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Manipulation of a grid-generated mixing with an active honeycomb dielectric barrier plasma discharge

N. Benard¹, A. Mizuno² and E. Moreau¹

¹*Institut PPRIME (CNRS UPR 3346, Université de Poitiers, ENSMA)*

Dpt Fluide, Thermique et Combustion

Bld Marie et Pierre Curie

Téléport 2, BP 30179, 86962 Futuroscope, France

²*Toyohashi University of Technology*

Department of Environment and Life Science

Tenpaku-cho, Toyohashi 441-8580, Japan

Abstract

This study defines and characterizes a new system for turbulent and scalar mixing enhancement. This system is made of an active grid composed of 121 holes where the gas flows. A high voltage is applied between printed electrodes and embedded ground electrodes in order to produce a non-thermal surface discharge at the hole exits. The goal is to modify the flow downstream of the active grid. First, electrical and optical characterizations of the actuator are proposed. Secondly, it is shown that the discharge strongly modifies the flow distribution of the jets exhausting, and the flow change depends on the high voltage applied to the active plasma grid. A minimization of the potential core by 40% is reported when discharge frequency corresponds to jet column mode instability.

Turbulent mixing of scalar is important for a large number of practical and fundamental situations. Systems such as passive grids [1] or multiple jet configurations [2] have theoretically and empirically demonstrated that the obvious power-law decay of the turbulent components can be modified. Homogeneous and isotropic turbulence can quickly develop downstream of a fractal grid [3] or multiple grids in series [4], these two passive systems producing a better mean flow homogeneity and a high turbulent intensity while maintaining a low pressure drop. Another method for increasing the mixing of turbulent flow is the use of multiple jets. For instance, reduction of pollutant emissions (such as NO_x) can be achieved by stabilizing a flame thanks to the mixing improvement caused by a fuel jet confined by lateral oxygen jets [5]. A more complex system made of 6×6 interacting jets has been investigated in [6], which demonstrates a merge of the jets into a single jet after a certain distance. A lateral

deflection is caused by mutual entrainment between the jets and a low pressure region at the center of the jet array.

The present paper defines and demonstrates how the surface plasma discharges can be useful for mixing increase downstream of an active ‘grid like’ or ‘multi-jet like’ geometry. The use of non-thermal surface plasma discharge for flow control is now more than an emerging field [7, 8, 9, 10]. It involves more and more research groups, but the typical surface plasma actuator with asymmetric electrodes, as it was originally defined by Roth [11], is still the most used configuration.

The present paper aims at investigating a different type of electrode arrangement in order to tackle new applicative and fundamental problems dedicated to mixing enhancement. This type of complex electrode arrangement has been originally designed for gas cleaning by combination of non-thermal plasma and catalysts [12, 13]. The proposed research is an introduction of this new actuator regarding its electrical and optical characteristics, as well as preliminary flow measurements. The primary objective is to identify the effectiveness of such an active actuator for manipulating a turbulent flow. Indeed, this actuator can open new research direction taking advantages of the high frequency forcing capability of plasma discharges.

The geometry of the plasma discharge used in this paper is a new design compared to traditional surface DBD plasma actuator used in flow control applications. The system is made of a perforated ceramic plate (thickness of 1.27 mm) in which the grounded electrode is embedded in the dielectric material while the high voltage electrode is printed on one of the surfaces (Figure 1). The honeycomb has 121 holes with an inner diameter Φ of 2 and a height of 1.27 mm. The distance between the centers of two successive holes is 3.05 mm. Both electrodes are made of nickel with a thickness of about 10 μm . The active (high voltage)

electrode is made of 121 circular rings with an internal diameter of 2.7 mm, these rings being all connected together. The distance between the edge of an active electrode and the edge of the corresponding hole designed for the gas passage is 350 μm . By applying a sufficient AC high-voltage to the active electrode, surface discharge takes place at the surface of the perforated plate and at the inner wall of each hole. There is then one single discharge per hole. By analogy with the geometries used for investigating fundamental grid turbulence, one can calculate a grid solidity ratio σ (defined as the ratio of the surface obstructed by the grid to the total area of the grid [14]) that is here equal to 0.78.

