FLOW CONTROL BY PLASMA ACTUATORS

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INTRODUCTION

Surface dielectric barrier discharges (DBD) based on at least two electrodes mounted on both sides of a dielectric have been widely studied for ten years for their application in aerodynamic flow control [1-4]. On one hand, surface DBD based on two linear electrodes supplied by an ac sine high voltage (AC-DBD) produces an electrohydrodynamic force that results in an electric wind based-wall jet. Typically, single DBD can produce mean force and electric wind velocity up to 1 mN/W and 7 m/s, respectively. With multi-DBD designs, velocity up to 11 m/s has been measured and force up to 350 mN/m. Moreover, with specific designs, the produced flow can be strongly 3D, in order to induce vorticity for instance [5]. On the other hand, if the high voltage has a nanosecond repetitively pulsed waveform (NRP-DBD), the sudden gas heating at the dielectric wall results in a pressure wave with pressure gradient up to 1 kPa [6]. When the plasma actuator is mounted at the wall of an aerodynamic profile, these two mechanical phenomena (EHD force and pressure wave) can interact with the boundary layer and modify the near-wall flow, resulting in the control of the whole convective flow. In the present paper, recent advances on plasma actuator performance will be first presented. Secondly, examples of airflow control by these different actuators will be discussed.

PLASMA ACTUATORS

The most-used plasma actuator is the single DBD one based on two electrodes mounted on both sides of a dielectric. The air-exposed active electrode is connected to an ac high voltage power supply and the other one is grounded and encapsulated. Typically, geometrical parameters are as follows: electrode width of a few mm, electrode gap equal to zero or a few mm and a dielectric thickness from 50 µm to a few mm. The applied voltage ranges from a few kV up to 30 kV at a frequency equal to a few kHz (power consumption smaller than 1 watt per cm in span wise). In such conditions, a 2D linear wall jet is induced by the discharge, as illustrated by figure 1 that shows the time-averaged velocity field measured by PIV. However, the produced electric wind is strongly unsteady and periodic. For instance, figure 2 shows the velocity (in red) versus time when a sine high voltage at 1 kHz (f_{AC}) is alternatively switched on and switched off at a burst frequency f_{BM} = 20 Hz with a duty cycle of 30 %. It highlights that two time scales coexist in the produced electric wind: the electric wind oscillations at f_{AC} and larger amplitudes velocity fluctuations at f_{BM}. We will see that this characteristics is very useful for flow control. From this typical actuator design, lots of others actuator configurations have been developed such as multi-DBD actuators [4], DBD vortex generators [5] or sliding discharges [4]. In the case of DBD vortex generators for instance, the body force is perpendicular to the incoming flow in order to produce a longitudinal vortex, as depicted in figure 3.

Finally, a new type of actuator supplied by a nanosecond pulsed high voltage has been widely investigated in the last years. In this case, the electrohydrodynamic force is negligible and the major mechanical effect is the gas heating at the wall surface and the resulting pressure wave [6].

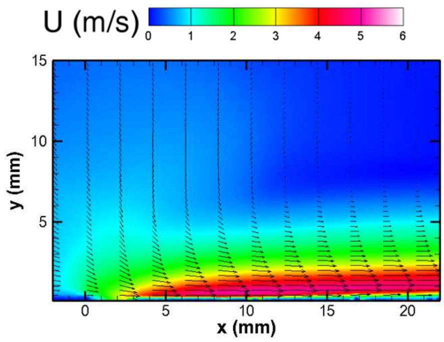

Figure 1: Velocity field produced by a single DBD.

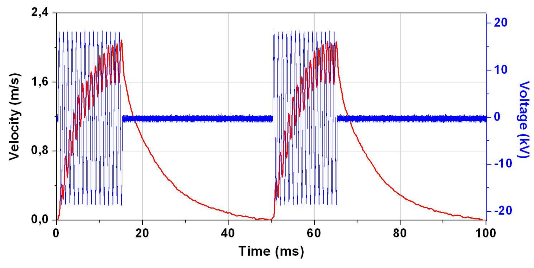

Figure 2: Local velocity versus time.

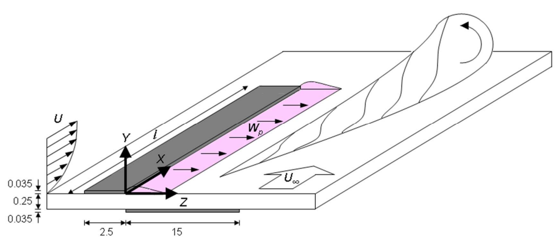

Figure 3: Schematic of a DBD vortex generators (from [5]).

FLOW CONTROL

For now a little bit more than 15 years, the ability of plasma actuators to manipulate airflow has been widely studied all over the world. Although it is not possible to summarize all these studies, major results will be discussed during the oral presentation. In the present abstract, we focus on turbulent separation control along an airfoil and manipulation of a shear layer developing downstream of a backward-facing step. In both cases, we will highlight the key role of the frequency actuation and the actuation location on the control effectiveness.

