Journal of Electrostatics 72 (2014) 99–106

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Comparative study of corona discharge simulation techniques for electrode configurations inducing non-uniform electric fields

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ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form
14 November 2013
Accepted 6 December 2013
Available online 25 December 2013

Keywords:
Corona discharge
Assisted corona discharge
Ionization
Modeling
Simulation
Method of characteristics

ABSTRACT

Numerical modeling of corona discharges has followed the same set of procedures for many years. Corona discharges on large scales are modeled only for ion drift, neglecting ionization. Studies of the ionization zone are often conducted in uniform axisymmetric configurations. However, in configurations that induce non-uniform electric fields, a combination of the two procedures is necessary to accurately capture the discharge physics and ion distribution. The present study conducts numerical simulations of a wire-cylinder corona using both the models and demonstrates the necessity of including the ionization physics to obtain improved accuracy, particularly in the presence of non-uniform electric fields.

1. Introduction

Corona discharges are partially ionized gas discharges that occur between a sharp electrode (called a corona source), typically a needle or a wire, and a blunt electrode (called a collecting electrode or counter electrode) such as a plate or a cylinder. Corona discharges have been a field of study since early in the 20th century as a detrimental mode of breakdown in high voltage conductors. But because of the wide variety of possible configurations and operating conditions, corona discharges have also been developed for applications as varied as electrostatic precipitation [1] and flow generation and control [2] to chemical analysis [3] and ozone generation [4]. Electrostatic precipitation and flow generation are particularly interesting applications as they both capitalize on the electrohydrodynamic (EHD) flow or ionic wind generated by the drift of ions away from the corona source to the counter electrode. In the 1990's, advancement in electronics renewed interest in corona discharges as an alternative technology for convective heat transfer, both as a mechanism for spot cooling [5,6], and for the development of ionic wind blowers [7–10]. Additionally, the miniaturization of corona discharge devices has been a topic of research interest with applications to both ionic winds and particle filtering [10–13].

Numerical simulation can play an important role in developing these devices, and numerical simulations have been used in many contexts to study corona discharges. However, the corona discharge is a complex multi-physics phenomenon. It is initiated by very fast transient streamers but in the steady state consists of two distinct zones – the ionization zone in a small region near the corona source where the charge creation processes occur and a drift zone in the interstitial region between the ionization zone and collecting electrode where significant charge transport occurs. For this reason, modeling approaches span many scales and methods. However, for steady state phenomena, simulation techniques typically fall into two camps. In cases such as EHD flow generation and electrostatic precipitation, the ion transport dictates the charge/flow coupling, and numerical simulations typically only consist of the drift zone with the ionization physics treated as a charge injection boundary condition [14–17]. In applications such as ozone production, the

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http://dx.doi.org/10.1016/j.elstat.2013.12.003

reaction chemistry is of particular interest, and the ionization zone is studied in detail to map the concentrations of the various chemical species that are generated by the discharge [18–21]. In both these cases, the governing equations are continuum-based and thus a wide variety of numerical techniques ranging from finite volume methods to boundary element methods have been employed [22].

Much of current research emphasizes enhancing the performance of conventional corona discharge configurations, and many developments have arisen from configurations that induce a significantly non-uniform electric field near the corona source – that is, where the electric field varies severely as function of the angle around the circumference of the corona source. As shown in Fig. 1, these configurations can take different forms. One approach has been to use multiple collecting electrodes (multi-electrode or triode configurations), where the different distances from the corona source to the primary and secondary collecting electrodes modifies the conventional electric field around the corona source as shown in Fig. 1a–c [10,23–25]. Alternatively, an auxiliary electrode at the same potential as the corona source can be used to distort the uniformity of the electric field and enhance ion transport toward the primary collecting electrode as shown in Fig. 1d [26,27]. In each of these cases, the potential on the secondary or auxiliary electrodes can be varied to effectively modulate the degree of non-uniformity around the corona source. However, as shown in Fig. 1e, simply offsetting a corona source in a nominally axisymmetric wire-in-cylinder configuration can also induce non-uniformity around the corona source. Lakeh and Molki proposed this configuration to enhance EHD flow from the inner wire to the cylinder, though they did not explore the effect of non-uniformity around the corona source in detail [15,28].

While non-uniform electric fields are present in many conventional configurations such as the point-to-plane or wire-to-plane, often the ionization zone is sufficiently small compared to the drift zone that the non-uniformity around the corona source is essentially negligible [26]. In contrast, these configurations represent examples where the non-uniformity can be more severe and exploited for advantageous device operation. For example, in our prior work [10] we demonstrated that the configuration in Fig. 1b generates a two-beam corona – one beam to the primary collecting electrodes and one to the secondary collecting electrodes. This multiple electrode configuration was shown to increase EHD flow generation by increasing the ion production (or total current) at the source. Similarly, the configuration shown in Fig. 1d has been explored to enhance particle charging for electrostatic precipitators [26,27].

