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Influence of the air-exposed active electrode shape on the electrical, optical and mechanical characteristics of a surface dielectric barrier discharge plasma actuator

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ABSTRACT

The influence of the air-exposed active electrode shape on the electrical, optical and mechanical behaviors of a surface DBD plasma actuator is investigated. For high voltage up to 24 kV, a first set of experiments highlights that the discharge current, the plasma morphology and the produced ionic wind are fully different, according to the active electrode shape. With a wire active electrode, the discharge is streamer-free, the ionic wind velocity is improved and more homogeneous along the active electrode compared to the typical baseline plate-to-plate surface DBD. On the contrary, with a sawtooth active electrode, the streamers are more intense and the velocity is higher in front of the tips and smaller between two successive tips, following the shape of the electrode edge. Finally, by increasing the high voltage up to 30 kV, maximum ionic velocities of 7.1 m/s and 8.65 m/s are reported, with a plate active electrode and a sawtooth one, respectively. To our knowledge, these are the highest ionic wind velocities that have never been measured with a single surface DBD based on two electrodes.

1. Introduction

Surface dielectric barrier discharges (DBD) based on two electrodes mounted on both sides of a dielectric have been widely studied for 15 years for their application in aerodynamic flow control by plasma actuators [1–3]. When the surface DBD is supplied by an ac high voltage, an electrohydrodynamic (EHD) force is produced, resulting in an ionic wind based-wall jet. Typically, single DBD based on two plate electrodes can produce mean EHD force between 0.1 and 0.5 mN per consumed electrical watt, corresponding to ionic wind velocity up to about 5 m/s. By optimization of the electrical and geometrical parameters such as the high voltage magnitude or the dielectric thickness, the actuator effectiveness and the ionic wind velocity can reach 1 mN/W and 6 m/s, respectively [4–14]. With multi-DBD designs, velocity up to 11 m/s has been measured and force up to 350 mN/m [4,5]. If the high voltage has a nanosecond repetitively pulsed waveform, there is no significant EHD force production, but the sudden gas heating at the dielectric wall results in a pressure wave with pressure gradient up to 10 kPa [15–21].

When the plasma actuator is mounted at the wall of an aerodynamic profile, these both mechanical and thermal phenomena can interact with the near-wall flow inside the boundary layer or modify its dynamic characteristics, resulting in the control of the whole flow around and downstream of the profile body. Indeed, many studies have shown the ability of plasma actuators to control airflow around different kinds of bodies such as flat plates, cylinders or airfoils [1,2].

In the present paper, we focus on the ionic wind produced by surface DBDs in quiescent air, the goal being to study the effect of the air-exposed active electrode shape on the discharge behavior and the actuator performances. Indeed, several studies have shown that the use of a wire active electrode instead of a plate one resulted in a streamer-free discharge and in a better actuator effectiveness in terms of force production [4,22,23]. Others investigations highlighted that the ionic wind topology could be strongly modified by using an active electrode whose the edge was not straight [24,25]. Hence, in the present paper, the electrical, optical and mechanical characteristics of three actuators using different active electrode shapes are compared. First, a typical DBD based on a planar active electrode is studied by discharge current and electrical power measurements, iCCD visualisations and ionic wind velocity characterisation. Then, the same measurements are performed with two others actuators, one using a 25-μm diameter wire active electrode, and a second based on a sawtooth active electrode. In the last part, these three actuators are compared and an optimized actuator is proposed and presented.

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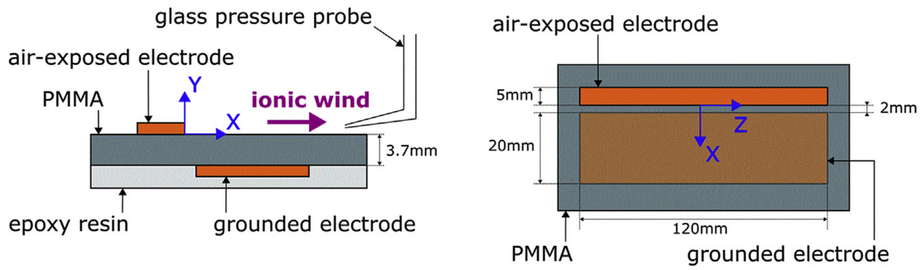

Fig. 1. Cross-view and top view of the baseline actuator, with a plate active electrode.

2. Experimental setup

The DBD plasma actuator is composed of an air-exposed active electrode and a 20 mm-wide grounded encapsulated electrode placed below the dielectric plate made of PMMA. The electrode gap and the dielectric thickness are equal to 2 mm and 3.7 mm, respectively. The electrode length in spanwise is equal to 12 cm. In this study, three different air-exposed active electrodes are used. The first one is an 80-μm thick plane electrode flush mounted on the dielectric surface, as illustrated in Fig. 1. This plane electrode is a 5-mm wide commercial aluminium scotch that presents a straight edge. It is the typical baseline plate-to-plate actuator. The second electrode is a tungsten wire (usually used for hot wire measurements) with a diameter of 25 μm, resulting in a wire-to-plate actuator. The third one is still a plane aluminium electrode, but with a sawtooth edge in order to concentrate the surface discharge in front of the tips (Fig. 2). For this last electrode, the distance between two successive tips is equal to 10 mm.

