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Electric wind produced by a surface dielectric barrier discharge operating in air at different pressures: aeronautical control insights

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Abstract
The effects of the ambient air pressure level on the electric wind produced by a single dielectric barrier discharge (DBD) have been investigated by Pitot velocity measurements. Pressures from 1 down to 0.2 atm were tested with a 32 kV_{p-p} 1 kHz excitation. This preliminary study confirms the effectiveness of surface DBD at low pressure. Indeed, the induced velocity is strongly dependent on the ambient air pressure level. Quite surprisingly the produced airflow presents a local maximum at 0.6 atm. The measured velocities at 1 atm and 0.2 atm are 2.5 m s^{-1} and 3 m s^{-1}, respectively while 3.5 m s^{-1} is reached at 0.6 atm. The position of the maximal velocity always coincides with the plasma extension. Mass flow rate calculations indicate that the DBD is effective in real flight pressure conditions.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Airflow control is currently widely investigated for aeronautical applications such as drag reduction, the increase in lift for post-stall regime or noise reduction for instance. A recent approach to control aerodynamic airflows at moderate velocities is based on surface non-thermal plasmas and, in particular, dielectric barrier discharges (DBDs) [1, 2]. Current investigations involving airflow control by DBD are operated at 1 atm but the pressure, ambient humidity and temperature vary according to the flight envelope or the climatic conditions. An effective active actuator thus needs to keep its capability to manipulate airflow even at critical atmospheric conditions.

Few authors have investigated the effects of external conditions on plasma actuators specifically designed for airflow control. In 2005, Anderson and Roy evaluated how the humidity rate affects DBD performances [3]. The results demonstrated that the actuation effects were not inhibited by the relative humidity rate. The effects of the ambient pressure level on the force produced by a single DBD have been evaluated by Abe *et al* in 2007 [4]. Electric measurements confirm that the current behaviour is strongly affected by the ambient gas pressure which results in changes in the thrust level. The authors observed that the thrust increases to a maximum value, and then decreases with decreasing pressure. Complementary measurements were performed by Gregory *et al* [5] in order to detail the mechanism of the time-averaged force production of a single DBD actuator operating in pressure conditions. The results demonstrated a linear time-averaged force reduction when the air pressure was decreased from 0.8 to 0.18 atm.

The approach proposed in this study differs from that of previous works. Instead of measuring the total force created by the DBD, the analysis is based on the 'electric wind' produced by the discharge. This study investigates the effects of the pressure on the electric wind produced by a single DBD