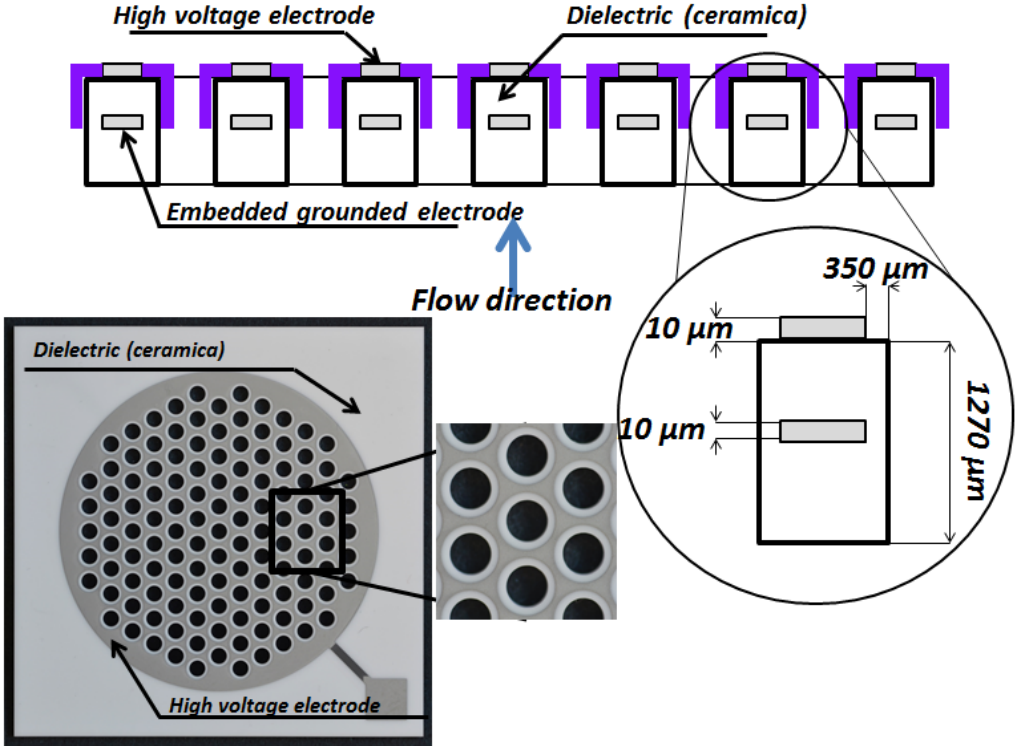


Figure 1 : Photograph, sketch and dimensions of the honeycomb DBD

A high voltage amplifier (Trek, model 30/40 mA) is used to apply a gain of 3,000 V/V to the input voltage provided by a function generator. The input signal is a sine waveform applied to the active electrode at the surface of the honeycomb. The applied peak-to-peak voltage does not exceed 14 kV_{pp} for AC frequencies (f_{AC}) from a few hundred of Hz up to 2000 Hz.

Top-views images of the plasma discharge (viewed from the active surface) are proposed in Figure 2 for two f_{AC} frequency values. In the present paper, a certain attention is paid to the influence of f_{AC} due to the advantages offered by the plasma discharges in attaining the momentum transfer at single as well as multiple frequencies [10]. Indeed, such approach should permit in a near future to explore new exciting active control scenario in grid-generated turbulence and multi-jet burners.

As seen in Figure 2, at the lower frequency ($f_{AC}=100$ Hz) the plasma discharge is already uniformly ignited and it covers all the surface of the honeycomb at the exception of the holes and the conductive air-exposed electrode. At the highest applied frequency ($f_{AC}=2000$ Hz), all the cells of the system are fully powered with a strong light emission. A zoomed view indicates that the plasma extends from the edge of the air-exposed electrode up to the border of the hole where a brighter region forms a ring. The whole surface of this region is ionized and some strong filaments, connecting the edge of the active electrode to the borders of the hole, are visible regardless of the applied frequency. At the highest f_{AC} , air ionization can also be observed beyond the diameter of the hole confirming that the plasma extends up to a certain distance inside the holes.