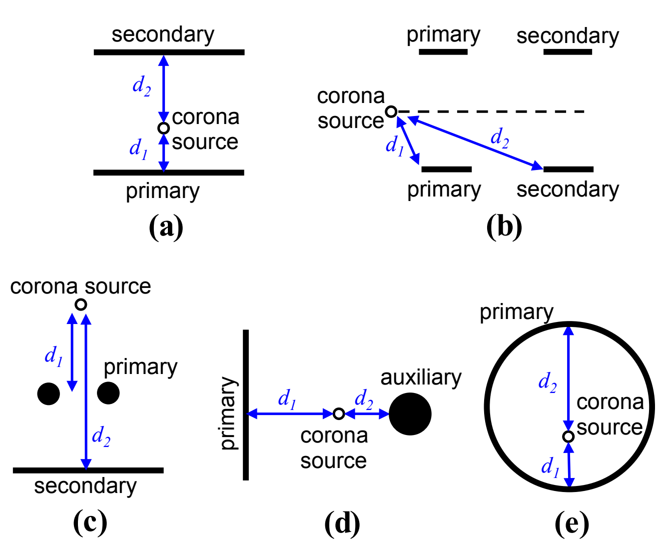

Fig. 1. Various configurations that induce highly non-uniform electric fields at the corona source. (a)–(c) Multi-electrode and triode configurations consisting of multiple collecting electrodes (primary and secondary) [10,23–25]. (d) Auxiliary electrode configuration where the auxiliary and corona source are at the same potential and the discharge is to the plate electrode only [26,27]. (e) Offset wire-in-cylinder configuration [15,28].

Simulating corona discharges in these non-uniform electric fields, however, presents a challenge to the conventional modeling methods and their typical assumptions. For example, the approach that models only the drift region typically assumes that the charge injection boundary condition is uniformly distributed around the corona source [7,15,28], although strategies have been proposed to address inherent non-uniformity. One of the proposed methods is to distribute the injected charge uniformly based on a combination of Kaptzov's hypothesis and Peek's breakdown criterion, using the local electric field on the electrode surface [26,29]. Another procedure is to estimate the local ionization based on a more explicit analysis of Townsend's ionization criterion [30]. However, even these approaches make an implicit assumption about the local non-uniform ionization, and it is not clear whether using classic simplifications like Peek's criterion and Kaptzov's hypothesis are valid. In studies that model the ionization zone, uniformity has also typically been assumed through axisymmetry so that the large number of reaction equations can be treated with one-dimensional models [18,20]. Clearly, these would also not be appropriate for cases where non-uniformity is significant. Thus in both models, conventional assumptions are insufficient to capture the physics for non-uniform conditions and thus will fail predict macroscopic properties such as the current distribution to multiple collecting electrodes.

In this work, we compare these two modeling techniques in analyzing a canonical wire-in-cylinder positive corona discharge configuration to explore the impact of non-uniform electric fields, where the non-uniformity is achieved through offsetting the wire as shown in Fig. 1e. The ionization model used in this study makes a choice of boundary condition that reduces the effects of forcing uniform boundary conditions for charge transport equations. The numerical results are compared against experimental measurements for the current distribution to the different portions of the collecting cylinder in order to determine the relative accuracy of the two approaches. Insights into the non-uniform discharge are revealed and discussed within the context of the geometric parameters that govern the problem.

2. Numerical modeling and experimental method

2.1. Governing equations and boundary conditions

Fluid models of a corona discharge, whether they are drift only or also include ionization, solve a set of scalar drift-diffusion equations for the charge transport

$$\nabla\cdot\left(\rho_k\mu_k\overline{E} - D_k\nabla\rho_k\right) = S_k, \tag{1}$$

where the subscript k reflects the charged species of interest – electrons (e), positive (p) and negative ions (n). ρ_k is the charge density of species k, μ_k is the species mobility in air, and D_k is the species diffusivity. S_k accounts for the production or depletion of the charge species k due to reactions between different species. The electric field $\overline{E}$ in the drift term is determined by solving Poisson's equation for the electric field

$$\nabla^2\Phi = -\nabla\cdot\overline{E} = -\frac{\rho}{\varepsilon_0}, \tag{2}$$

where Φ is the potential, ε_0 is the permittivity in free space, and ρ is the net space charge density ($\rho = \rho_p - \rho_e - \rho_n$). The product of