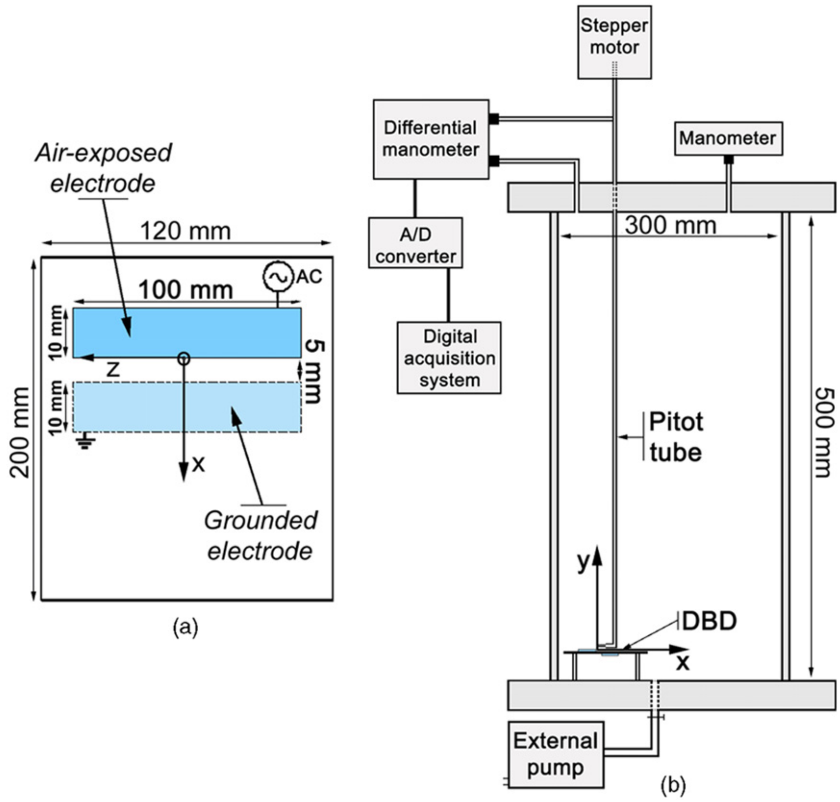

Figure 1. Top view of the single DBD device (*a*) and a sketch (side view) of the test chamber (*b*).

actuator mounted on a flat plate. This work is the preliminary result of a more global investigation about the atmospheric effects on electrohydrodynamics of DBD actuators operating in different pressure, humidity and temperature conditions.

2. Experimental setup

The plasma actuator consists of a single DBD mounted on a flat plate made of PMMA (figure 1(*a*)). Two thin aluminium foils (thickness of about 0.1 mm) act as electrodes, each electrode of identical size in span and length (10 mm and 100 mm, respectively). These electrodes are asymmetrically stuck on the plate with a small gap of 5 mm. The PMMA (4 mm thick) acts as a dielectric barrier. The electrode located under the plate is grounded and encapsulated with a silicon gel to avoid discharge formation below the plate. The air-exposed electrode is powered by a sine high voltage (Trek 30 kV/20 mA, New York, USA) set to 32 kV_{p-p} and 1 kHz. The electrical discharge results in a momentum transfer from the charged particles to the neutral atmospheric air components inducing the production of a local wind of a few metres per second [6–8].

The pressure test chamber shown in figure 1(*b*) can be operated down to 0.1 atm. It is composed of a circular cylinder made of glass. The pressure is set by an external pump and a digital manometer measures the internal static pressure. In this study, pressures from 1 down to 0.2 atm are tested. These pressure levels cover the pressure conditions of the flight envelope for a commercial aircraft (0.2 atm corresponds to a high-flying cruise condition of about 12 km). A Pitot tube made of glass is a reliable way to measure the induced velocity directly in the discharge region. The time-averaged pressure and the resulting velocity are acquired using a Furness© FCO352 differential manometer which allows ±10 Pa full scale measurements with an accuracy of ±0.25%. The velocity at each acquisition position corresponds to the average of samples recorded every 10 ms, for 20 s. Velocity profile measurements are performed at $x = 5$, 10, 15 and 20 mm.

3. Results

Photographs of the plasma discharge and electrical measurements are shown in figure 2. Under excitation, the space above the dielectric is ionized and a luminous surface discharge appears. A small discharge region is formed at 1 atm and the plasma region significantly extends when the ambient air pressure is diminished (see figures 2(*a*)–(*c*)). At 0.2 atm, the plasma is more diffuse and extends further in the x-direction and also laterally. A visual diagnostic indicates that the plasma surface extends linearly over the investigated pressure range even if ions may drift further than this visual limit (figure 3). It could be noticed that the plasma length extends beyond the end of the grounded electrode for the lowest pressure, demonstrating that a wider grounded electrode would be more suitable. Voltage and current typical curves are presented in figures 2(*d*)–(*f*) for one excitation cycle. The current signal presents high intensity pulses during the positive half cycle which behave similarly to a typical positive corona (figure 2(*d*)) [9]. When the air pressure is decreased (figure 2(*e*) and (*f*)), the series of current pulses that corresponds to one or several simultaneous micro-discharges are more numerous and

