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Electrohydrodynamic force produced by a corona discharge between a wire active electrode and several cylinder electrodes – Application to electric propulsion

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A B S T R A C T

Low-speed electric propulsion systems for long-duration near-space travels by using solar energy could be based on the electrohydrodynamic force produced inside a corona discharge. This paper is a contribution to a better understanding of these types of thrusters, in order to enhance the produced thrust and their electromechanical effectiveness. Three different simple designs are experimentally studied and compared. The first one is composed of a wire active electrode and a single cylinder grounded one. For the second three-electrode design, the single grounded cylinder is replaced by two cylinders. Finally, the last design is composed of an active wire supplied by a positive voltage, two grounded electrodes and two others cylinders at a negative voltage. On one hand, results show that the use of two grounded electrode instead of a single one results in an increase of the discharge current. Moreover, whatever the electrode gap d, the current-to-thrust conversion is more effective with the three-electrode design. It changes from 31 to 58 N/A (+87%), from 74 to 85 N/A (+15%), and from 104 to 120 N/A (+15%), for electrode gaps d = 10, 20 and 30 mm, respectively. The thruster effectiveness θ is improved by 2 mN/W. On the other hand, the use of two collecting electrodes supplied by a negative high voltage does not result in an effectiveness enhancement because the power consumption is significantly increased.

1. Introduction

When a sufficient potential difference is applied between two electrodes in atmospheric air, the high electric field around the sharpest electrode induces the ionization of the air molecules, resulting in a corona discharge. The sum of Coulomb forces acting on every produced ion results in a volume electrohydrodynamic (EHD) force (in N/m^3). In the drift region, there are many collisions between charged species in motion and neutral air molecules, resulting in a momentum transfer that produces a gas flow from the active high voltage electrode to the grounded collecting one. This flow is usually called electric wind or ionic wind. This electrohydrodynamic phenomenon can be used as an electromechanical actuator without moving part, that directly converts electrical energy into mechanical energy. Electric wind has been theoretically and experimentally studied for its many applications such as electrical blowers without fan [1–10], enhancement of heat transfer [11–13], plasma actuators for flow control [14–19] and propulsion by EHD thrusters [20–28].

In 1961, Robinson investigated the ability of volume corona discharges to perfect blowers in absence of any moving part [1]. For about 10 years, several others groups have been investigating corona discharges, in order to increase the electric wind velocity or to enhance the resulting flow rate and the electromechanical efficiency of such devices [6–10]. For instance, in the case of a needle-to-grid corona discharge occurring inside a hollow tube, Moreau and Touchard [7] measured maximum electric wind velocity and flow rate up to 10 m/s and 1 L per second, respectively. Power consumption was low (<200 mW) and efficiency was in the order of 1%. With a device composed of six stages in series, where each of them consisted in an inner ring electrode with multi-pins and an out ring electrode, Kim et al. [9] reached a flow rate up to 3.3 L per second with a electrical power consumption of 90 W. In Refs. [10], Colas et al. optimized a two-dimension EHD device based on five electrodes. They measured velocity up to 10 m/s and they computed EHD force up to 350 mN/m with a power consumption of 210 W/m.

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In 1967, Christenson and Moller [22] published the first paper on EHD propulsion. They investigated theoretically and experimentally the capabilities of corona discharge to be used as thruster. In 2009, NASA published a report on ionic wind propulsion [25]. They concluded that if values of effectiveness equal to 20 N/kW and thrust per unit surface of 20 N/m^2 could be attained simultaneaously, EHD propulsion might be practically useful for near-space travels (typically 30–50 km in altitude). In practise, low-speed propulsion systems for long-duration near-space platforms would use solar power and photovoltaic energy conversion to produce electricity needed to supply the corona-based thrusters.

The long-term objective of the present work is to optimize future electric thruster designs. In a previous paper [28], the electromechanical behavior of a thruster composed of a thin wire and a single cylinder electrode has been widely investigated, theoretically and experimentaly, and the influence of lots of geometrical parameters has been investigated. The goal of the present paper is to compare the performance of such a device with devices composed of several collecting cylinder electrodes. From discharge current and thrust measurements, different electrical and mechanical characteristics can be plotted and compared to theoretical behavior. A set of three equations can summarize the thruster performances (see Ref. [28] for more details):

$$I = C \times V(V - V_0) \tag{1}$$

$$T = F_{EHD} - F_D = \frac{I \times d}{\mu} - F_D \tag{2}$$

$$\theta \approx \sqrt{C} \times \left(\frac{d}{\mu}\right)^{3/2} \times \frac{1}{\sqrt{F_{EHD}}} \tag{3}$$

