Journal of Electrostatics 96 (2018) 23–29

Contents lists available at ScienceDirect

Journal of Electrostatics

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

On the prediction of current-voltage characteristics for positive wire-to-cylinder corona discharge

Mario Sánchez*, Antonio J. Conesa

Instituto Nacional de Técnica Aeroespacial (INTA), Área de Aerodinámica Experimental, Torrejón de Ardoz, Carretera de Ajalvir, Km 4 28850, Madrid, Spain

ARTICLE INFO

Keywords:
Current-voltage characteristics
Corona discharge
Wire-to-cylinder arrangement
Inception voltage
Empirical formula
Ionic wind

ABSTRACT

The current-voltage curves in wire-to-cylinder arrangement are investigated for positive corona discharge varying the electrode gap and the emitter radius. Two well-known expressions are used to relate the corona current as a function of the voltage. Then, the dependencies of the equation parameters on geometrical characteristics of the electrodes are studied. The main results are as follows: 1) the dimensional parameter K shows a directly dependence with the emitter radius whereas an inversely dependence is observed with electrode distance; 2) the inception voltage V_0 increases with both emitter radius and electrode gap; 3) the exponent m varies inversely with emitter radius and it is proportional to the electrode gap. Based on the experimental results, a derived empirical formula for positive corona current discharge is proposed as a function of the applied voltage and the geometrical characteristics of the electrodes. Finally, the empirical equation is examined with data of previous studies to assess its validity.

1. Introduction

Corona discharge is a gas discharge between two asymmetrically electrodes separated by a distance or gap. One electrode receives the name of emitter, usually a sharp point or wire, whereas the other one is defined as collector (mostly a plate or cylinder). A non-uniform electric field is created when a high voltage is applied between both electrodes appearing an ionization region concentrated very close the emitter electrode. The ionization region is composed of ions and electrons and as Goldmand et al. stated [1] the predominant ions are of the corona polarity, that is, positive ions in positive coronas and negative ions in negative ones. The electric field produces ions movement from emitter toward collector in a zone called the drift region. In the drift region, charged species transfer momentum to neutral air molecules resulting in a gas flow usually known as ionic wind. The ionic wind generated by corona discharge is used in different commercial and industrial devices such as electrophotography, electrostatic precipitators, electrospraying, enhance cooling of electronic devices, food and water treatment, among others [2–10]. A great review of corona discharge processes and its possible uses can be found in the literature [11].

The current-voltage curves (CVCs) characterize the performance of corona discharges and they are of high importance for stablishing the operation range of devices using this technology. Regarding CVCs, the majority of the investigation were carried-out through two approximations i.e. analytical [12–15] or numerical [16,17]. For the analytical approach, the well-known Townsend's relation [18] has been used in the determination of the CVCs for different arrangements obtaining good results [12,19–27]. This relation can be expressed in the following form:

$$I = C{\cdot}V\,(V - V_0) \qquad (1)$$

where C is an experimentally determined dimensional parameter, V is the applied voltage and V_0 is the inception voltage. As can be seen, the feature characteristic of equation (1) is a quadratic behaviour of the current with the voltage. Recently, Moreau et al. [26] found that equation (1) interpolates correctly the experimental measures for positive point-to-plane arrangement when applied voltage is equal or smaller than 14 kV. However, when applied voltage is higher than 14 kV, the corona current starts to evolve linearly instead of in a quadratic form with the voltage when the streamer regime appears. This fact makes necessary the use of other equations to approximate better the corona current discharge. Indeed, Meng et al. [27] proposed another empirical formula (2) that introduces an exponent m for point-to-plane configuration. This equation can be expressed as follows:

$$I = K{\cdot}(V - V_0)^m \qquad (2)$$

where K is another dimensional parameter as C and the exponent m falls in the limited scope of 1.5–2.0 for their experiments. Equation (2) interpolates correctly the experimental measures for point-to-plane [27]

---

* Corresponding author.
E-mail addresses: sanchezgma@inta.es, m.sanchez.garcia0206@Gmail.com (M. Sánchez).

https://doi.org/10.1016/j.elstat.2018.09.003
Received 20 July 2018; Received in revised form 31 August 2018; Accepted 11 September 2018

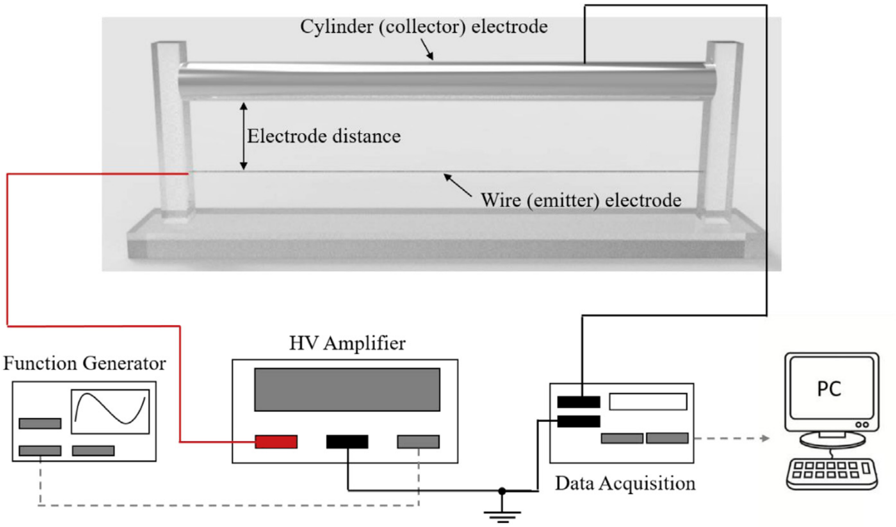

Fig. 1. Sketch of the experimental set-up.

and wire-to-plane [19] geometries but, for our knowledge, it has not been used for wire-to-cylinder arrangement yet.