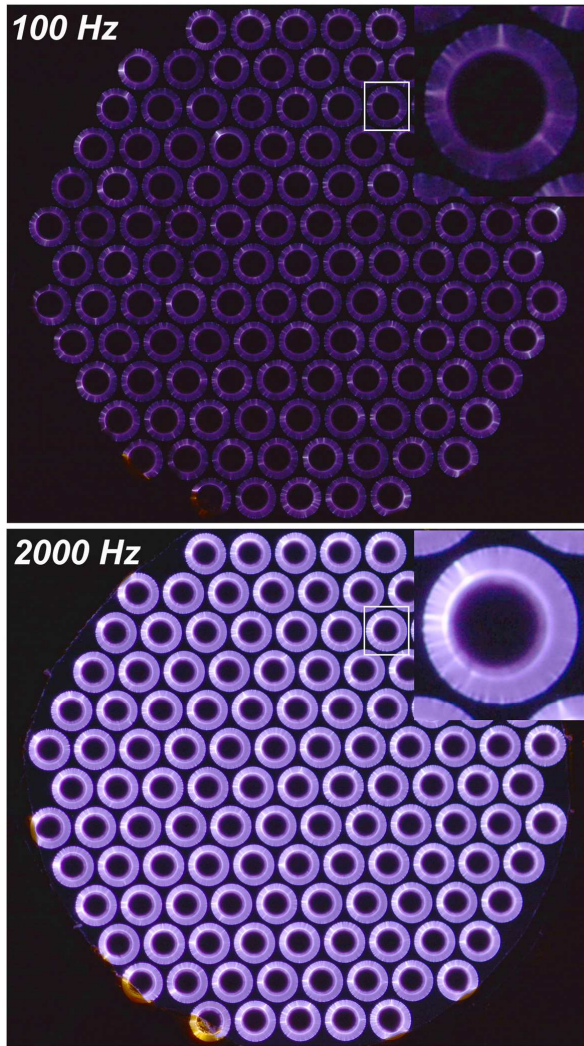


Figure 2: Front view of the plasma discharge for two f_{AC} (14 kV_{pp}).

In order to propose a brief description of the electrical characteristics of this particular discharge, the voltage and current time signals are recorded with a high-resolution oscilloscope (Lecroy HDO6054). The discharge current is measured by a shunt resistor (100Ω) connected to the grounded electrode. A typical trace of voltage and current time evolution is illustrated in Figure 3 for an applied voltage of 14 kV_{pp} and a frequency of 2000 Hz. This plot confirms that the honeycomb discharge behaves as a typical dielectric barrier discharge with two remarkable regimes. On one hand, numerous positive current peaks with amplitude of about 20-70 mA are observed during the positive-going cycle of the voltage due to the streamer propagation (positive discharge). On the other hand, the negative-going cycle

of the voltage results in small amplitude negative current peaks caused by a glow-like negative plasma regime. A measurement of the consumed electrical power indicates that a maximum consumption of 14.3 W is achieved when the actuator is operated at 14kV_{pp} and frequency f_{AC} of 2000 Hz.

As it was predicted by the temporal trace of the current, two plasma discharges form over one period of the AC cycle. In order to observe both positive and negative discharges, the front view visualizations by fast imaging have been performed (Figure 3). An EMICCD camera (Princeton PIMAX 4) with a 200 mm Nikkor objective and a Nikon teleconverter has been placed in front of the honeycomb to capture a zoomed region of 9×9 mm². The camera is gated according to the positive and negative-going cycles. The positive-going cycle of the voltage corresponds to a corona-like discharge covering the distance from the active electrode edges to the border of the holes. This discharge corresponds to some intense streamers with strong light emission (responsible for the high amplitude positive current peaks) superimposed on the current caused by the ion drift.

According to the ICCD images, only one streamer occurs per hole observed in the field of view. However, that is corroborated by a current peak analysis (Figure 3) showing that over 10 AC cycles, the mean number of positive current peaks is 121 ± 4 during one streamer period (data not shown). For the negative-going cycle of the voltage, the current trace evokes a glow regime. The fast imaging indicates that many straight filaments are initiated for this period of the voltage signal as in a conventional DBD [10] (with light intensity three times smaller than those observed during the streamer regime). They connect the edge of the active electrode to the border of the hole, several of them being observed per hole.

