Positive and negative sawtooth signals applied to a DBD plasma actuator – influence on the electric wind

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Abstract

The influence of the electric signal shape applied to a surface dielectric barrier discharge (DBD) actuator is investigated in order to optimise the produced electric wind. This report also gives insights on the mechanisms involved in the electro-fluido-dynamic (EFD) operated by actuators based on atmospheric non-thermal discharges in air. The parameters of the electric signal that maximises the produced electric wind in quiescent air are investigated with a positive and negative sawtooth waveforms. The induced airflow properties are observed with a particle image velocimetry (PIV) set-up. The positive sawtooth waveform results in a more filamentary discharge and generates an electric wind with maximum velocities close to the active air exposed electrode. This contrasts with the negative sawtooth waveform that does not create as many filaments and induces electric wind velocities more homogeneously distributed along the dielectric surface. Even though the velocities values are of the same order, the shape of the vortex generated above the air exposed electrode is very dependant on the waveform.

1. Introduction

In the past few years, plasma actuators have demonstrated their ability to manipulate airflows for the aeronautic industry. Numerous scientific investigations are currently in progress to evaluate the potential applications of electrical discharges for airflow control [1,2]. This type of actuator presents many advantages over micro-jets or micro-electro-mechanical devices. They have a very short response time, they do not bring any additional mass to the airflow and they consume few electric power. In addition they can operate in a wide range of relative humidity and pressure [3] that planes encounter during commercial flights. Plasma actuators are suitable for many geometries, in particular they can affect the properties of a boundary layer existing around various aerodynamic shapes such as airfoils [4,5] and cylinders [6]. They are also efficient in enhancing the mixing at the exit of a jet nozzle [7,8]. Most of these plasma actuators are used in subsonic regimes and are based on atmospheric pressure surface dielectric barrier discharges (DBD). These electrical discharges are strongly affected by the waveform of the signal used to power them. It is thus necessary to investigate how these parameters may affect the discharge and thereby the induced electric wind. In the present study the influence of the high voltage excitation is studied in the case of a discharge occurring in air. In this report, the effects of the sign of a sawtooth signal are investigated using a particle image velocimetry (PIV) apparatus. Unlike Pitot tube measurements that provide local information on the horizontal component of the velocity, we have focused on the general topology of the induced airflow by using a PIV system. Even though the PIV spatial resolution is lower than the accuracy achievable by Pitot tube, it gives access to the global properties of the electric wind.

Two test signals were used, one composed of increasing ramps and the second one of decreasing ramps. This results in the emphasis of the asymmetric behaviour of the discharge (whether the air exposed electrode is the instantaneous anode which attracts electrons or instantaneous cathode which repels electrons). Only a few experimental investigations dedicated on this asymmetric behaviour have been conducted. They concern force measurements [9,10] made with balances which is a global value that does not allow the airflow description. Local time resolved measurements have also been performed by laser Doppler velocimetry [11–13] on sinusoidal waveforms. They show that in air the falling part of a sinusoid results in stronger electric wind than the rising part in the vicinity of the active electrode. Yet they do not afford for the global behaviour of the electric wind and they are not describing the airflow when positive and negative sawtooth signal are used.

More recently numerical fluid models [14–17] but also particle in cells (PIC) models [18] have been developed in order to increase
our comprehension of the electro-mechanical conversion operated by the electrical discharge. These models show that the momentum transfer is due to collisions between charged particles accelerated by the local electric field and neutral species of the surrounding gas. However, simulations give numerical results concerning the local force induced by the discharge and do not give information concerning the gas velocity unless they are coupled to a fluid mechanics model. Hence the proposed PIV analysis is complementary to the force measurement, the LDV and the numerical results. In this study the voltage and the current curves as well as the electric wind velocities are measured. We also discuss on the electro-mechanical processes involved for each tested waveform.