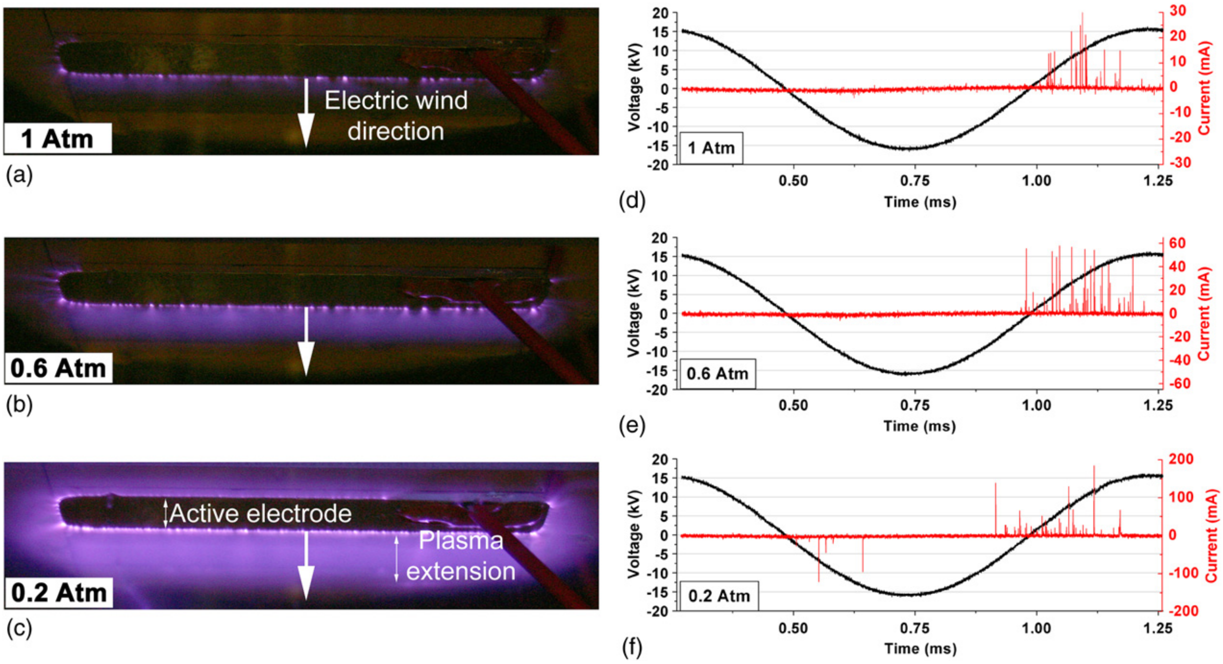

Figure 2. Photographs (top view) of the plasma discharge with a 1 s exposure time (*a*)–(*c*) and voltage and current of the DBD at 1 atm (*d*), 0.6 atm (*e*) and 0.2 atm (*f*).

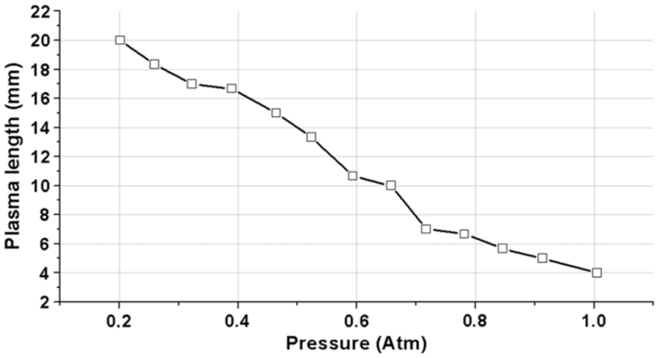

Figure 3. Plasma extension.

