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Study and Design of a Plasma Reactor Using a Porous Dielectric Barrier

Fatha Tounsi
Mustapha Stambouli University of Mascara

Rabah Ouiddir
Djillali Liabes University of Sidi Bel-Abbes

Houcine Miloudi
Djillali Liabes University of Sidi Bel-Abbes

Mohamed Miloudi
Djillali Liabes University of Sidi Bel-Abbes

Abdelber Bendaoud
Djillali Liabes University of Sidi Bel-Abbes

Abstract: To continuously improve actuator performance, it is necessary to study the discharge to better understand its operation. Therefore, this work focuses primarily on the ion wind and its stability. In other words, the goal is to obtain the maximum possible ion wind without generating arcs. To increase the ion wind speed, it is necessary to increase the discharge current (recall that the ion wind speed is proportional to the square root of the discharge current i) (5), thus increasing the potential without reaching the breakdown voltage in air. It is therefore important to observe the behavior of the ion wind for several discharge configurations and to find the optimal configuration suitable for flow control. The main parameters essential to study are: the electrode diameter, the inter-electrode distance, and the nature of the dielectric on which the discharge occurs.

Keywords: Ionic wind, Ionic wind velocity, Discharge current, Flow rate control

Introduction

Dielectric Barrier Discharge (DBD) is a type of plasma that is not in thermodynamic equilibrium. It was discovered by Siemens in 1857 for ozone generation (Dubus et al., 2009). It is characterized by the coating of one or two flat or cylindrical electrodes with a layer of dielectric material. This material allows for the accumulation of charges on its surface, which limits the electric field between the two electrodes, thus preventing the formation of an electric arc. The use of a high-voltage (HV) alternating current supply is therefore necessary in this case to compensate for these charges created on the surface with each alternation, in order to prevent the plasma from being extinguished (Dubus et al., 2009), (Nozaki et al., 2001). Today, Dielectric Barrier Discharges (DBDs) are of great interest due to a very wide range of applications: ozone generation, removal of Volatile Organic Compounds, treatment of gaseous effluents, flow control, activation and surface treatment, CO_2 laser, excimer lamp, plasma screens… This process is also found in many industrial fields: electronics, textiles, packaging, automotive (Allegraud et al., 2008; Alban et al., 2001). However, all these applications face robustness issues due to the fragility of the dielectric barriers used, as well as the thermal effect accompanying the electrical discharge, which necessitates the use of a cooling system. Therefore, the overall operating and maintenance cost of a continuously operating installation can increase significantly.

The research on Dielectric Barrier Discharges (DBDs) has still much to say about electromagnetic phenomena that occur in high-voltage and high-frequency areas (Mohammed et al., 2024; Bermaki et al., 2023; Hakmi et al., 2024; Mohamed Miloudi et al., 2019; Yacine et al., 2024), such as those in converter-fed electric drives. One of the results of the fast voltage transients generated by Pulse Width Modulation (PWM) converters is the partial discharge and the generation of strong electric fields in the motor insulation systems which in turn cause electromagnetic interference and insulation degradation (Miloudi et al., 2022; Lahlaci et al., 2024; Houcine et al., 2023; Naima et al., 2025). Analyzing DBD behavior makes the insulation design more efficient, it allows the conducted and radiated emissions to be controlled better, and it also facilitates the electrical machines and converter systems in having good electromagnetic compatibility (EMC).

The work presented in this article has one main objective: to improve the electrothermal performance of a DBD reactor. Indeed, one of the primary objectives of a plasma reactor is to provide the necessary quantity of charge or molecules for any given application, with minimal energy consumption and without degrading the DBD discharge. Low-temperature plasma jets are unique plasma sources capable of delivering plasma outside the confinement of electrodes and away from enclosures/gas chambers. With these jets, plasma can be easily delivered to a target located at a distance from the generation area (Henri et al., 2008; Eid et al., 2015).

Various power generation methods have been used to ignite and sustain low-temperature plasma jets. These include direct current (DC), pulsed direct current, radio frequency (RF), and microwaves. In particular, atmospheric-pressure low-temperature plasma jets are playing an increasing role in many plasma processing applications, including surface treatment and biomedicine (Eid et al., 2015).

