DEVELOPMENT AND CHARACTERIZATION OF A PULSED JET ACTUATOR BASED ON SONIC FLOW CONTROLLED BY PLASMA

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ABSTRACT

The modulation of a sonic flow in view of high authority actuator design is based on the increase of the temperature at a sonic throat with the help of a plasma discharge. Indeed, for a perfect gas, the flow rate being proportional to the inverse of the square root of the temperature at a constant settling chamber pressure, the jet flow rate should be able to be varied. In view of flow control actuator design, the frequency is then no limited by any mechanical constraint. The discharge can be either continuous or pulsed at high frequencies. The influence of the settling chamber pressure and electrode gap distance have been investigated. For an aerodynamically steady actuation, the jet flow rate can be reduced down to 70% of its nominal value (30% of flow rate reduction), the best effectiveness being obtained with a DC discharge. The temperature increases from 290K to up to 650K for sonic regime. The speed of sound (and then the jet velocity for sonic conditions) is increased by a factor of 1.5 when the plasma is operated Transient phenomena are evidenced by high speed Schlieren. A low velocity version is obtained with a channel added downstream In this case, a modulation of the subsonic (37m/s) jet velocity is observed, with a max velocity of 60 m/s with a large increase of the velocity fluctuations when the plasma is activated. This actuator has several interests when compared to conventional pulsed jets: no mechanical device, high frequency response. The pulsed jet contains high velocity (by a factor of 1.5), high temperature (by a factor of 2) impulses with lower flow rate and high turbulence levels.

INTRODUCTION AND EXPERIMENTAL DESIGN

In most cases, active flow control requires high frequency actuators. Particularly for high velocity (eventually supersonic) flow control configurations, high frequency and high authority (in terms of flow rate) are required Cattafesta and Sheplak (2011), Gatski and Bonnet (2014). Some recent developments for supersonic flow control can be found in Emerik *et al.* (2014), Hupadhyay *et al.* (2016). Usual pressurized flowing jets monitoring through mechanical valves have a high potential but they are limited in terms of frequency (up to typically a few hundred of Hz).

In this project, we developed a new flowing jet driven by a plasma discharge. The principle is to increase the temperature at a sonic throat located upstream of the jet exit with the help of a plasma discharge located at the throat (Fig. 1). For a perfect gas, the flow rate being proportional to the inverse of the square root of the temperature at a constant settling chamber pressure, the jet flow rate can be varied. Although using a plasma discharge, the present method is then quite different from the Spark Jet described by Emerik *et al.* (2014) in which a continuous flow of fresh air is introduced. Indeed, in this operation, the Spark Jet is associated to an extra air for cooling the cavity that is otherwise heated by the spark.

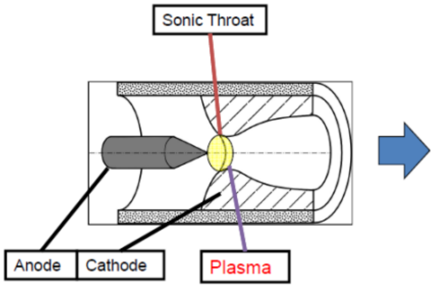

Fig.1. Schematic of the plasma pulsed jet actuator.

In a first part of the present study we quantify the maximum mass flow reduction that can be obtained by different types of discharges ignited in the vicinity of the sonic throat. In a second part, we will characterize the flow under the plasma activation. Three different power supplies are used (Fig. 2). The first power supply is a DC one, Technix SR15 P 3000. In this case, the discharge is either switched off or switched on and both of the cases are compared. The second power supply is composed of the DC power supply followed by a high voltage switch transistor Behlke, allowing us to pulse the discharge with small duration high current pulses. Finally, the last study deals with a pulse discharge with long duration small amplitude current pulses. As far as the flow itself is concerned, two parameters have been varied, namely the settling chamber pressure and the distance between the electrodes. The aerodynamic effects are observed by considering the flow rate measured by a direct flow meter and the temperature of the jet measured by a 1 mm encapsulated thermocouple.

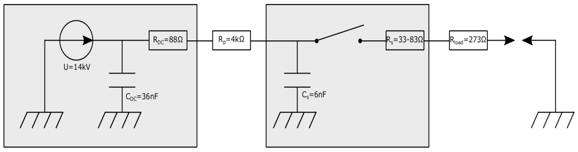

Fig. 2. Schematic of the electrical setup.