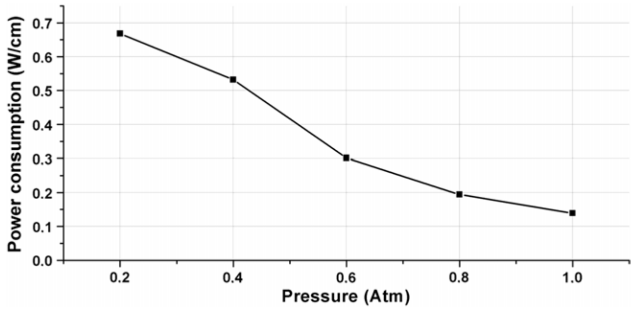

Figure 4. Electrical power consumption per unit length of the DBD actuator (values time-averaged over 100 cycles).

intense. Moreover, the period presenting positive current peaks is longer and starts earlier during the positive ramp of voltage with decreasing ambient pressure. At 0.2 atm (figure 2(*f*)), large negative current pulses occur at the end of the negative voltage ramp.

According to the increase in current pulse values and numbers, the time-averaged electrical power consumption is greatly increased when the pressure is reduced (figure 4). This result is in full agreement with previously reported results [4] and it demonstrates that the DBD can be operated at low air pressure even if an increase in the power consumption is observed when the high voltage is kept constant (i.e. 32 $kV_{p\text{–}p}$ here). The last observation concerns the plasma extension which increases linearly with the power consumption (positive ratio approximately equal to 3).

Plasma ignition occurs when the electric field is locally sufficient to induce breakdown of the air. It involves the creation of ionized channels promoting the formation of micro-discharges. In the case of a DBD, some charges transferred by the micro-discharges remain on the dielectric and eventually screen the electric field which finally decreases below the minimum value necessary to maintain the plasma. If the external applied voltage continued to increase, the local field would rise over the breakdown threshold again and another micro-discharge would be created. It was observed that the voltage required to create a discharge decreases with the pressure. Consequently, micro-discharges are created more often at a low ambient pressure level when the applied voltage is kept constant. When the gas density is reduced, current pulses become more intense as the electric field is kept constant and fewer collisions between charged particles and surrounding neutrals occur.

The experiments are performed without external flow and the horizontal electric wind (u) produced by the DBD device is estimated using Pitot measurements at four different locations along the x-direction (i.e. $x = 5$, 10, 15 and 20 mm). The data acquisitions are performed in the plasma region at $z = 0$ mm and it is expected that the time-averaged electric wind remains almost constant over the spanwise direction (z-direction). The velocity distribution above the plate (in the y-direction) is