1.1. Experimental set-up

In order to investigate separately the effects of a positive sawtooth signal and a negative sawtooth signal, a simple surface DBD is created. The experimental set-up is presented in Fig. 1. It consists of a classical DBD configuration with electrodes flush mounted across a 4 mm-thick Plexiglas (polymethyl methacrylate, PMMA) dielectric layer. The electrodes are made of aluminium and are 80 micron-thick. They are both 10 cm span wise. The bottom electrode is completely encapsulated in epoxy resin to avoid any ionisation of the gas below the dielectric. Indeed, if a plasma would be created under the dielectric, the current curve would account for both the top and the bottom discharge while we aim to investigate the “positive” discharge and the “negative” discharge separately. The top electrode is referred to as the “active” electrode. The left edge of the active electrode which is not over the grounded electrode is encapsulated to prevent undesired electric wind in the wrong direction.

The applied high voltage is generated by a TREK power supply (30 kV/40 mA) amplifying the sawtooth output signal of a TTI function generator (TG1010A). The excitation frequency is set to 1 kHz and signal amplitudes ranging from 10 kV to 20 kV are tested. Because of the presence of the dielectric layer only AC signals can be applied to the DBD. Two signal waveforms are tested. The first signal is composed of rising periods of 1 ms and a rapidly decreasing voltage drop. This voltage drop slew rate is limited by the TREK amplifier characteristics (500 V/µs). This waveform will be referred to as the “positive sawtooth” signal. The second tested waveform is the complementary signal symmetrical to the first one relative to the 0 V reference; it will be referred to as the “negative sawtooth” signal. To measure the discharge current a 100 Ω resistor is inserted in series with the grounded electrode. A voltage probe plugged in a 100 MHz Lecroy digital oscilloscope converts the analogical signal at a sampling rate of 2 GigaSamples/s.

As sketched on Fig. 2 the DBD actuator set-up is enclosed in a glass box (30 cm × 40 cm × 80 cm) in which the air is quiescent. The airflow induced by the discharged is observed by means of a PIV apparatus composed of a double cavity Nd:Yag Laser and a CCD camera. The Laser is equipped with a cylindrical lens creates a 1 mm-thick green light sheet (wavelength of 532 nm) perpendicular to the flat. It delivers a power of 27 mJ per pulse at the repetition frequency of 0.4 Hz. The glass box is seeded with incense smoke (particle average diameter of 0.3 µm) reflecting the Laser coherent light to the camera objective lens. The agreement between Pitot tube and PIV measurements has been preliminary tested to ensure the consistency of the two methods.

The Lavision CCD camera captures the 60 mm × 20 mm zone situated over the DBD actuator with a spatial resolution of 0.06 × 0.06 mm² which is sufficient to describe the boundary layer region (a similar configuration was investigated by means of Pitot tube [19]). The aperture of the CCD camera is operated in the dual frame mode with the opening triggered at the end of the ramp (rising ramp in the case of the positive sawtooth, falling ramp in the case of the negative sawtooth). The length of the opening window is adjusted for each velocity to obtain a displacement of 4 pixels for all the measured velocities which enhances the detection of correlation peaks. The CCD opening window of the PIV system is phased locked at the centre of the rising ramp in case of the positive sawtooth and at the centre of the falling ramp in case of the negative sawtooth. The gate opening width is set to 500 µs. Given the 0.06 × 0.06 mm² spatial resolution this gate width leads to an error on the velocity of 0.12 m s⁻¹. The recording frequency is set to 0.4 Hz and 200 pictures are taken for each phased acquisition. A statistical analysis demonstrates that 150 snapshots are sufficient to reach convergence for first and second order quantities. A cross-correlation algorithm with adaptative multipass, interrogation
windows of 128 × 128 to 32 × 32 pixels and a final overlap set to 50% is applied to the digital couples of images to compute the instantaneous vector fields.