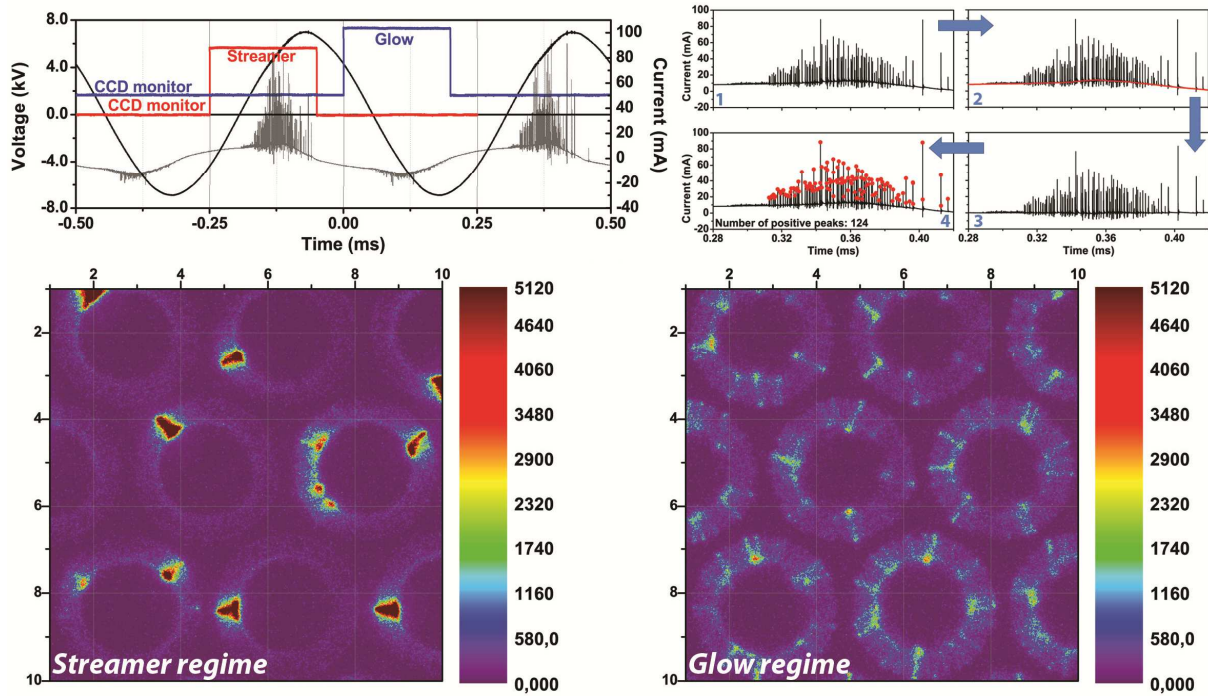


Figure 3: Time evolution of the total current through the honeycomb discharge, **current peak analysis** and front view of the plasma discharge by short time exposure (200 μ s) with ICCD camera. The voltage is 14 kV_{pp} and the frequency 2000 Hz.

The primary purpose of this new plasma discharge concerns about the active manipulation of turbulent jet flows. In order to identify the potential benefit of this system, it has been implemented in a circular open-air type wind-tunnel. A detailed description of a similar round free jet facility can be found in [15], with the only difference being the honeycomb plasma discharge placed at the exhaust of the convergent nozzle. The local velocity (U_0) at the center of one hole of the honeycomb plasma actuator is fixed at 10 m/s (Reynolds numbers of $Re_\phi=1970$). For a Reynolds number of about 2000, a round jet becomes turbulent very close to the exit as, for example, discussed and illustrated in [16]. At a distance of 30 mm on the centerline of the plasma device, pressure probe measurement indicates that the velocity (U_{0_core}) is reduced to 7.5 m.s⁻¹.

Flow visualizations are performed using a short-pulsed Nd:YLF laser (Terra PIV 527-100-M) synchronized with a fast camera (Photron SA-Z). This optical diagnostic is operated at 1300 Hz. Dielectric oil (Ondina 915) is atomized into fine droplets to permit the laser light scattering (particles with mean diameter of 0.36 μm , measured by an aerosol spectrometer). For each of the tests, a flow sequence of 5000 images has been recorded. The data processing on the raw images consists of computing the minimum intensity at each pixel location in all recordings and then of subtracting the minimum intensity from each images of the dataset. In a final stage, the averaged grey level of the 5000 images is computed. The images of the mean flow without plasma discharge for streamwise and cross-stream flow visualizations are presented in Figure 4. The mean flow visualizations indicate that the multi-jet quickly evolves as a single jet with a potential core whose length can be easily estimated. A virtual diameter, D , can also be defined from the flow images. The global jet at the exit of the multi-jet system corresponds to a virtual diameter D of about 28 mm (see Figure 4). In the initial region of the global jet, the individual jets can be observed up to a few centimeters and a significant deflection of the peripheral jets is revealed. Beyond this location, and in the inner part of the global jet, the individual jets interact with the others. In the present flow configuration, the jet column extends up to 165 mm. By considering the flow velocity U_{0_core} , the Reynolds number based on the virtual diameter is about 14000. The potential core of the global jet extends up to 5.6 D (with an uncertainty on its determination based on a grey level analysis of $\pm 0.2D$), a value in agreement with numerical and experimental results ($\sim 6D$) for a single turbulent jet [17, 18]. Finally, the present investigation demonstrates that multi-jet configuration rapidly evolves into a single jet due to deflection of peripheral jets towards the centerline of the device as in [6].