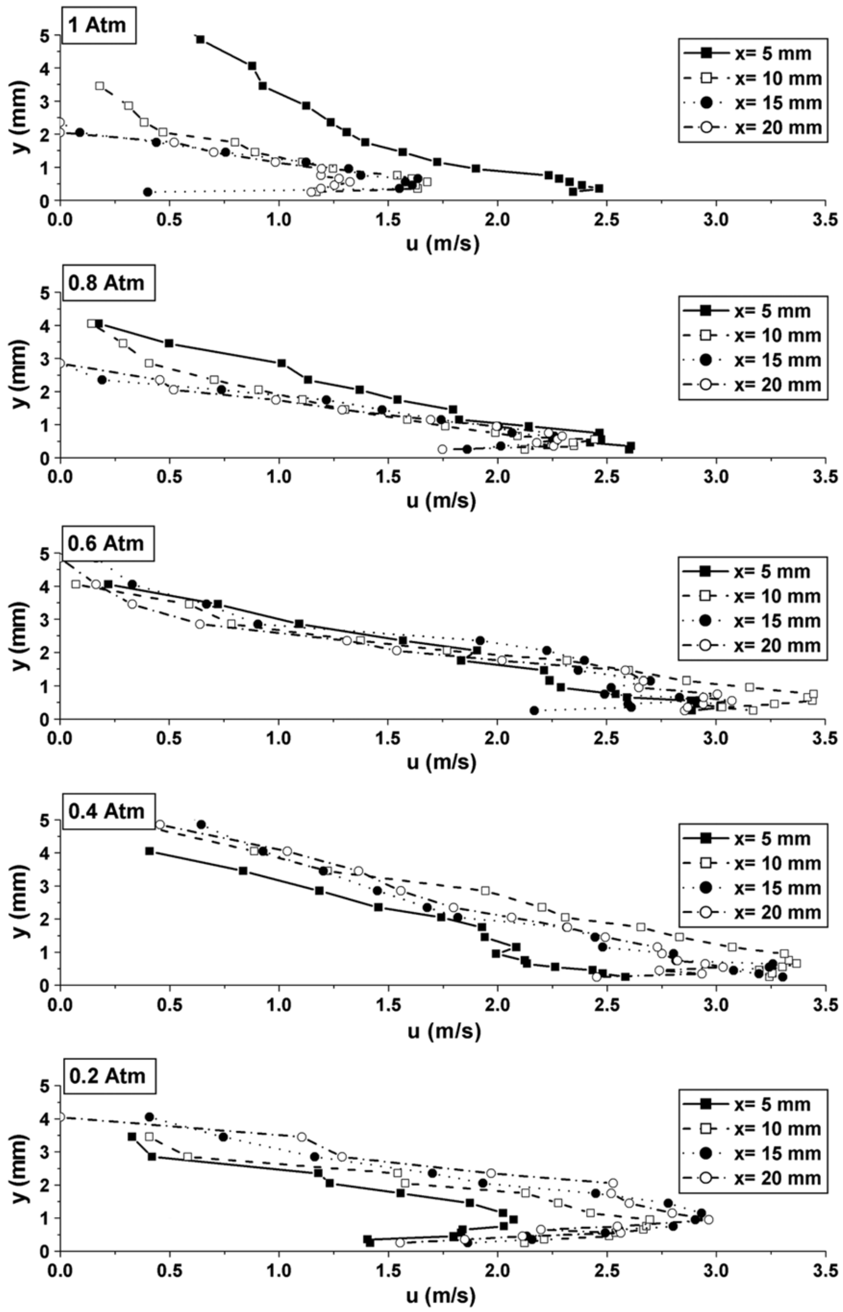

Figure 5. Velocity profiles at $x = 5$, 10, 15 and 20 mm for ambient pressure level ranging from 1 down to 0.2 atm.

evaluated by measuring the differential pressure ΔP. The local time-averaged velocity is computed using the following expression:

$$V = \sqrt{\frac{2\Delta P \times 287 \times T}{P}}, \qquad (1)$$

where T is the ambient temperature (295.13 K) and P is the static pressure inside the test chamber. The velocity profiles at $x = 5$, 10, 15 and 20 mm are plotted in figure 5 with pressure level decreasing from 1 down to 0.2 atm. The first observation concerns the maximal velocity reached by the induced airflow with a decreasing ambient pressure. Figure 5 demonstrates that the induced velocity increases at first (for pressure level decreasing from 1 down to 0.6 atm) and then decreases. Thus, a maximal produced velocity of about 2.5 m s^{-1} is reached at atmospheric condition while the velocity is increased up to 3.5 m s^{-1} at 0.6 atm.

The shape of the velocity profile (in the y-direction) is not dependent on the ambient pressure level. But for a constant pressure it varies in the x-direction. Indeed, velocity profiles measured close to the air-exposed electrode are thin in contrast to the profiles at locations greater than 5 mm. The natural diffusion promotes thicker velocity profiles above the dielectric wall. The diffusion is greatly enhanced at the lowest pressure level which results in a displacement of the maximal velocity in the y-direction (the maximal velocity is located at 0.45 mm and 1.05 mm above the wall for 1 atm and 0.2 atm, respectively).

The last observation concerns the longitudinal location (x-direction) of the maximal velocity at each pressure level.

The results demonstrate that the maximal velocity is dependent on the x position. For instance, at 1 atm the maximal velocity is located close to the air-exposed electrode (at $x = 5$ mm) whereas at 0.2 atm this location corresponds to the lower measured velocity. According to figure 3, the plasma linearly extends when the ambient pressure level is decreasing due to the reduction of particle densities. At 1 atm, the plasma extension is shorter and the position of the maximal velocity matches the end of the plasma discharge.

