Modification of a Rarefied Supersonic Flow over a Flat Plate Using an Electrical Discharge

E. Menier, E. Depussay, L. Leger, V. Lago and J.C. Lengrand

Laboratoire d'Aérothermique, CNRS, 1C av. de la recherché scientifique, 45071 Orléans Cedex 2, France

Abstract. A description of the experiments carried out at the Laboratoire d'Aérothermique in the field of plasma flow control is given in this paper. The interaction of an electrical discharge created above a flat plate and a rarefied and supersonic flow is studied. Emphasis is put on the description of the experimental setup and a few preliminary results are given.

Keywords: Flow control, Plasma, Supersonic, Rarefied.
PACS: 47.85.L-, 47.50.Ef, 47.65.-d.

INTRODUCTION

Flow control with help of plasma actuators is a growing field of research. In particular, electrical discharges created around bodies have been studied both in subsonic [1] and supersonic [2] conditions. Modifications of the flows have been observed, for example, a reduction of the drag [3] or even an elimination of the shock wave [4]. Explanations of phenomena as well as some results are controversial. For sure, in subsonic conditions the ionic wind plays a role; that is to say, the transfer of momentum between the accelerated ions (accelerated by the electric field) and the neutral induces a secondary flow so that the main flow can be modified. Results have been observed for speeds up to 75 $m.s^{-1}$ [5]. In supersonic, it is more complicated because this transfer of momentum seems too low to explain the modifications observed. The electrical discharge produces heating of the flow, for some authors, the non uniformity of this heating is the only reason of the flow modification [6]. Anyway, some results dependants of the polarity of the electrodes [7] seem to be unexplainable only by a thermal effect. An activity in this field of research is born recently at the Laboratoire d'Aérothermique, the work is both numerical and experimental; this paper focuses on the experimental part.

EXPERIMENTAL SETUP

Wind Tunnel Description

Every experiment is performed in the wind tunnel MARHy (previously known as SR3) which delivers rarefied supersonic and hypersonic flows. It runs in continuous bias a powerful pumping group. Using the appropriate nozzle, the range of conditions given in Table 1 can be achieved. Please read [8] for a full description of the facility.

TABLE 1. Any Working Conditions of the MARHy Wind Tunnel

Po (Pa)	To (K)	Mach	Re (cm^{-1})	T (K)	U ($m.s^{-1}$)	λ (mm)
21	300	2	25.6	167	518	0.82
63	300	2	77	167	518	0.27
400	300	4	176	71	678	0.22
1200	300	4	527	71	678	0.07
3.5×10^5	1100	20.2	284	13.3	1503	0.67
10×10^5	1100	20.0	835	13.6	1502	0.23
120×10^5	1300	20.5	7250	15.3	1634	0.0.

Aerodynamic conditions

A Mach 2 nozzle is mounted in the wind tunnel for these experiments. It has been designed in order to work with a pressure equal to 63 Pa in the stagnation chamber and a static pressure of 8 Pa in the experiment chamber. Then, using the isentropic relation for the expansion of ideal gases in nozzles, all the macroscopic quantities on its axis can be calculated. They are given in the Table 2.

TABLE 1. Flow parameters.

Stagnation conditions	Flow conditions	
p_o = 63 Pa	p_e = 7.9 Pa	Ma_e = 2
T_o = 300 K	T_e = 163 K	$\mu_e = 1.1\times10^{-5}$ Pa.s
$\rho_o = 7.44\times10^{-4}$ kg.m^{-3}	$\rho_e = 1.71\times10^{-4}$ kg.m^{-3}	λ_e = 0.375 mm
	V_e = 511 m.s^{-1}	$q_m = 3.34\times10^{-3}$ kg.s^{-1}

Measurements of total pressure at the exit of the nozzle with a Pitot probe are performed in order to characterize the supersonic flow. A value of 45.7 Pa is measured on the axis; it leads to an experimental Mach number of 1.99. The size of the uniform core, defined like the area where the total pressure is constant is also measured. For that purpose, the jet exit is scanned by the tube in the radial direction. The diameter of the uniform flow is about 14 cm.

Test Model

The model under investigation is a flat plate with a sharp leading edge. Its dimensions are given in Figure 1. The plate is provided with two aluminum strips simply glued on it. They act as electrodes, one is linked to a power supply and the other one is linked to the mass of the building. The test model was first in Plexiglas but it was deformed or even burned when a potential was applied. Thus, first physical evidence is that a part of the electrical power dissipates (heats) in the plate. Then a plate in quartz which is more resistant to heating is used. Symmetric electrodes, 35×80 mm² each are used; the space between them is equal to 20 mm.