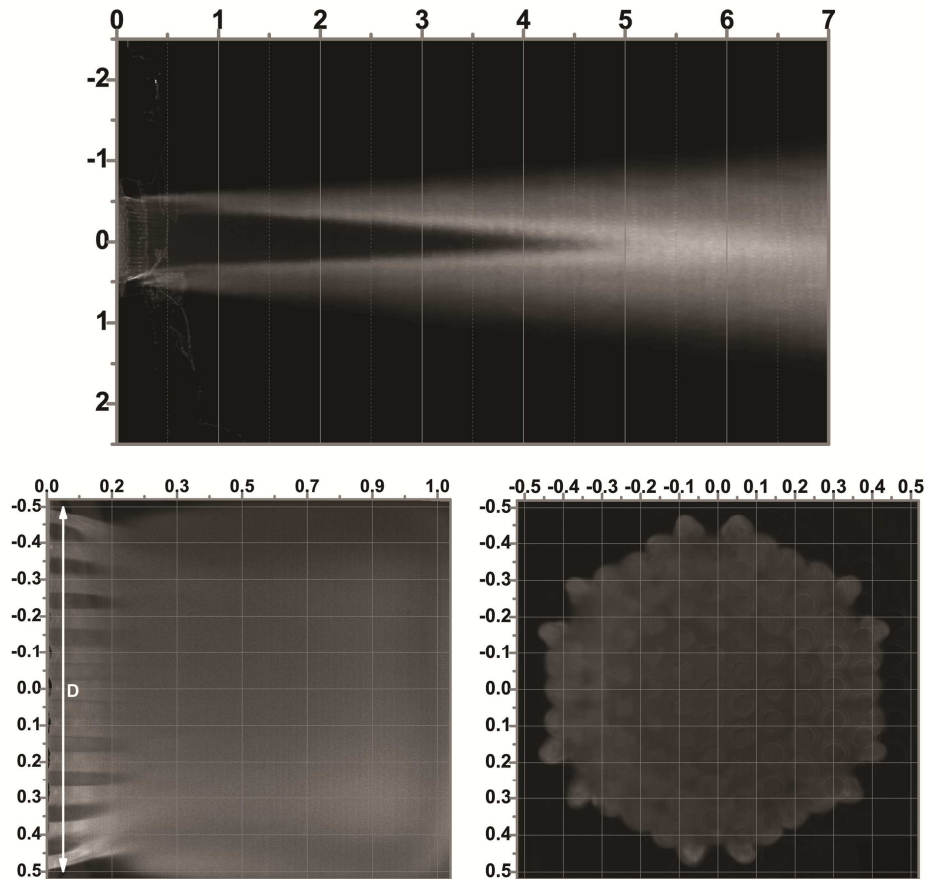


Figure 4: Streamwise (including a zoomed view of the initial region) and cross-stream visualizations of the mean flow downstream of the multi-jet plasma device (the actuator is turned off). Dimensions are normalized by the virtual diameter D .