In the present configuration, a single 0.95mm diameter, 3mm long cylindrical hole is used as shown on Fig. 3. The figure also shows a view of the plasma operating in a steady-state mode.

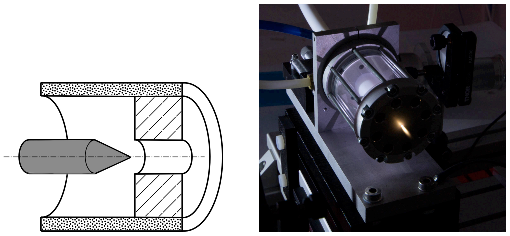

Fig. 3. Schematic of the demonstrator and view during the plasma discharge.

In order to be able to provide a lower velocity actuator, we install a secondary tube downstream of the sonic throat. This channel is 3mm in diameter and 20 mm long. Then, the output velocity is subsonic (≈ 40 m/s). This configuration restricts the primary objective of defining an actuator for high speed (including supersonic) flows, but in this configuration it can be used for low velocity applications.

The settling chamber pressure can be adjusted from 1.4 up to 5 bar (the theoretical minimum pressure for sonic condition being 1.893 bar). The electrical characterization of the system is not given here, the main focus being on the discharge effect on the flow modulation. Details on the electric data can be found in Acher *et al* (2016).

EXPERIMENTAL RESULTS

We performed a parametric study of the different parameters of the device. Both electrical and geometrical parameter effects are investigated with the secondary tube, i.e. for the subsonic jet configuration. In a second part, we present preliminary results of the dynamic of the flow generated by the device in the sonic jet configuration.

Parametric study for subsonic jet configuration

We introduce the parameter $\Gamma = Q\sqrt{T}/P$, where Q is the flow rate measured from the settling chamber characteristics, T is the total temperature and P the pressure in the settling chamber. This parameter should be constant when the flow is sonic at the throat (Γ = 2.8 10^{-8} m² under the present conditions). Fig. 3 shows the evolution of this parameter. From the figure, it can be observed that the flow rate follows the isentropic theory for the natural as well as for the plasma actuated flows (Thompson, 1972).

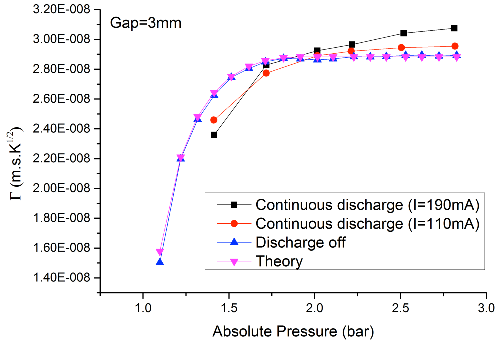

Fig. 3. Evolution of the parameter Γ (Gap 3 mm).

Figure 4 shows the air jet temperature T measured 2 mm downstream of the subsonic jet exit, and the corresponding thermal power P_{th} versus discharge power P_d for several pressure values in the DC mode. First, one can observe that both quantities increases nearly linearly with the power injected by the discharge to the flow. Secondly, the jet temperature reaches about 650°K for P = 2 bar and P_d = 200 W.

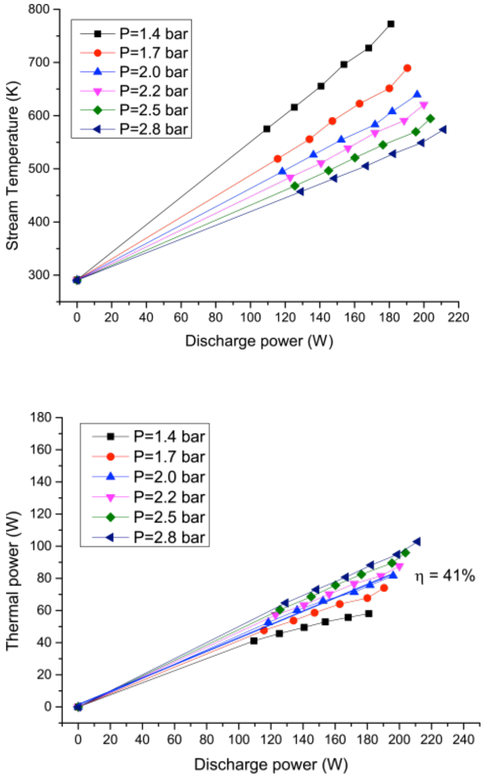

Figure 4. Evolution of the temperature (top) and thermal power (bottom). Gap 3 mm.

