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Elongating the area of plasma/fluid interaction of surface nanosecond pulsed discharges

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Plasma-assisted flow control is of high industrial interest, but practical applications at full scale require a large surface of interaction. Nanosecond pulsed Dielectric Barrier Discharge (DBD) have demonstrated promising results of flow control, but their interacting region is limited to only a few cm^2. In this paper, the conditions to extend a surface nanosecond DBD are documented. It is shown that a sliding discharge regime can fully fill an inter-electrode distance of 40 mm. This discharge regime promotes the formation of two hemispheric pressure waves originating from both air-exposed electrodes while an horizontal region of pressure gradient is also observed.

Introduction

A part of the gas in contact with aerodynamic objects can be easily ionized by exciting the air molecules using an electric field exceeding the breakdown voltage of the air at atmospheric conditions. This localized ionization finds several applications in aerodynamic. Among the numerous investigations related to the flow manipulation by surface electrical discharge, the reduction of flow separation over curved or inclined surfaces, the drag reduction in view of fuel consumption improvement or the manipulation of laminar-to-turbulent transition are some of the practical applications where non-thermal plasma discharges demonstrated a good effectiveness at least for in-lab conditions. At the beginning, surface corona discharges were investigated to modify a laminar boundary layer [1] or to mitigate flow separation [2]. In parallel, surface Dielectric Barrier Discharges (DBD) were also developed as flow control actuators [3–7]. These two types of non-thermal plasma discharges take advantages of the momentum transfer induced by the collision of charged and neutral particles in order to dynamically affect the flow conditions at the surface of an aerodynamic object. More recently, it has been demonstrated that repetitive nanosecond pulses can replace the usual ac waveform high-voltage (HV) usually applied for gas ionization. The use of fast-rising HV pulse is clearly effective for flow separation control over a wide range of Reynolds number as it is shown in Refs. [8–11] but the flow control mechanism is no more based on the momentum addition as for ac DBD. For such discharge the flow control mechanism has still to be fully elucidated but some scenarios have emerged, all of them being related to the fast and localized deposition of heat at the dielectric surface, this heat release resulting in a pressure gradient (pressure wave) propagating above the dielectric wall [12,13]. Good effectiveness has been demonstrated more specifically when the outer flow velocity is high [8,14]. As for DBD supplied by ac voltage, optimization of the electrode geometry or of the applied signal is expected to be a way to improve the performance of the nanosecond pulsed discharge [15,16]. Among these optimizations, the need for a large surface of plasma/fluid interaction is even more essential for plasma-assisted flow control implemented on aerodynamic model having realistic scale factor.

The present experimental investigation aims at demonstrating that the surface discharge produced at the edge of the high-voltage electrode supplied by nanosecond pulses can be extended over a longer distance using a third counter-electrode. This configuration is similar to the three-electrode configuration known as *sliding discharge* for ac voltage source where a third electrode with a negative DC component can force the drift of ionized species in the inter-electrode region leading to the formation of a large scale plasma layer [17–19]. Similar configuration is used in Ref. [20], but using microsecond pulses as voltage source in place of an ac one. Again, the longer plasma extension caused by the sliding effect is

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observed. In 2012, Song et al. [21] changed the microsecond pulses source for series of nanosecond pulses as it is conducted in the present investigation. They confirm the capability of three-electrode configuration for promoting longer plasma extension but several essential information, such as the inter-electrode distance, the deposited energy or conditions to ignite a sliding regime, are not documented in Ref. [21].

Here, the primary objective is the definition of the electrical conditions necessary for extending the propagation path of a nanosecond pulsed discharge. Measurements of the electrical consumption of the actuator are also introduced because this consumption is partially related to the energy deposited on the dielectric surface and surrounding gas. It was already demonstrated that the local heat release is fully corroborated with the electrical deposited energy, a heat production mainly caused by the vibrational excitation [22]. This heat release is responsible for a sudden pressure gradient that causes a pressure wave propagating normally to the dielectric wall surface, the strength of this pressure wave linearly increasing with the consumed energy as it was numerically and experimentally shown in Refs. [12,13,22,23]. In a second part of the paper, qualitative optical visualizations of the induced pressure wave and heat release signature are proposed by using a Schlieren test bench. These experiments are designed to reveal the modifications on the induced pressure wave when a sliding discharge forms.

Experimental setup

In all tested configurations, the dielectric is made of a 2-mm thick flat plate (Polymethyl methacrylate, $\varepsilon_r = 3.3$). The electrodes are made of aluminum foil with thickness of 75 µm. The reference single DBD (S-DBD) consists of two electrodes placed in regard and separated by the dielectric barrier. In this case, as in all following designs, the active electrode (electrode 1 in Fig. 1) has a width of 10 mm. The grounded electrode (electrode 2 in Fig. 1a) is 40 mm wide as in Ref. [18]. The third electrode (electrode 3 in Fig. 1b) can be connected to the ground (configuration called G-DBD later in the paper), let floating (F-DBD) or can be supplied by a negative DC component to establish a so-called sliding discharge as it will be shown later in this letter (SL-DBD). For all the actuators, the spanwise length is maintained at 120 mm (i.e., maximal plasma covered surface of 4800 mm^2).