The flow, in case of an actuation by the DBD plasma actuator at frequencies f_{AC} of 100, 500 and 2000 Hz, is shown in Figure 5. The far-field turbulence cannot be resolved, but the reduction in the potential core length of the jet can be observed because of a higher spreading rate of the annular turbulent shear layer developing at the periphery of the jet. Here, a maximal reduction of 30% is observed for a plasma discharge operating at $f_{AC}=100$ Hz (3.8D). The flow control mechanism cannot be elucidated by the present measurement system. However, for every hole, one can suspect that the produced ionic wind is mainly radially distributed and directed from the circular edges of the surface electrode to the center

of each hole as suggested by the intense light emission at the surface of the honeycomb. Moreover, ionic wind can also occur along the inner surface of the holes. Here, the flow produced by the discharges is supposed to promote a strong shearing in the initial region of the single jet issuing from each hole. Because, the produced ionic wind linearly increases with f_{AC} [7, 8, 9, 10], a better control effectiveness is expected for an excitation at $f_{AC}=2000$ Hz. Here, it is shown that the larger influence on the flow is obtained for low frequency forcing despite of a produced EHD force that is not maximized. One might expect to get much better results at lower f_{AC} (i.e., lower than 100 Hz). In fact, as for a round turbulent single jet [19], the flow issuing from the present multi-jet system is highly sensitive to the frequency of the periodic perturbations imposed in the initial region of the jet. In the present flow configuration, the most effective forcing at $f_{AC}=100$ Hz is close to the well-known best periodic forcing that excites the instability of the jet column mode or preferred mode of a turbulent jet [20]. Based on a forcing frequency of 100 Hz, the corresponding Strouhal number St_D (with $St_D = \frac{f \times D}{U_{0_core}}$) is $St_D=0.37$, a value in the 0.3-0.4 range reported many times in the literature [21]. Unfortunately, the present flow diagnostic is only qualitative and cannot provide detailed information regarding the flow control mechanism but the better influence for periodic forcing at $St_D=0.37$ clearly indicates that the control effect relates to an excitation of the instability modes of the jet column. This suggests that an actuation with a forcing frequency lower than 100 Hz would not be more effective.

For 2000 Hz, the ionic wind produced by the plasma significantly increases compared to the one at 100 Hz [7, 8, 9, 10]. However, only a minor influence is observed here. As for a round turbulent single jet, the flow issuing from the multi-jet system is highly sensitive to the frequency of the periodic perturbations imposed in the initial region of the jet. The Strouhal

number St_D (with $St_D = \frac{f \times D}{U_{0_core}}$) corresponding to a physical forcing at 100 Hz is $St_D=0.37$, a forcing condition close to the well-known best periodic forcing that excites the instability of the jet column mode or preferred mode of a turbulent jet [19].

Knowing that the use of ‘burst modulation’ is an effective method for maximizing the amplitude of the imposed periodic perturbations [10], this type of actuation is conducted for a sinusoidal waveform with voltage amplitude of 14 kV_{pp} and f_{AC} frequency of 2000 Hz, the actuator being turned on and off by a gate function operated at frequency f_{BM} (with 50% duty-cycle). The frequency f_{BM} imposed by the burst modulation ranges here from 5 up to 400 Hz ($St_D=0.018$ to 1.49). The potential core lengths estimated by grey level analysis and a few visualizations of the mean flow are introduced in Figure 5. This figure confirms that the thickness of the shear layer, its spreading rate and thus the length of the potential core are modified accordingly to the forcing frequency introduced by the burst modulation. For the worst cases, the length of the potential core remains similar to the one reported for the natural flow. However, a minima is found at $St_D=0.37$ ($f_{BM}=100$ Hz) for which the maximal reduction of the potential core length reaches approximately 40% by comparison with the natural flow. This result supports a control mechanism scenario related to an excitation of the jet column mode where forcing influence is primarily related to the frequency of the imposed perturbation rather than to its amplitude. This further confirms that continuous forcing at f_{AC} lower than 100 Hz would not be more effective. However, as already observed for the control of separated turbulent shear layer, the use of burst modulation instead of a continuous AC signal improves the influence of the discharge on the characteristics of the mean jet flow. Here, as for the continuous forcing mode, the reduction in the potential core is caused by a rapid growing of the annular shear layer and higher mixing rate is expected beyond the end of the potential core. The influence of the discharge on the isotropic character of the turbulent

flow field, on the Reynold stress components, on the integral length scales or on the decay law along the centerline of the global jet has to be explored by quantitative measurements in future investigations.

