EXPERIMENTAL STUDY OF THE OZONE PRODUCED BY A PLASMA ACTUATOR USING SURFACE DIELECTRIC BARRIER DISCHARGE

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ABSTRACT

According to recent results in literature, the use of plasma actuator is a relevant technique to modify the aerodynamic characteristics of a vehicle and to decrease the energy consumed for a displacement. But this gain on fuel consumption must not increase pollution due to the electric discharge in air. So this study focuses on the ozone produced by the most commonly used plasma actuator (sinusoidal driven surface dielectric barrier discharge) for different configurations and operating parameters. Although ozone production is much weaker from a SDBD actuator compared to a DBD-based ozonizer, our results show that ozone production is not negligible and must be taken into account in plasma actuator developments for vehicle applications.

1. INTRODUCTION

Optimizing a vehicle to minimize its energy consumption, like the myth of Sisyphus, son of Aeolus, is an endless process. Since the work initiated by Roth [1], the use of plasma on wing or car profiles seems an interesting solution to pursue this goal by acting on the characteristics of the surrounding airflow. Indeed, non-thermal plasma actuator can change the velocity profile in the boundary layer via the ionic wind induced by the electric discharge, and then reduce the turbulence level and the drag of a vehicle [1-2]. This kind of actuator does not require moving parts, enables faster action, allows a more flexible use and operates with low cost.

Unfortunately, an electrical discharge in air produces ozone. Ozone is present in many applications, but it is a harmful gas and a European directive set the alert threshold at 180 $\mu g/m^3$ in air [3]. It is thus important to minimize the ozone produced by plasma actuators, in addition to optimize their aerodynamic performances.
There are already several structures of plasma actuators. Initially, corona discharges were used [4, 5], but they were rapidly replaced by a dielectric barrier discharge which prevents the glow-to-arc transition. The plasma can also be formed in a micro-cavity producing a gas jet [6] or onto a surface [2]. For the power supply, although recent researches have focused on nanosecond pulsed discharges [7], the most used remains the sine high voltage.

The objective of the present work is to experimentally quantify the ozone produced by a plasma actuator commonly used for airflow control. This study was done with a surface dielectric barrier discharge (SDBD) driven by a sine power supply. We first present the experimental setup, and a simple model describing the temporal evolution of the ozone concentration in a closed vessel with a regular renewal of gas. Then, the measurements conducted under different experimental conditions are presented. The production rate, which is the amount of ozone produced per unit of power dissipation, was calculated for these different experimental conditions. It was found that the production rate was more or less constant for all configurations.

2. EXPERIMENTAL SETUP

The most studied plasma actuator is built with two thin copper electrodes placed asymmetrically on the both sides of a polyamid dielectric. In this study (see Fig.1), the dielectric was made with one Mylar® layer between two Kapton® layers. Three electrodes configurations were investigated: two in straight form with a gap of 0 and 3 mm respectively, and one with a saw-tooth shape for the active electrode. This last configuration has been tested recently by several teams in order to obtain a stronger ionic wind [8]. The grounded electrode was encapsulated to prevent plasma formation on the opposite side.

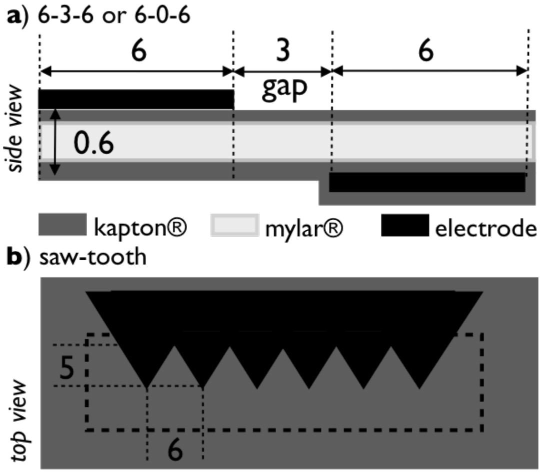

Fig. 1: Surface DBD designs (all distances are in mm); a) side view of straight electrodes with a gap of 0 mm or 3 mm between them, b) top view of a saw-tooth design for the active electrode.

As shown in Fig. 2, the actuator was placed in a tight reactor where two electrical feedthroughs ensure the connections to electrodes and where two opposite apertures of 4 mm in diameter allow the gas flow with one of them connected to an ozone-meter (IN-USA, model IN2000_1). The total volume of the chamber and tube was 2.12 l and the flow rate of feeding gas was fixed at 1.4 l per minute.

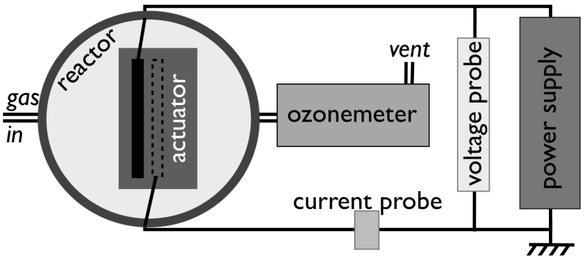

Fig. 2: Experimental setup.