The plasma actuator consists of applying a potential difference between at least two electrodes placed on the surface of an obstacle. Under the effect of the electric field (by extension of Coulomb forces), a flow resulting from a transfer of momentum between the charged species and the neutrals of the surrounding gas appears above the obstacle: the electric wind (Jolibois et al., 2009).

Geometric Configuration of the Plasma Actuator

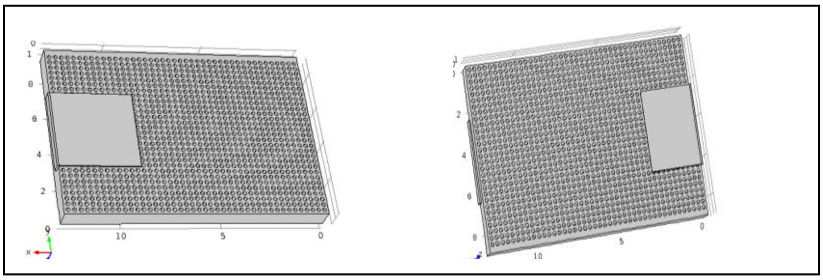

Figure 1. Geometric configuration of the plasma actuator to be implemented

Figure 1 represents a schematic representation of the two reactor faces. Dielectric barrier: Among the various dielectric materials used in reactors, we chose ceramic because it stabilizes the discharge across its entire surface, minimizing the risk of electric arcing, and it also offers better resistance to high temperatures. This dielectric is porous (Figure 2). The pore diameter is 1 mm, uniformly distributed over a surface area of (130×90) mm². The thickness of the dielectric is 10 mm.

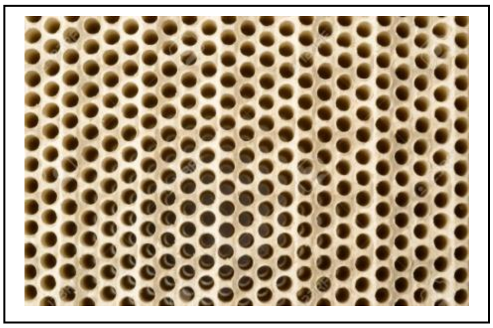

Figure 2. Photograph of the porous dielectric used.

The electrodes: are rectangular pieces of adhesive aluminum tape in an asymmetrical position. They are glued on either side of the dielectric barrier.

High-voltage DC power supply: The plasma is obtained by applying a high-voltage DC current of negative polarity to one of the electrodes; the other electrode is grounded. The voltage is supplied by a Spelleman brand high-voltage generator (SL60, Umax = 40kV, Imax = 7.5mA).

Experimental Study of Flow Control

This part of this work consists of studying the feasibility of controlling a flow by applying either a direct or alternating voltage. We optimized our actuator to achieve the most efficient control possible. This flow control was carried out using incense smoke as the gas to be controlled. The composition of smoke produced by burning incense is highly diverse. It contains numerous pollutants that can be classified into two categories: gaseous pollutants and aerosols. Gaseous pollutants include carbon monoxide (CO), nitrogen oxides (NOx), acid sulfides (SOx), and volatile organic compounds (VOCs). Aerosols, on the other hand, consist of solid and liquid particles containing toxic metals. An example of the particle size distribution of these incense particles is illustrated in Figure 3. It shows that the particle size distribution has a peak around 0.3 µm where the number of particles is greatest.