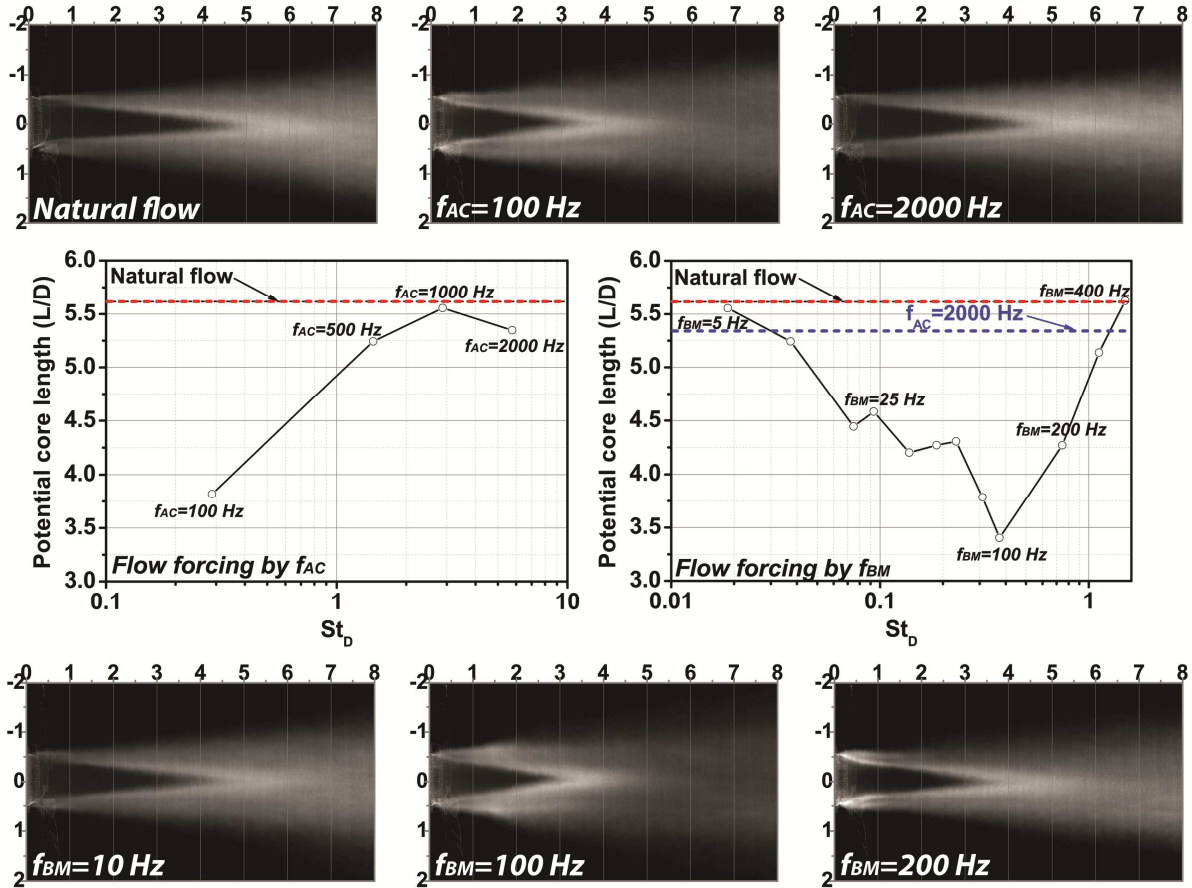


Figure 5: Streamwise fast visualizations of the flow downstream of the multi-jet plasma device and influence of St_D on the length of the potential core for continuous forcing (flow forcing by f_{AC}) and burst modulation (flow forcing by f_{BM}).

The present study has defined an original device dedicated to the enhancement of mixing mechanisms and the manipulation of turbulent flow. These preliminary measurements confirm the potential of this device. The reduction in the potential core length is significant (-40%) which suggests remarkable modifications in the far-field region. It is clearly shown that the plasma actuator can affect the spatial distribution of the mean flow fields. However, the question of an active manipulation of the turbulent scales and energy cascade by such actuator

is not solved here. A lot of studies by time-averaged and time-resolved measurements have to be conducted on this specific actuator. In particular, the response of a turbulent flow to a multi-frequency actuation will be investigated experimentally. The primary objective will be a precise control of the mixing-rates but it is expected that this device will help in emphasizing on certain length-scales of the turbulent flow to stimulate embedded small scale combustion processes.