The thermal conversion efficiency η, defined as the ratio between the thermal power and the discharge electrical power, increases from 32−37% at 1.4 bar (not a sonic condition) to 48−50% at 2.8 bar, with a mean value equal to 41% for P = 2 bar.

As shown in Fig. 5, the value of the gap between both electrodes is important if the discharge power is considered.

The reduction of the flow rate being the major goal of the study, the results are plotted in Fig. 6 in terms of discharge power and temperature ratios. The results are compared with the theoretical law corresponding to a pure thermal effect $Q/Q_0 = \sqrt{T_0/T}$. First, one can see that a flow rate reduction down to 70% can be achieved. , Moreover, it seems that a better efficiency can be expected for a high current pulse discharge.

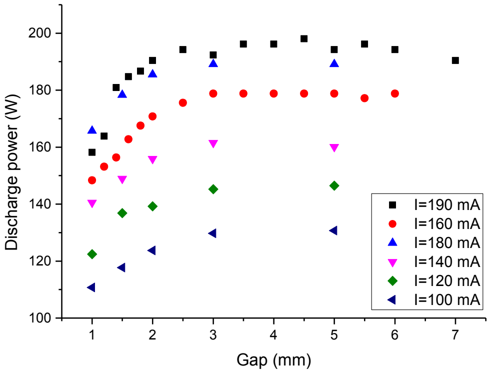

Fig. 5a. Influence of the electrode gap (DC power supply) (P =2 bar).

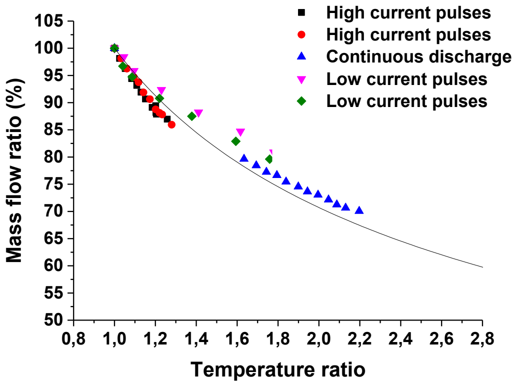

Fig. 6. Mass flow ratio versus temperature ratio for Gap = 3 mm, P = 2 bar.

Flow characterization

Unsteady effects of the sonic jet configuration.

The effect of the plasma discharge is here observed from conditional instantaneous Schlieren visualization. Figure 7 provides some views of the flow at the nozzle exit when the discharge is switched on. The synchronization between the discharge and the CCD camera of the Schlieren system allows us for a temporal description of the flow modifications provoked by the discharge at the sonic throat. In Fig. 8 is shown the flow when the discharge is switched off. When the plasma is applied, a pressure wave is emanated (Fig. 7) and is visible up to 0.06 ms. A pocket of hot fluid is clearly visible and spreads downstream. Initially the convection velocity is close to the local speed of sound. Farther downstream, the hot bubble expands laterally and the propagation velocity corresponds to the mean jet velocity. As an example, it requires about 0.04 10^{-3} s for the hot fluid to reach 1 cm downstream of the exit.

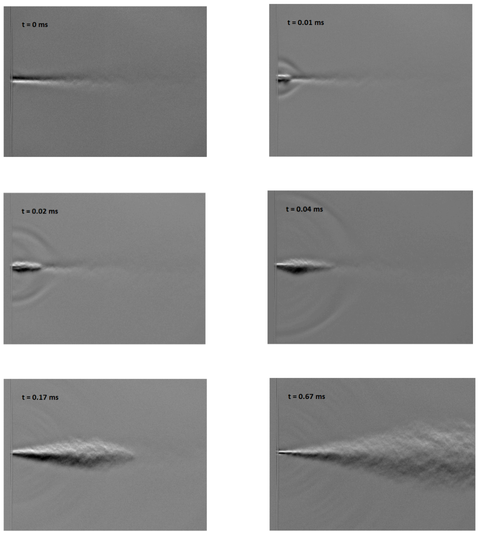

Figure 7. Flow visualizations during the initial phase for several time delays (in ms). Vertical frame scale 27mm.