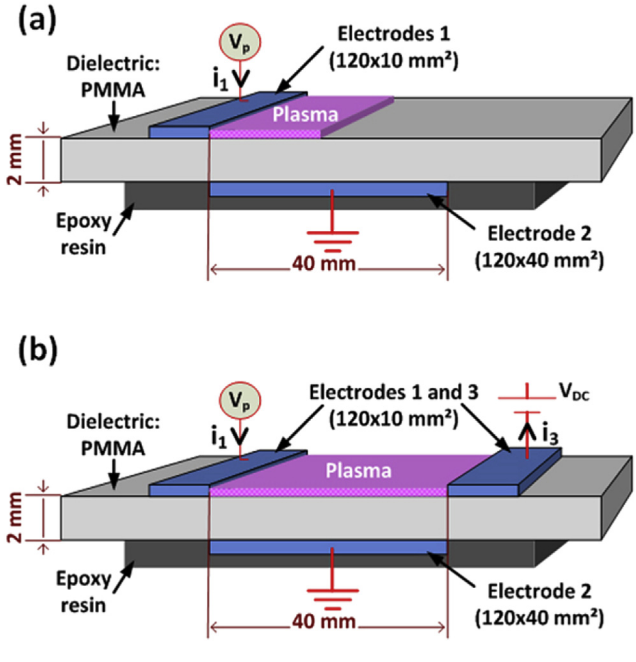

Fig. 1. Sketches of the electrode arrangement for the reference S-DBD (a) and the configuration used for a floating, grounded or negatively biased third electrode (b).

The voltage on the electrode (3) is provided by a negative dc power supply (SPELLMAN, −40 kVmax, 150 W). The choice of a negatively biased voltage on electrode (3) refers to the literature data where sliding regime can be produced only for negative dc component on electrode (3) [18]. In all the tests, the electrode (1) is connected to a fast-rising pulse generator (FID FPG 40-30NK, 30 kVmax, 35 mJ), producing HV pulses at a repetition rate of 1 kHz. The total currents flowing through electrodes (1) and (3) are measured using current transformers (Bergoz CT-D5.0 and CT-D1.0) connected to a WaveRuner oscilloscope (Lecroy, 204 mxi, 2 GHz bandwidth), these two currents being considered in the computation of the electrical energy consumption.

In complement to the electrical measurements, an optical characterization of the discharge is performed by using an intensified CCD camera (Princeton, PI-MAX4 1024 EM) coupled with an UV lens (100F/2.8). The camera opening gate width is synchronized with the electrical system. The iCCD camera is placed above the plasma sheet and directed toward the dielectric (top-view with field of view of 36 × 40 mm^2). The exposure time is fixed at 60 ns in order to observe the full extension of the plasma layer over the dielectric surface. In a final experiment, the pressure wave caused by the surface heat deposition is characterized by using a Schlieren optical bench. The light source (nanolite twin flash) is focused on a 1 mm pinhole by a condenser lens (see Fig. 2). The pinhole is positioned at the focal distance of the concave mirror 1 (a cylindrical flat mirror is used to compact the optical bench). Parallel light beams are produced between mirrors 1 and 2 while the actuator is located at the center of these two concave mirrors. The light from the source point is then focused on an horizontal knife edge in order to visualize vertical pressure gradients. The images are collected by an ICCD camera (PIMAX4) equipped with a 180 mm objective (Nikkor), this equipment leading to a spatial resolution of 5.4 pixels per mm. A delay generator (SRS DG 645) is used to trigger the light source, the applied voltage and the ICCD camera. The light source produces a 25 ns flash at a repetition rate of 5 Hz. The pulse voltage is repeated at 1000 Hz and the conducted measurements concern the 100th HV pulse. Images are recorded 60 µs after the voltage pulse applied to electrode (1). Only side views have been

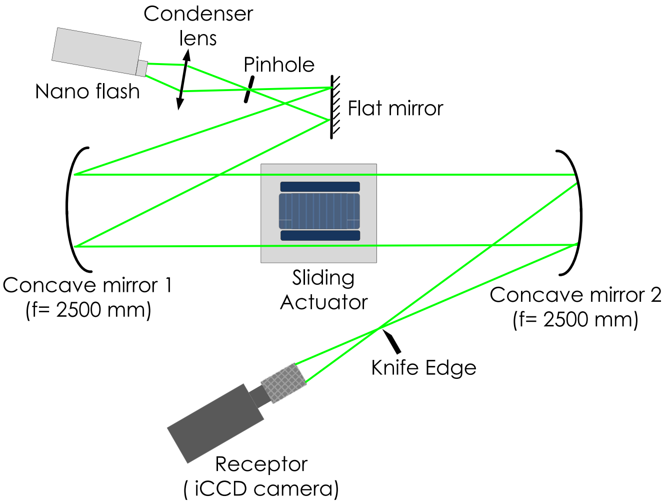

Fig. 2. Sketch of the Schlieren setup for the produced pressure wave characterization.