2. Results

2.1. Electrical behaviour

The electrical behaviour of the discharge differs tremendously according to the sign of the applied sawtooth signal. As illustrated on Fig. 3 for 20 kV amplitudes the rising part of the positive sawtooth results in a current curve composed of numerous high current peaks. Many of these peaks reach values between 100 mA and 150 mA. They are due to the gas breakdown occurring after a phase of low current Townsend discharge. This breakdown is possible when the active electrode is the anode (the grounded electrode is the instantaneous cathode). The electrons move quickly to the anode (where they are collected) whereas the positive ions are drifting slowly towards the grounded electrode and release secondary electrons when they hit the dielectric surface. Eventually the positive space charge becomes sufficient to alter the geometry of the electric field and a plasma is formed above the anode. This plasma spreads over the dielectric surface and positive ions are deposited. This corresponds to the rising part of the current peaks detected during the positive ramp. A multitude of filaments about 5 mm in length are visible. When the plasma filaments reach a certain length their conductivity is reduced. At head of the discharge the potential is not sufficient to sustain the plasma and
Fig. 5. PIV vector fields for 20 kV signals.

Fig. 6. Velocity profiles for U extracted from PIV vector fields for 16 kV sawtooth signals.
the current drops. Let us note that after the rising part of the positive sawtooth, the voltage drops drastically with a slew rate limitation due to the amplifier. This of course generates an undesired but short life-time electrical discharge (approximately 80 μs for a 40 kV voltage drop). The CCD opening window of the PIV system is phased locked in the middle of the rising ramp to minimise the effects of this reversed discharge on our measurements.

In the case of the negative sawtooth, the active electrode is the instantaneous cathode during the falling ramp. Unlike the previous case, only low amplitude (<50 mA) current peaks are detected. In the present situation, the electrons are charging the dielectric surface quickly which prevents the electric field from reaching to high values. Hence the breakdown of the discharge is much weaker than in the positive sawtooth case. Here the ionic sheath is located directly at the edge of the electrode and secondary electrons are emitted from the cathode. Small luminous points are visible only at the cathode edge. As the discharge is occurring in the ambient air, negative ions also exist and they drift in the same direction than electrons and play a role in the induced electric wind.

2.2. Induced electric wind

The electric wind measured by means of PIV in the case of positive and negative sawtooth signals are presented on Fig. 4 (for 16 kV amplitudes) and Fig. 5 (for 20 kV amplitudes). The vector field represents the norm of the electric wind velocity.

The system of coordinates is represented on Fig. 1. The edge of active electrode sets the origin. The grounded electrode is located at \( y = -4 \) mm and extends from \( x = -20 \) mm to \( x = 80 \) mm. In the case of a 16 kV amplitude, small differences are noticeable between each vector field. The negative sawtooth leads to lightly faster electric winds (maximum of 3.2 m/s) than the positive sawtooth (2.4 m/s). The high velocity positions also extend further downstream in the negative sawtooth case. Moreover, it is noticeable that the profile obtained in the positive sawtooth case is thinner downstream with high velocities concentrated near the surface. Finally, the shape and position of the vortex created at the edge of the active electrode are strongly affected by the sawtooth sign. Due to the induced velocity near the wall, a zone of lower pressure is generated above the discharge region which generates a fluid motion downwards. This suction is mostly vertical in the positive sawtooth case. In the negative sawtooth case the recirculation is more pronounced with the centre of the vortex visible at \( x = 16 \) mm, \( y = 7 \) mm. This is also confirmed by the greater value of the V component which is much greater over the active electrode in the negative sawtooth case (1 m/s downwards versus 0.2 m/s in the positive sawtooth case).