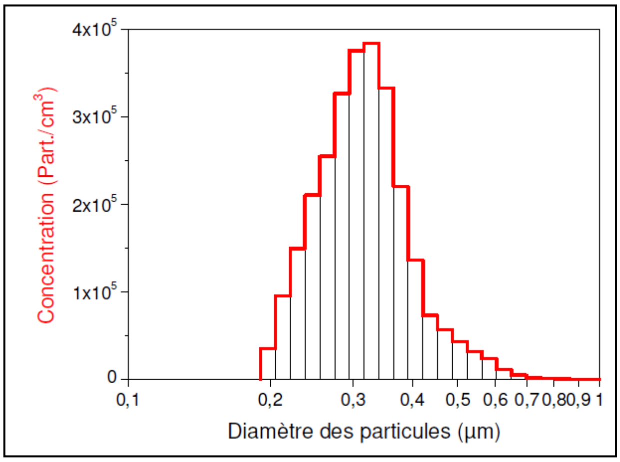

Figure 3. Example of a particle size distribution

Experimental Setup and Equipment

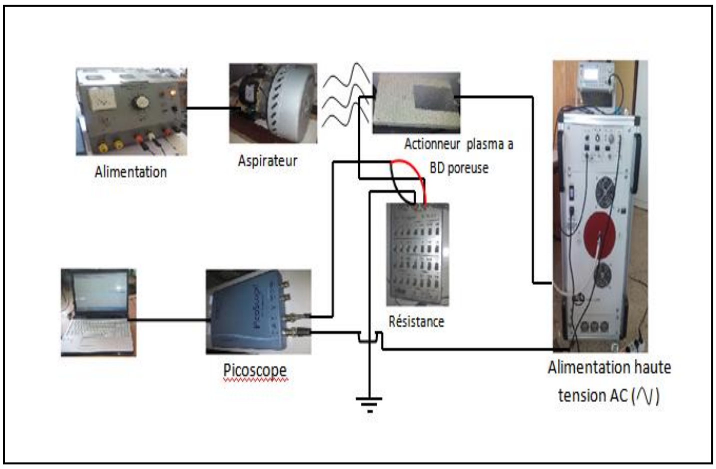

Figure 4. Experimental setup for flow control under alternating voltage.

The experimental setup created for flow control in alternating mode is illustrated in Figure 4. A voltage amplifier (Trek 30/20A) was used to power our actuator. The supply voltage in this study is fixed at 18 kV, while the frequency is variable. To improve control efficiency, the inter-electrode distance was reduced to 1 cm.

Frequency-Dependent Flow Control

The flow control tests, performed at a fixed suction flow rate of 120 m^3/h, showed that the signal frequency is a highly influential factor on control efficiency. This efficiency was evaluated based on the angle of smoke deflection relative to the initial position, i.e., before the voltage was applied.

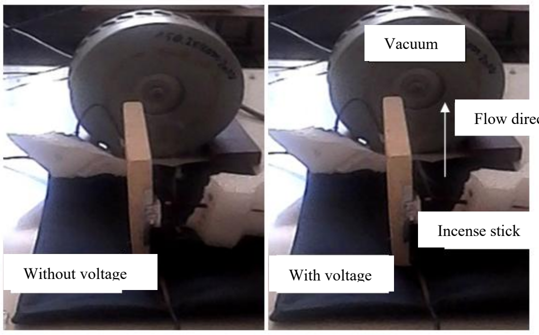

Figure 5. Observation of the smoke deflection angle for a frequency of 50Hz

After processing images of video sequences taken from the same position relative to the horizontal plane of our actuator, we were able to evaluate the angle of smoke deviation as a function of frequency. Using the trigonometric rule, the angle of smoke deflection can be easily calculated. Table 1 shows the numerical values of the angle of deflection as a function of frequency.

$$\cos\alpha = \frac{a}{b}$$

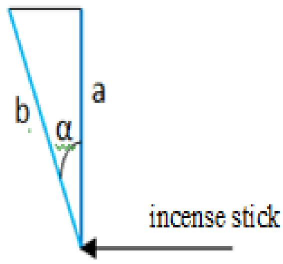

Figure 6. Determination of the smoke deflection angle.

Table 1. Variation of the smoke deflection angle as a function of frequency

Frequencies [Hz]	50	500	1000
Angles of deviation [°]	20.65	49.40	51.94

Figure 7. Observation of the smoke deflection angle for a frequency of 500Hz.