A high voltage is applied to the active electrode with voltage amplitude V_{AC} up to 30 kV and frequency f_{AC} ranging from 50 Hz to 2 kHz, with the help of a Trek amplifier (30 kV, 40 mA). The discharge current is measured with a shunt non-inductive resistor (100 Ω) placed between the ground electrode and earth. To compute the electrical power, the resistor is replaced by a 47 nF capacitor in order to plot the charge-voltage curve that is integrated to determine the discharge energy per high voltage period [26].

The optical characteristics of the surface DBD are studied by fast-imaging of the ionization process. Images of the surface discharge are collected by a fast gateable iCCD camera (Princeton, Pi-max2 Gen2) with a 1024 × 1024 pixel^2 matrix and a spatial resolution of about 20 μm/pixel. The exposure time is equal to 400 μs.

The mechanical effects of the plasma actuators are characterized by measuring the induced ionic wind with a home-made glass pressure tube connected to a Furness manometer (0–12 m/s, precision lower than 0.01%, bandwidth 50 Hz). With such a condition, only the horizontal component of the velocity is measured. The location of measurement can be displaced along the three (x, y, z) axis with a 3D motorized displacement system (Fig. 1), allowing us to measure velocity profiles along the three axis. The internal diameter of the glass tube is equal to 0.7 mm. In this work, a particular effort has been made to conduct very accurate velocity measurements. First, the home-made glass tube has been calibrated and compared with a Furness Pitot tube; that highlighted that there is no difference between a high quality Pitot tube and our home-made tube. Secondly, an experimental protocol has been defined for the velocity measurements. Each velocity is a time-averaged value of 5000 measurements (5 s at 1 kHz), assuring the convergence of the velocity. In such conditions, the rms values of the velocity are usually smaller than 1% of the time-averaged ones.

3. Baseline case: plane active electrode

Fig. 3 shows an example of voltage and discharge current versus time. The high voltage has a sine waveform with a magnitude V_{AC} equal to 24 kV. In such a condition, there are two different discharges. During the positive-going cycle, the high current peaks (up to 70 mA) show that a positive streamer discharge occurs, as already reported in several papers [4,10,13]. The presence of streamers is confirmed by iCCD visualizations that presents top views of the discharge during the positive and the negative-going cycles. During the positive-going cycle, streamers propagate from the active electrode edge on the dielectric surface, with an extension of about 10 mm in this case. However, the streamer propagation length increases with V_{AC} and f_{AC}. During the negative-going cycle, a glow discharge characterized by small current peaks occurs.

Fig. 4a presents the discharge electrical power consumption versus high voltage; it highlights that the curves can be well-fitted by the theoretical Townsend expression such as in Refs. [3,26]:

$$P_{elec} = K\ (V_{AC} - V_0)^2 \tag{1}$$

with K a constant varying here from 2 to 36 × 10^{-3} W/V^2, V_{AC} the applied high voltage magnitude and V_0 the voltage for which the discharge ignites (≈6.5 kV). However, some authors preferred to use the following expression [9–11]:

$$P_{elec} = K\ V_{AC}^n \tag{2}$$

where n varies typically between 2 and 3.5. On one hand, this expression cannot correctly interpolate our electrical power curves because the present plate-to-plate DBD is based on a 3.7-mm thick dielectric when this last expression is satisfying when the DBD actuator uses a thin dielectric (< 300 μm). On the other hand, we will see later in the paper that expression (2) can be relevant when the active electrode shape is modified. Fig. 4b presents the electrical power consumption versus high voltage frequency. It shows that it increases in a

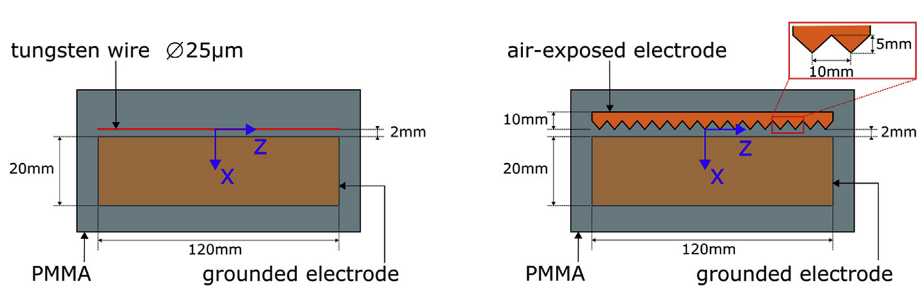

Fig. 2. Top views of the wire and sawtooth actuators.