The sine high voltage was provided by a TREK amplifier (model 30/20A) driven by a function generator (TTi – TG4001). The voltage amplitude and the frequency varied from 5 to 10 kV and from 0.1 kHz to 2 kHz, respectively. The applied voltage was controlled thanks to a high voltage probe (Lecroy PPE20kV) and the current was measured thanks to a current transformer (Bergoz CT-C1.0-B), both being connected to an oscilloscope (Lecroy WaveRunner HRO 66Zi).

3. RESULTS AND DISCUSSION

Ozone concentration as a function of time:

Ozone is formed in a three-body reaction: $O + O_2 + M \rightarrow O_3 + M$, where M could be O_2, O_3, O or also N_2 in air [9]. The oxygen atoms come from the O_2 dissociation due to collisions with electrons or with N_2 in excited states [9], but also from NO_2 in the case of air pollution. The NOx concentration in case of plasma actuators being generally too low to be measured, its role is thus negligible.

Many mechanisms may be involved in the ozone destruction, but as the gas temperature is low in our case, the destruction rate by collisions is low. The main reduction of ozone concentration in the chamber is due to the ozone-meter that pumps 1.4 l of gas per minute for measurements.

Assuming that V_0 is the total volume of the chamber, and that V_{OZ} is the ozone volume, the volume concentration of the ozone (in ppmv) is then given by the relation: $C_{OZ}=V_{OZ}/V_0$. At the beginning of the actuator operation, the balance between the production and destruction of ozone is described by the following equation (with Δt very small):

$$C_{OZ}(t+\Delta t)V_0 - C_{OZ}(t)V_0 = K_{OZ}\Delta t - SC_{OZ}(t)\Delta t \quad (1)$$

where K_{OZ} is the rate of ozone production and S the pumping speed in liters per second.

When production is exactly balanced by destruction (more exactly, the reduction due to the pumping), the medium is in steady state and the concentration, denoted as $C_{OZ}(\infty)$, is constant. In this case, $K_{OZ} = SC_{OZ}(\infty)$. (2)

Now, with $\tau=V_0/S$, one can deduce from (1): $\frac{dC_{OZ}(t)}{dt} = \frac{C_{OZ}(\infty)}{\tau} - \frac{C_{OZ}(t)}{\tau}$, which has for solution:

$$C_{OZ}(t) = C_{OZ}(\infty)\left(1 - e^{-\frac{t}{\tau}}\right). \quad (3)$$

When the actuator is switched off, the concentration of ozone decreases and equation (1) remains valid with $K_{OZ}=0$. One can deduce:

$$C_{OZ}(t) = C_{OZ}(0)e^{-\frac{t}{\tau}}. \quad (4)$$

The concentration of ozone as a function of time was measured, when the actuator was working at 1 kHz and 7.7 kV during 10 minutes, and 7 minutes more after its switch-off. The experimental data are presented in Fig. 3 and the curves using the laws of variations (3) and (4) was also plotted. It can be seen that a good agreement has been obtained with τ =94 s. This shows that the simple model presented above is realistic. At atmospheric pressure and ambient temperature, 1 ppmv in ozone concentration corresponds to 2 mg/m^3 (i.e. 2 mg of ozone in 1 m^3 of air). The concentration of ozone at steady state is 215 ppmv or 430 mg/m^3. According to (2), the ozone production rate can be calculated as 10 µg/s.

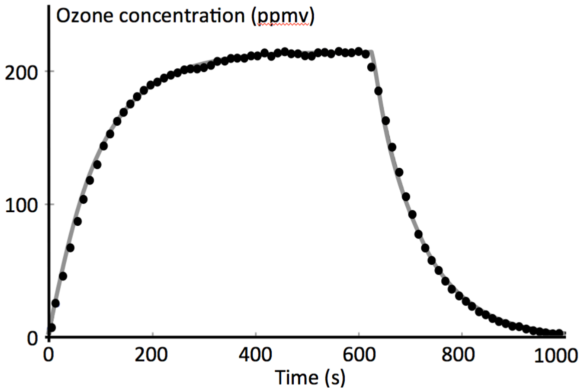

Fig. 3: Concentration of ozone in ambient air as a function of time (actuator OFF after 600 seconds). Experimental data: circles; Model in continuous line. (6-0-6 configuration and 80 mm in wingspan, 1 kHz and 7.7 kV).

Ozone concentration as a function of design:

The concentration of ozone was measured for three electrode configurations, i.e. 6-3-6, 6-0-6 and saw-tooth, respectively (see Fig. 1). The electrodes length was 80 mm. The frequency was 1 kHz and the voltage amplitude 8 kV. Table 1 presents the value of ozone concentration at steady state for each case.

Table 1: Ozone concentration at steady state for three configurations (1kHz – 8kV – ambient air).