With I the discharge current (A/m), V_0 the onset voltage (V), C a constant depending on the electrode geometry and gas properties, T the produced thrust (N/m), F_{EHD} the electrohydrodynamic force, F_D the drag due to the electric wind flowing around the collecting cylinder electrode, d the electrode gap (m), μ the ion mobility and θ the electromechanical effectiveness (N/W). Equation (2) highlights that F_{EHD} increases with the current I and the gap d and that a way to increase the thrust T is to reduce the drag F_D. Unfortunately, Equation (3) shows that the electromechanical effectiveness decreases when F_{EHD} increases. Moreover, since drag $F_D \propto v$ (with v the electric wind velocity) and $v \propto \sqrt{I}$ (see Ref. [28]), Equation (2) can be expressed as follows:

$$T = \left(\frac{d}{\mu} - \alpha\right) \times I \tag{4}$$

where α is a constant. Equation (4) shows that thrust is theoretically proportional to discharge current.

2. Experimental setup

The corona discharge is generated between a high voltage 25-μm diameter wire of tungsten and one or several collecting electrodes (Fig. 1). Because the polarity of the high voltage applied at the active wire electrode has no significant influence on the current-to-thrust conversion and effectiveness [28], the choice was made here to supply the wire electrode with a positive high voltage. The first configuration is based on two electrodes: a thin wire and a single grounded cylinder having a diameter equal to 12 mm (Fig. 1a). The gap d between both electrodes can be adjusted between 5 and 30 mm.

As shown by Equation (2), the thrust T produced by this two-electrode corona discharge is minored by the drag F_D due to the electric wind that flows around the grounded electrode (see Fig. 1a). Therefore a way to reduce drag is to use two grounded electrodes, such as in Fig. 1b, because electric wind flows mainly between both grounded electrodes. Their diameter is still equal to 12 mm and the electrode gap still ranges from 5 mm to 30 mm. The distance s between both grounded electrodes is set to 16 mm.

The last design is composed of five electrodes (Fig. 1c): the thin wire where a positive high voltage is applied, two grounded electrodes and two others electrodes supplied by a negative voltage, such as in Ref. [10]. The objective of both additional negative electrodes is to increase the distance traveled by ions, and then the EHD force. In fact, the role of both grounded electrodes is mainly to increase the electric field at close vicinity of the wire and then to enhance air ionization. Both negative electrodes should play the role of collecting electrodes. The gap between the wire and the grounded electrode is called d_1 when d_2 is defined as the distance between both grounded electrodes and the negative ones. The distance d_2 is fixed at 20 mm and experiments are conducted with d_1 equal to 5, 10, 20 and 30 mm The distance s between two electrodes in regard is equal to 16 mm.

All the electrodes are parallel. Then one expects a two-dimensional electromechanical behavior despite some 3D effects can occur at the electrode edges. The wire span wise length is equal to 150 mm. Therefore the discharge occurs on a length equal to 150 mm. As illustrated by Fig. 2, all the electrodes are held by two horizontal pieces in Teflon (numbered as (1) in Fig. 2). These pieces are screwed to two vertical supports in PVC (2). The gap d can be

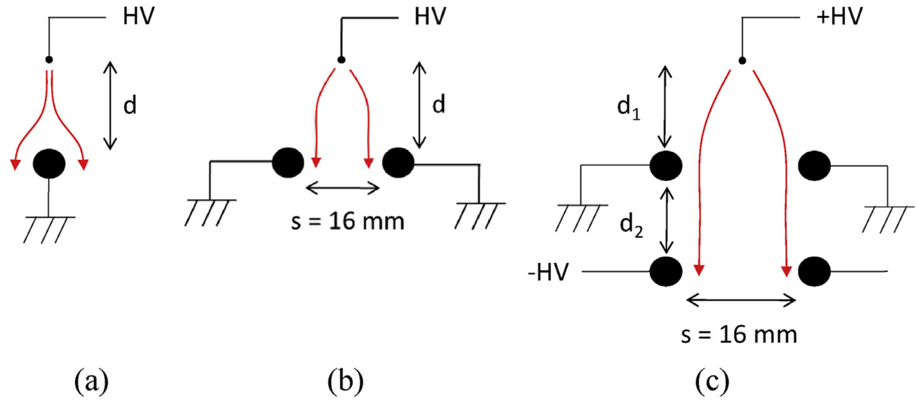

Fig. 1. Schematic cross-view of the three thrusters: two-electrode design (a), three-electrode design (b) and five-electrode design (c).