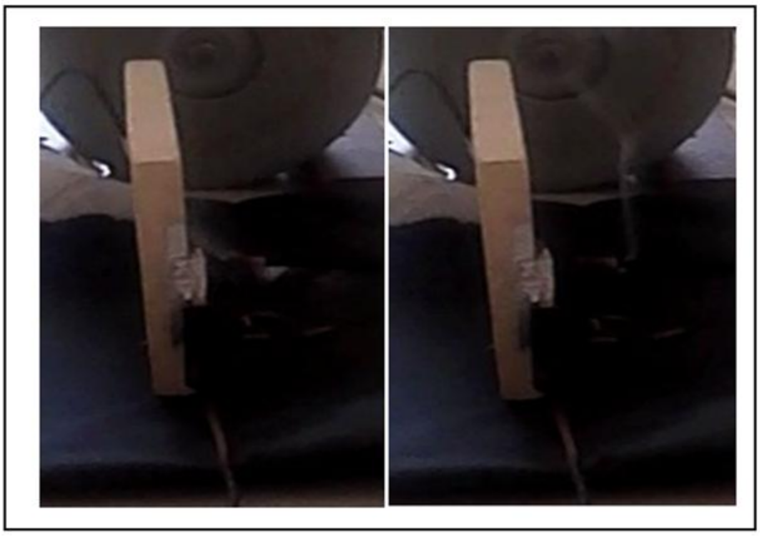

Figure 8. Observation of the smoke deflection angle for a frequency of 1kHz.

We can therefore conclude that increasing the frequency allows for better control of the flow with a considerable reduction in turbulence.

Continuous Voltage Flow Control

Now, we will apply a direct current voltage of negative polarity for the same inter-electrode distance (d=1cm) and the same voltage (U = 18 kV). The angle of deviation this time is equal to 30°.

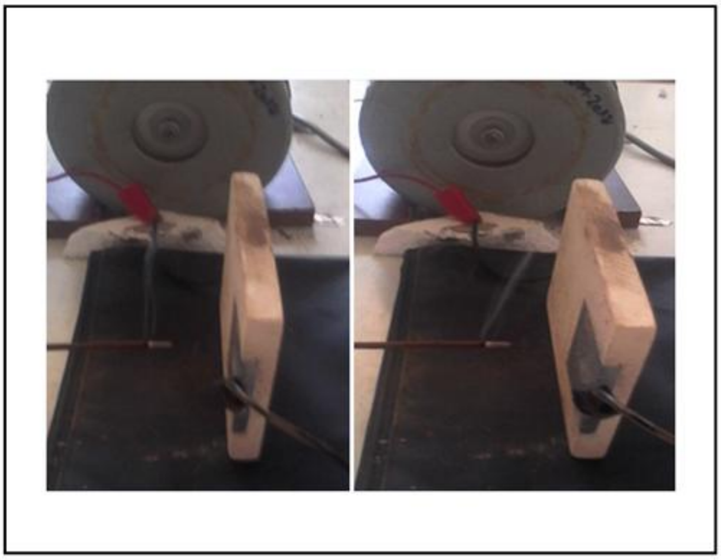

Figure 9. Observation of the angle of deflection of the smoke under negative direct voltage (U=18kV, d=1cm)

Conclusion

The dielectric barrier discharge (DBD) used here consists of an electrical discharge established in air at atmospheric pressure on the surface of an insulator. This discharge ionizes the surrounding air, and the generated charged species, subjected to the Coulomb force, induce a flow called electric wind through momentum transfer. Recently, the ability of this type of device to control flow around airfoils has been explored. The DBD used in this way is called a plasma actuator. These actuators can modify boundary layer flows near the wall via electric wind. The objective of this work is to contribute through an experimental mechanical study to calculate the angle of deviation of the ionic and electro-thermal wind, of a plasma actuator with a porous dielectric barrier.

Scientific Ethics Declaration

* The authors declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Fatha Tounsi
Mustapha Stambouli University of Mascara
11, Chemin Doudou Mokhtar, Ben Aknoun – Alger – Algeria

Rabah Ouiddir
APELEC, Djillali Liabès University
Sidi Bel-Abbès, Algeria

Houcine Miloudi
APELEC, Djillali Liabès University
Sidi Bel-Abbès, Algeria

Mohamed Miloudi
APELEC, Djillali Liabes University of Sidi Bel-Abbes
Sidi Bel-Abbès, Algeria
Contact e-mail: *prof.mohamed.miloudi@gmail.com*

Abdelber Bendaoud
APELEC, Djillali Liabès University
Sidi Bel-Abbès, Algeria

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