Configuration	Ozone concentration (ppmv)
6-0-6	245
6-3-6	115
Saw-tooth	273

For the same working voltage, the production of ozone is highest with the saw-tooth configuration and lowest with the 6-3-6 configuration. The power dissipated calculated with the Lissajous method [10] shows that with the same high voltage, the power dissipation is highest with the saw-tooth configuration and lowest with the 6-3-6 configuration. There is a correlation between the production of ozone and the power dissipation.

While keeping all the other parameters unchanged, we measured the concentration of ozone in steady state for another electrode length: 40 mm. We found 123 ppmv for the 6-0-6 configuration. Doubling the length of the electrode causes a doubling in the ozone concentration, for a given voltage.

Ozone concentration as a function of electrical parameters:

Table 2 shows the ozone concentration in steady state as a function of the electrical parameters for the 6-0-6 configuration (length of 80 mm) in dry air.

Table 2: Ozone concentration as a function of electrical parameters (6-0-6; 80mm; dry air)

Voltage (kV)	Frequency (kHz)	Ozone concentration (ppmv)
5	0.5	63
6.5	0.5	122
8	0.5	229
9.5	0.5	289
9.5	1kHz	494
9.5	0.1kHz	73

For a given electrode configuration, the reduced electric field increases with the magnitude of the voltage. Ionization is therefore more effective and the electron density is greater. This implies a higher oxygen atom density and therefore a higher ozone production. In addition, for a given frequency (i.e. a given time cycle), the duration of the discharge is longer in each half cycle because the discharge begins earlier at larger voltage amplitude.

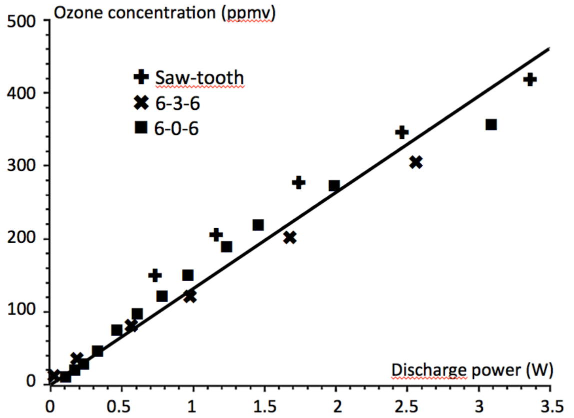

Fig. 4: Ozone concentration versus the active power dissipated by SBDB in air at atmospheric pressure for three electrode configurations. The straight line is the best linear fit of the experimental data from three configurations

Then, it seems that it is more appropriate to determine the ozone production on the basis of the power dissipation, also called active power. Active power can be measured using Lissajous figures or directly calculated from the empirical formula [11]. It was done and presented in Fig.4 for the three electrode configurations. Only for the 6-0-6 configuration, the ozone concentration as a function of discharge power was calculated by using the empirical formula (■symbol in Fig. 4).

It can be seen that all these experimental data are well fitted with a straight line passing through the origin. The slope of this straight line is about 132 ppmv/W.

From the experimental values given in Fig. 4 with $\tau = 94$ s, we found that the ozone production of this kind of actuator is about 21.2 g/(kWh). This value is much lower than the 90 g/(kWh) obtained in dry air by Simek *et al.* [12], but it is not negligible.

Ozone concentration as a function of dielectric:
Kapton® is the most commonly used dielectric in plasma actuator. The dielectric constant of Kapton® is 3.3, while the one of glass is 3.8.

Table 2: Ozone concentration as a function of dielectric (1kHz – 8kV – Pure oxygen)

Dielectric	Ozone concentration (ppmv)
Kapton®	637
Glass	222

Table 3 presents the ozone concentration at steady state for Kapton® or glass as dielectric in pure oxygen. The glass thickness is 1.92 mm. It seems that we can reduce ozone concentration by using thicker dielectric for which the dissipated power is lower for a same voltage.

Ozone concentration as a function of gas:
The same experiments were done with three different working gases, i.e. ambient air, dry air and pure oxygen. Steady-state concentrations were respectively 256 ppmv, 367 ppmv and 637 ppmv, with the 6-0-6 configuration (length of 80 mm), and applied voltages of 8 kV and 1 kHz. Production with pure oxygen was 1.7 times higher than with dry air. This ratio is very close to that obtained by Simek *et al.* [12]: in pure oxygen, their value is 170 g/kWh, which is 1.9 times greater than 90 g/kWh obtained in dry air.

In ambient air, this lower production is due in part to the OH radicals produced in the discharge via the following reaction, $OH+O_3 \rightarrow HO_2+O_2$ [13]. In presence of water molecules, the discharge is different and ozone production is lower.

4. CONCLUSIONS

In this paper, the ozone produced by a SDBD actuator was quantified for the first time and this for different configurations and different operating parameters. It was found that ozone production depends mainly on the dissipated power by the discharge and was about 21 g/kWh under our experimental conditions. This is still too high and should be minimized by a factor of 100 if a plasma actuator would be used on a land vehicle.

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