One particularity of the DBD actuator is that it does not induce mass addition to the controlled flow but it allows the modification of the flux distribution. Indeed, DBD actuators are usually used to entrain mass flux of the external flow towards regions of lower velocity such as boundary layers. A way to evaluate the effectiveness of the actuator consists of calculating the external mass flow attracted by the plasma region. The induced airflow is supposed to be bi-dimensional and the mass flow rate can be quantified from the velocity profiles:

$$Q = \rho l \int_0^\infty u(y)\,\mathrm{d}y, \tag{2}$$

where $l = 100$ mm is the length of the electrodes. The calculated mass flow rates are plotted in figure 6. The mass flow rate evolution varies with the air pressure level and the measurement location. It demonstrates that the mass flow rate first increases with decreasing air pressure down to 0.6 atm and then drastically decreases. The reason why the maximal velocity and mass flow rate are observed at 0.6 atm remains unclear and requires additional measurements. However, one can assume that decreasing the pressure results in a larger ionization level and a wider plasma region but it also reduces the gas density and thus the momentum transfers by collision. An ambient pressure of 0.6 atm could be the best compromise between the two phenomena. In addition, this result is in agreement with Abe *et al* [4], who reported that the thrust does not decrease monotonically but increases at first (down to approximately 0.7 atm) and then decreases. In this study, the mass flow rate at 0.6 atm can be about 50% higher than at 1 atm (at $x = 15$ and 20 mm) while the mass flow rate at 0.2 atm can be about 33% lower than at atmospheric condition (decrease of about 60% at $x = 10$ mm). In contrast to the velocity, the maximal mass flow rate is not dependent on the x position. At each ambient pressure level, the maximal mass flow rate occurs almost at $x = 10$ mm. This observation is of primary interest for airflow control as it demonstrates that an improvement of the control could be expected for such a DBD device located at 10 mm from the receptivity region. This enhancement is effective over the whole pressure range occurring during the flight envelope of commercial aircraft.

4. Conclusion

The electrical characteristics and the produced electric wind of a single DBD are investigated for several ambient air pressure values. The electric wind is measured inside and above the plasma region using a Pitot tube. Images of the plasma discharge confirm that the non-thermal plasma is affected

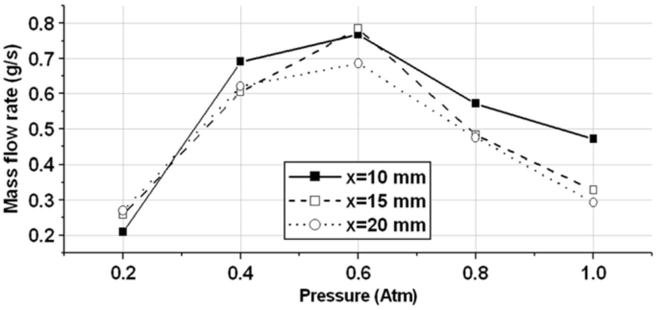

Figure 6. Mass flow rates at different ambient air pressure levels.

by the pressure level with an extension of the discharge at low pressure. The analysis of the current demonstrates that a decrease in pressure induces an increase in the consumed power (at constant voltage), and an increase in the current peaks in number and intensity. The produced electric wind is also greatly modified by the ambient air pressure conditions. For instance, the maximal velocity is increased with ambient pressure decreasing from 1 down to 0.6 atm and decreases for lower pressures. The calculation of the mass flow rate confirms that the flow rates first increase as pressure decreases and then the mass flow rate is reduced. The study of the mass flow rate demonstrates that the most effective actuation is performed at $x = 10$ mm regardless of the ambient pressure.

Future investigations will concern the electromechanical measurements for DBD operating in different air humidity ratios or temperature conditions. The main aim of this work is to study the DBD behaviour at pressure, humidity and temperature undergone by an aircraft during its flight envelope.

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