionic wind generation in a point-to-cylinder negative corona discharge operating in the Trichel regime. They observed that flow velocity and the EHD body force have opposite directions in the ionization region, close to the tip, and in the ion drift region, further away from the tip.

In the present work, the generation of EHD wind will be modeled for a parallel wire-to-plate electrode geometry, both for the positive and negative polarities. Corona discharges are time-dependent phenomena, and a complete description of the problem would require solving a fully dynamic numerical model, which demands very long computational times. Therefore, in this study, a stationary or steady-state model will be used to formulate the governing equations of the corona discharge for electrons, positive ions and negative ions. This type of model allows the evaluation of the spatial distribution of time-averaged corona parameters with less numerical effort, and they have been widely used in the scientific literature [15,18,19]. The governing equations will be solved semi-analytically, so that simple relations of the time-averaged spatial distributions of ions, electrons and their fluxes are obtained. These approximated solutions are useful in modeling studies and applications of coronas and, in particular, to evaluate the electrical force that originates the EHD motion. Thus, in a second step, the electrical force will be used in the Navier-Stokes equation to compute the 2D spatial distribution of the gas velocity. Special attention will be paid in this study to the ion wind structure in the vicinity of the corona wire for each polarity, as well as to the influence of the geometrical parameters (wire radius and inter-electrode separation) and electrical parameters (applied voltage) on the ion wind intensity.

The present study is based in previous models of corona discharge, which have been applied to different electrode geometries [18,20–22]. These models have been validated by comparing their results with other numerical techniques [20,22] and, indirectly, with the experimental measurements of the ozone produced by the corona discharge [21]. This work also follows the same strategy as that adopted in Ref. [23], where the electric wind generated in positive corona discharge was evaluated. However, the emphasis of that work was placed on the effect of the EHD motion on the spatial distribution of the chemical species generated by the corona discharge. In contrast, the goal of the present study is to investigate the differences in the ion wind produced by positive and negative coronas, and how it is affected by geometrical and electrical parameters.

2. Governing equations

The correct assessment of the charged particles densities and of the electric field is essential to have a good approximation of the EHD force acting on the fluid. This force is an input parameter in the Navier-Stokes equations, which ultimately will determine the gas flow profile. Therefore, in this section, the mathematical model of the positive and negative corona discharge will be firstly presented in section 2.1. Then, the expression for the EHD force will be defined in section 2.2. Finally, in section 2.3, the mechanical equations governing the fluid flow will be introduced.

2.1. The corona discharge model

Corona discharge is assumed to take place in air at atmospheric pressure and room temperature using a parallel wire-to-plate electrode configuration. DC high voltage is applied to the wire, while the plate is grounded. The radius of the wire and the distance between the wire and the plate will be designated as r_0 and d, respectively. The electrical discharge is supposed to have translational symmetry in the direction of the wire, so that it can be modeled as a plane 2D problem. Furthermore, it is assumed that the electrical discharge is symmetric with respect to the symmetry axis of the electrode configuration. These assumptions are quite reasonable when modeling positive coronas. However, negative coronas may appear either as a glow, with a very uniform distribution of current, or concentrated into small active spots, which are usually called “tufts” or “beads” [24,25]. The first mode, termed “ideal corona” by Vann Bush and Snyder, is favored by the used of smoothly polished wire. Therefore, the previous assumptions fit well into this first mode of negative corona.

Corona discharge can be successfully simulated using a fluid approximation, which consists in solving a set of continuity equations for the charged particles coupled with the Gauss equation for the electric field. Usually, only three generic types of charged particles (electrons, positive ions, and negative ions) need to be considered for the physical modelling [26,27]. In the case of a positive corona, negative ions and electrons spread over a short distance ($\sim 10\ \mu\text{m}$) from the wire [22], but the negative ion density is much weaker than the electron density. Therefore, for the purpose of this work, negative ions can be ignored in the positive corona.

Assuming a stationary discharge, the governing equations can be written as

$$-\nabla\cdot \mathrm{J_e} = (\alpha - \eta)|\mathrm{J}_e|, \tag{1}$$

$$\nabla\cdot \mathrm{J}_p = \alpha|\mathrm{J}_e|, \tag{2}$$

$$-\nabla\cdot \mathrm{J}_n = \eta|\mathrm{J}_e|, \tag{3}$$

$$\nabla\cdot \mathrm{E}=\frac{e_0}{\varepsilon_0}(N_p - N_e - N_n), \tag{4}$$

where subscripts e, p and n correspond to electrons, positive ions and negative ions; $\mathbf{J}_i$ and N_i denotes the flux and the number density of particles of type i ($i = e$, p and n), respectively; $\mathbf{E}$ is the electric field, α and η are the ionization and attachment coefficients, respectively; ε_0 is the air permittivity; and e_0 is the elementary charge. The flux of each type is given as $\mathbf{J}_i = \mu_i N_i \mathbf{E}$, where μ_i is the electrical mobility of particle i.

As shown in previous works, bipolar coordinates [28,29] are particularly adequate to formulate electrostatic problems in wire-plate electrode geometry, since the coordinate curves $\sigma =$ const. coincides with the Laplacian field lines (Fig. 1). Therefore, in order to solve semi-analytically (1)–(4), the same strategy as that adopted in Ref. [21] for