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References

- ¹P.E. Roach, ‘The generation of nearly isotropic turbulence by means of grids,’ *Int. J. Heat Fluid Flow* **8**, 82-92 (1987)
- ²Q.F. Liang, Q.H. Guo, G.S. Yu, and F.C. Wang, ‘An experimental investigation on characteristics of individual flame and multi-jet flame,’ *Energy Sources* **35**, 1476–1485 (2013)
- ³S. Laizet and J.C. Vassilicos, ‘DNS of Fractal-generated turbulence,’ *Flow Turb. Combust.* **87**, 673-705 (2011)
- ⁴N. Mazellier, L. Danaila, and B. Renou, ‘Multi-scale energy injection: a new tool to generate intense homogeneous and isotropic turbulence for premixed combustion,’ *J. of Turbulence* **11** (2010)
- ⁵T. Boushaki, M.A. Mergheni, J.C. Sautet, and B. Labegorre, ‘Effects of inclined jets on turbulent oxy-flame characteristics in a triple jet burner,’ *Exp. Thermal Fluid Sci.* **32**, 1363-1370 (2008)

- ⁶S. Ghahremanian, K. Svensson, M.J. Tummers, and B. Moshfegh, 'Near-field development of a row of round jets at low Reynolds numbers,' *Exp. Fluids* **55**, 1789 (2014)
- ⁷E. Moreau, 'Airflow control by non-thermal plasma actuators', *J. Phys. D* **40**, 605 (2007).
- ⁸T.C. Corke, C.L. Enloe, and S.P. Wilkinson, 'Dielectric Barrier Discharge Plasma Actuators for Flow Control,' *Ann. Rev. Fluid Mech.* **42** (2010).
- ⁹Wang, J.-J., Choi, K.-S., Feng, L.-H. and Jukes, T.N., 2013. 'Recent developments in DBD plasma flow control', *Prog. in Aerosp. Sci.* **62**, 52-78 (2013)
- ¹⁰N. Benard and E. Moreau, 'Electrical and mechanical characteristics of surface AC dielectric barrier discharge plasma actuators applied to airflow control,' *Exp. Fluids* **55**, (2014)
- ¹¹J.R. Roth, 'Electrohydrodynamically induced airflow in a one atmosphere uniform glow discharge surface plasma,' 25th IEEE Int. Conf. Plasma Science, 1998.
- ¹²A. Mizuno, 'Generation of non-thermal plasma combined with catalysts and their application in environmental technology,' *Catalysis Today* **211**, 2-8 (2013)
- ¹³K. Shimizu, M. Blajan, and T. Kuwabara, 'Removal of indoor air contaminant by atmospheric microplasma,' *IEEE Trans. on IAS* **47**, pp. 2351-2358, 2011
- ¹⁴G. Comte-Bellot and S. Corrsin, 'Simple Eulerian time correlation of full- and narrow-band velocity signals in grid-generated, 'isotropic' turbulence'. *J. Fluid Mech.* **48**, 273–337 (1971)
- ¹⁵N. Benard, J.P. Bonnet, G. Touchard and E. Moreau, 'Flow control by dielectric barrier discharge actuators: Jet mixing enhancement,' *AIAA Journal* **46** (2008)
- ¹⁶S.J. Kwon, and I.W. Seo, 'Reynolds number effects on the behaviour of a nonbuoyant round jet', *Experiments in Fluids* **38**, pp.801–812, (2005)
- ¹⁷C. Bogey, and C. Bailly, 'A study of the influence of the Reynolds number on jet self-similarity using Large-eddy Simulation,' in *Direct and Large-Eddy Simulation VII*, Volume 13 of the series ERCOFTAC Series, pp 11-16, (2010)
- ¹⁸J. Mi, and G.J. Nathan, 'Statistical properties of turbulent free jets issuing from nine differently-shaped nozzles,' *Flow Turbulence and Combustion* **84**, pp. 583-606, (2010)
- ¹⁹S.C. Crow, and F.H. Champagne, 'Orderly Structure in Jet Turbulence,' *Journal of Fluid Mechanics*, Vol. 48, pp. 547–591 (1971)
- ²⁰K.B.M.Q. Zaman, and A.K.M.F. Hussain, 'Vortex pairing in a circular jet under controlled excitation. Part 1: General jet response,' *Journal of Fluid Mechanics* **101**, pp. 449-491 (1980)
- ²¹A.K.M.F. Hussain and K.B.M.Q. Zaman, "The 'preferred mode' of the axisymmetric jet", *Journal of Fluid Mechanics*, Vol. 110, pp 39- 71 (1981)