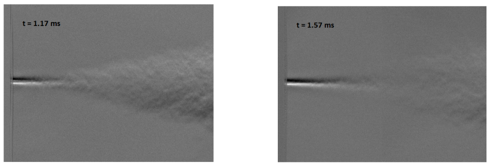

Figure 8. Flow visualizations when the discharge is switched off (in ms). Vertical frame scale 27mm.

Mean velocity of the subsonic jet configuration.

We perform preliminary LDV measurements with one component device (λ_i = 4.37 µm, measurement volume 77 µm x 1.26 mm) operating with a DANTEC BSA F/P 80. The flow is seeded inside the settling chamber with 1 µm diameter oil droplets. For practical purposes linked to the spatial resolution of the LDV, we cannot process to measurements with the 1 mm exit diameter of the jet and we concentrate the measurements with the 3 mm diameter added channel (subsonic jet).

Figure 9 presents the evolution of the axis velocity observed at 2 mm downstream of the exit of the added channel. The velocity ratio is typically 1.5. This value corresponds to a temperature increase of 2.25. This ratio corresponds to the results given on Figure 4 with a maximum value of 650K when compared to the initial temperature of 290K.

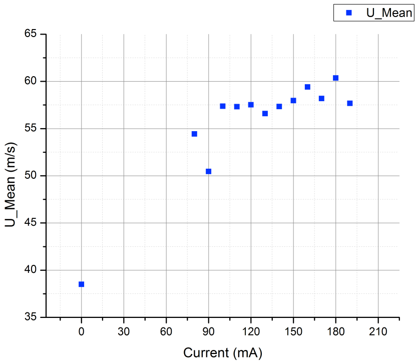

Figure 9. Evolution of the axis mean longitudinal velocity measured 2 mm downstream of the exit plane.

The RMS values obtained on the jet axis are given in Figure 10. A large increase of the initial values is observed, the effect of the discharge corresponds to 2 times higher fluctuations, this being in agreement with the Schlieren visualizations showing strong perturbations of the jet.

It should be noticed that for the transonic configuration, i.e. without the added cannel, the mean exit velocities (not measured by LDV but estimated here by Pitot tube) are in the same ratio, evolving from 300 m/s without plasma discharge to 450 m/s when the plasma is activated.

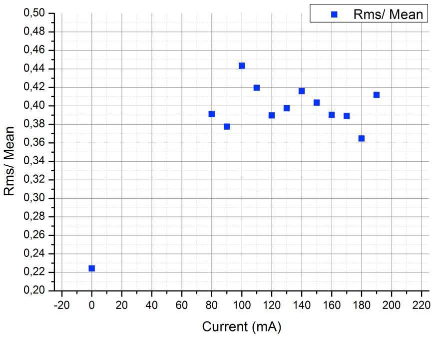

Figure 10. Evolution of the axis values of the relative longitudinal velocity fluctuations.

CONCLUSION

We present a new method to control a sonic flow by introducing an electric discharge at the throat. The effect of the plasma is essentially a thermal one. Reduction up to 30% of the mass flow rate can be obtained, opening new perspectives for high authority, high frequency actuators in view of active flow control without any mechanical part. The transient phenomena observed when the plasma is activated are particularly complex and can have further impacts for fundamental understanding of compressible flows and possible other applications in high speed flows. For a lower velocity configuration, corresponding to subsonic use, a channel has been added. In this case the velocity ratio of 1.5 is observed when the plasma discharge is activated. In this case, the turbulence level is increased by a factor of 2. This actuator can then be applied to high velocity (supersonic regimes) or lower velocity flows.

This actuator has several specific characteristics when compared to conventional pulsed jets: no mechanical devices, high frequency response. We demonstrate that the jet velocities domains range from 40 m/s up to transonic regimes. With a lower flow rate when the plasma is switched on, the pulsed jet contains high velocity (by a factor of 1.5), high temperature (by a factor of 2.3) and high turbulence impulses. These characteristics provide new capabilities of efficient perturbation of flows in view of their control.

The next studies will include the direct high frequency drive of the high voltage output in order to include the control jet as actuator for closed loop strategies.

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