For all the tested amplitudes (10 kV, 13 kV, 16 kV, 18 kV and 20 kV) the previous remarks are valid and the differences gets more obvious as the voltage is increased. For the sake of readability we only present here the results obtained with 16 kV and 20 kV. For 20 kV (Fig. 5) the intense breakdowns occurring during the positive sawtooth result in maximum velocities (up to 3 m/s) located close to the wall at approximately \( x = 18 \) mm, \( y = 2 \) mm with a profile getting thinner further downstream (in the case of the positive sawtooth, the filaments are longer than in the negative sawtooth case and they can spread far from the edge of the active electrode, hence the dissipative effects occur further downstream where the electric field becomes weaker). The flow resulting from the suction comes from the left above the active electrode. This contrasts with
the PIV field obtained with the negative sawtooth. The velocity distribution is much more homogeneous over the surface when electrons charge the dielectric because the discharge is free of strong filaments (as seen in the current curves in Fig. 3). The negative ions also drift in the electric field and participate to the induced airflow. In the case of a negative sawtooth the electric field is more constant in space than in the positive sawtooth case because the region of high space charge is localised on a much smaller region directly over the edge of the active electrode [15]. These negative ions drifting slowly possibly participate to the airflow homogeneity. The induced airflow velocities are greater (up to 4 m/s), and the region of strong velocity spreads over a much larger area downstream and above the surface. The presence of a steady vortex rotating anti-clockwise is also remarkable and easily characterised on the V component contour. In the negative sawtooth case the suction force is probably stronger and has a greater vertical component than in the positive case.

From PIV vector fields it is possible to extract velocity profiles along the y axis (U component of the velocity) to emphasis the momentum transfer occurring in this direction. On Figs. 6 and 7 the velocity profiles are presented for x = 5 mm, x = 10 mm, x = 15 mm and x = 20 mm and voltage amplitudes of 16 kV and 20 kV respectively. In the region from x = 0 to x = 15 mm the profiles exhibit important differences. Up to x = 15 mm, the positive sawtooth signal results in a U profile with mostly positive values whereas the negative sawtooth signal creates a vortex that results in negative velocities above y = 6 mm. This left directed velocity can reach 0.5 m/s up to x = 15 mm in the case of a 20 kV amplitude.

The vertical positions of the maximum velocity are almost identical in both cases regardless of the horizontal position. The maximum velocity is reached with the negative sawtooth waveform which is consistent with previous LDV measurements [11,12]. When observed further downstream (after x = 15 mm) both profiles tend to coincide due to the dissipative effects of the viscous force experienced by the fluid. The velocities of the electric wind generated by the negative sawtooth signal dominate at the bottom of the profile and are slightly lower at the top. This is of major importance since it results in a greater momentum transfer in the x direction close to the surface for the negative sawtooth waveform. This result is also in good agreement with the force measurement made with similar ramp signals. A greater thrust is measured on the balance when a negative sawtooth signal excites the surface DBD [9,10].

3. Conclusion

The electric wind generated by positive and negative sawtooth signals has been compared by mean of particle image velocimetry. Even though the gas breakdown mechanisms are very different whether fast electrons or slow ions are charging the dielectric surface, both signals generate airflow velocities of the order of 3 m/s. However, when observed in details each waveform results in a particular airflow topology. On one hand, the positive sawtooth, creating intense filaments close to the active electrode, leads to maximum velocities in its vicinity. On the other hand, the negative sawtooth signal results in a more homogeneous velocity distribution with higher velocities above the surface. The negative ions present in this air discharge probably play an important role in the profile thickness and homogeneity. During the negative sawtooth ramp their drift in the electric field possibly contributes to the uniformity of the velocity vector field. In the case of the positive sawtooth ramp the electric field is strongly modified by the plasma filaments so that it is concentrated on a small region at the head of the filament. The presence of a counter clockwise rotating vortex at the discharge front when the negative sawtooth signal is used is also very remarkable. This makes the airflows easily distinguishable and further LDV measurement are currently in progress to analysis in details the formation process of this vortex during the negative sawtooth ramp. These results give insight in the momentum transfer mechanisms for typical electric signals and show that a negative sawtooth waveform is probably more appropriated to induce homogenous and rapid airflows near the surface of an aerodynamic shape, in the boundary layer region. Moreover it appears that on a large scale more momentum is imparted to the gas when the active exposed electrode is the cathode.

References