Figure 4 presents the velocity field along an airfoil (NACA 0015) at $U_0 = 40$ m/s ($Re = 1.33 \times 10^6$). The boundary layer is turbulent (tripper at the leading edge) and the angle of attack is equal to 11.5°. In such conditions, the flow naturally separates at 50 % of the chord length. With a single DBD actuator located at 18 % of chord, the separation has been delayed up to 64 %. With a multi-DBD device located between 18 and 36 % of chord, the separation has been delayed to about 70 % when the actuator acted in a steady mode (figure 4). Finally, using an unsteady actuation at $f_{BM} = 50$ Hz (f+ = 3) allowed us to reattach the flow up to 80 % of chord since the actuation had no effect when operating at f+ = 1.

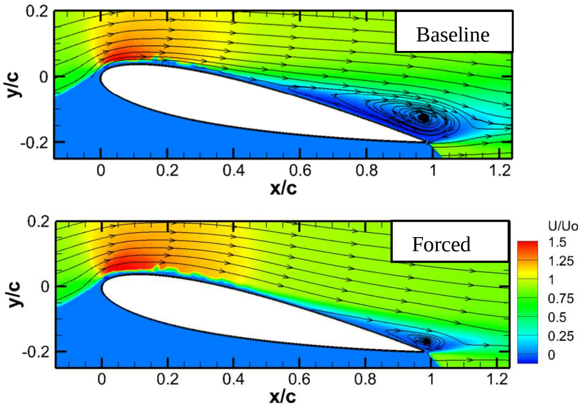

Figure 4: Flow control by DBD ($Re = 1.33 \times 10^6$).

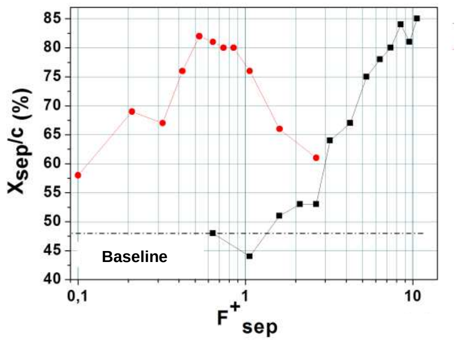

Figure 5: Separation location versus frequency actuation in steady mode (■) and burst mode (●).

In the same aerodynamic configurations, the ability of a single nanosecond pulsed DBD actuator to manipulate the flow has been investigated. This study shown that the discharge had no effect when the boundary layer was tripped. Then, the tripper has been removed and the actuator has been located at the leading edge (1 % of chord). In such conditions, the natural laminar flow was very sensitive to the actuation perturbations, as illustrated by figure 5. On one hand, when operating in steady mode (■), one can see that the separation point is displaced gradually to the trailing edge when the discharge frequency increases, up to about 85 %, certainly because the energy deposited by the DBD at the dielectric wall is proportional to frequency. On the other hand, figure 5 highlights the strong dependency of the flow to the actuation frequency when this one is modulated (●).

The objective of the second study presented in this abstract was to find the optimal actuation produced by a DBD plasma actuator for controlling the flow downstream of a 30-mm-height backward-facing step. The flow velocity was fixed at 15 m/s ($Re = 3 \times 10^4$, $Re_\theta = 1650$). The boundary layer was fully turbulent. This experimental investigation highlighted that when the actuator is placed upstream the step corner, the DBD is able to manipulate the first stages of the free shear layer formation and consequently the actuator can modify strongly the flow dynamics. To illustrate the control effectiveness, figure 6 presents the streamlines of the time-averaged free flow and when it is forced by a DBD at $f_{BM} = 125$ Hz, corresponding to St = 0.25 (Strouhal of the shear layer in the growing period at $x/h \approx 2$). One can see that the reattachment length has been reduced from 5.85h down to 4.68h.

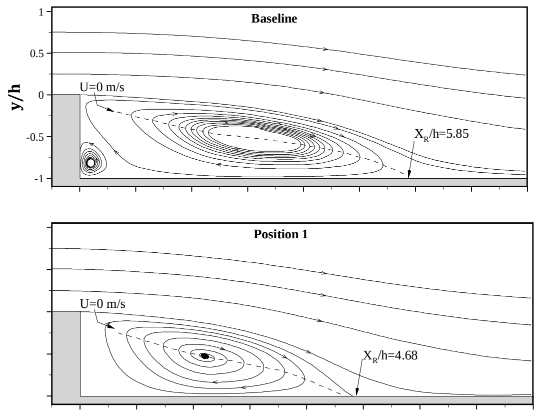

Figure 6: Streamlines of the flow downstream a backward-facing step with and without actuation.

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