The difference between equations (1) and (2) is that expression (1) depends on two parameters (*C* and V_0) whereas expression (2) depends on three parameters (*K*, V_0 and *m*). All of them are influenced by both geometrical factors and ambient conditions. As geometrical factor can be highlighted the emitter radius (*r*), the electrode distance (*d*) and the collector radius (R_C), while as ambient conditions the pressure (P), the temperature (T) and the humidity (H). Unless sudden changes in ambient conditions occur, their effect over the geometrical factors can be neglected. Some remarks should be considered: Nouri et al. [25] stated that *K* and V_0 decrease with increasing the relative humidity whereas V_0 is proportional to the increase of pressure. A lower value of V_0 is observed when the temperature increases by Fuliful [28]. Besides, the effect of temperature over *K* was studied by Yamada [29] showing that *K* increases with temperature in point-to-grid geometry.

Wire-to-cylinder configuration has been studied for different researchers due to the strongly inhomogeneous field created when a high voltage is applied, producing an ionic wind that can be used, among others, in electric propulsion systems [30–38]. As ionic wind is directly proportional to the corona discharge current, several studies about the influence of different parameters on the CVCs were carried out since they play a fundamental role: 1) Moreau et al. [30] investigated the influence of the polarity, humidity, electrode distance and grounded electrode on the CVCs for a fixed wire radius of 12.5 μm; 2) Kiousis and Moronis [33] examined the dependence of corona current on the cylinder radius and the electrode distance, keeping the wire radius ($r = 25$ μm) constant; in a later publication [34] they determined the relation between the corona current discharge and the geometrical characteristics of the electrodes ($r = 50$, 100 and 250 μm; $R_C = 5$, 10 and 15 mm); 3) Monrolin [35] investigated the electrode shape varying both the emitter ($12.5 \le r \le 100$ μm) and the collector radius ($1.5 \le R_C \le 5$ mm), the electrode distance and the use of two collecting electrode, however they did not deeply focus on how these parameters affect CVCs; 4) Masuyama and Barret [32] characterized the performance of wire-to-cylinder configuration ($r = 100$ μm; $R_C = 6.35$ mm) varying the electrode distance, and they also investigated the influence on the corona current discharge of adding a collinear intermediate electrode; 5) in a previous work [12] we investigated wire-to-cylinder arrangement ($r = 15.8$ μm and $R_C = 5$ mm) varying the electrode distance and the polarity of the discharge. Also, we showed that the thrust could be calculated with a simple approximation knowing corona current values. According to the literature, reducing the emitter radius and the electrode distance result in an increase of the corona current discharge. However, smaller wire radii and electrode gaps imply an augmentation in the fabrication and robustness difficulties. Finally, the collector radius should be as high as possible to increase the corona current, finding always a compromise solution between both electric and aerodynamic effects (drag) in electric propulsion cases.

In this paper, series of measurements varying the electrode gap ($5 \le d \le 50$ mm) and the emitter radius ($6.25 \le r \le 50$ μm) are carried out for positive wire-to-cylinder corona discharge arrangement. This selection for wire radii is done because they have not previously been studied in detail as reviewed above; while the choice of positive polarity is due to the random nature of the tufts seen in negative polarity which makes the discharge more unstable. Although Townsend's relation has been widely applied, the validity of Meng's equation has still not been proved for wire-to-cylinder configuration, therefore it will be studied in a first section. Then, the dependencies of the equation parameters on the emitter radius and the electrode distance are investigated. By introducing these dependencies in equation (2), the study proposes an empirical formula for determining the CVCs only based on the geometrical factors and the applied voltage. Finally, a method to take into account different collector sizes is presented to extend the range of application of the formula. Predicting the characteristics of corona discharge is of importance when corona devices are designed and optimized for electric propulsion system as well as other applications. Therefore, an empirical equation can considerably reduce the high economic and computational tests needed by the complex physical processes that surround them.

2. Experimental set-up

A sketch of the experimental set-up is shown in Fig. 1. The wire which acts as emitter is connected to a high voltage (HV) system and the cylinder which acts as collector is grounded. The parameters of study are the wire radius and the electrode gap. Five wire radii are used: 6.25, 12.5, 15.8, 31.75 and 50 μm, while the cylinder has a constant radius of 15 mm. The electrode distance can be varied from 5 to 50 mm in steps of 5 mm. The model has a length of 400 mm and at this length it is verified that end effects do not affect current measurements. Both wire and cylinder are polished before the experiments to avoid possible irregularities of the surface and they are placed parallel to each other by two insulating supports. A function generator (Agilent 33500B) is used to select the voltage and then it is amplified (1:2000 ratio) by the HV equipment (ac high voltage Trek model 20/20C amplifier). Between the cylinder and ground is placed a data acquisition system (Keysight 34972A) to measure the current. The data