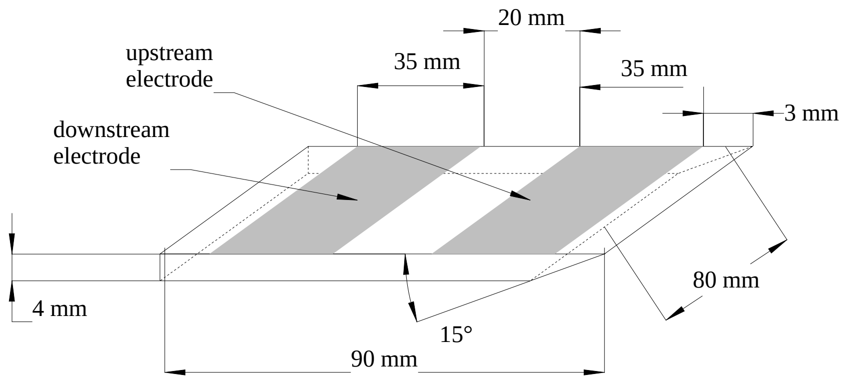

FIGURE 1. Drawing of the model and electrodes.

Electrical Power

As stated before, the gas is ionized using an electrical discharge. The source of power that is used here is a DC power supply by Spellman. Either a negative or a positive high voltage can be applied, up to |15| kV, it delivers a maximum current of 400 mA, if this value is exceeded, the device stops automatically. An indicator integrated to the power supply provides the value of the voltage and mean intensity delivered with a precision of 10 V and 1 mA respectively.

Diagnostics

A Pitot probe is used for aerodynamic measurements. Because of the presence of the electrical discharge, it is made of glass instead of metal. The tube has a 6mm outer diameter and 1 mm thick. It is link to an Mks Baratron capacitance manometer which covers a range from 0 to 133 Pa with an accuracy of 1.33 Pa. No rarefaction effect is taken into account. Indeed, the correlation parameter the most commonly used is order to quantify the viscous effect due to low pressure is:

$$\mathrm{Re}_2\left(\frac{\rho_2}{\rho_1}\right)^{\frac{1}{2}}$$

Where Re_2 is the Reynolds number calculated behind the shock front and based on the inner diameter of the tube and ρ_2/ρ_1 is the ratio of density downstream to upstream of the shock front. In the present conditions, a value of the correlation parameter of 48.4 is found. Regarding [9] the ratio between the measured pressure and the real pressure is very close to 1. A three components displacement system allows moving the probe anywhere above the plate.

Information on temperatures is of primarily importance in this kind of problems. Measurements with an infrared camera are under preparation; anyway, from now thermocouples are used. One is glued along the Pitot probe and one is maintained 1 mm under the flat plate.

Results obtained with the following diagnostics won't be produced in this article but in order to have a full description of the experiment, they are quickly described. A strain gauge is mounted on the support of the plate in order to measure the force applied to the system in the longitudinal direction. For the plasma characterization, a spectrometer allows determining existing species and rotational and vibrational temperatures and an electrostatic probe allows determining electron density and local electric field.

The system: plate, Pitot probe and strain gauge are represented on figure 2.

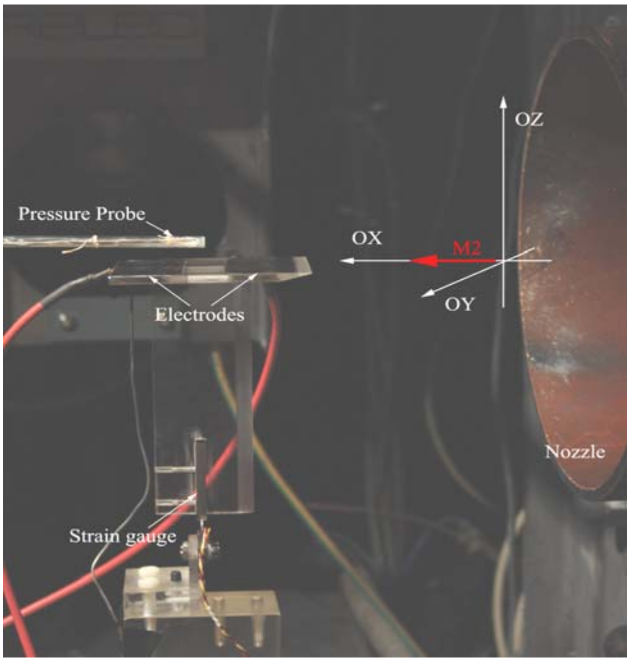

FIGURE 2. Picture of the experiment.

EXPERIMENTAL RESULTS

Preliminary Measurements

In order to characterize the flow, Pitot probe measurements above the plate are performed. Pressures in the reservoir and the experiment rooms are set to their nominal values (see table 2) and air is taken from the operating room. This experiments are confronted with a numerical simulation of the same configuration [10], as shown in figure 3, the agreement is correct.

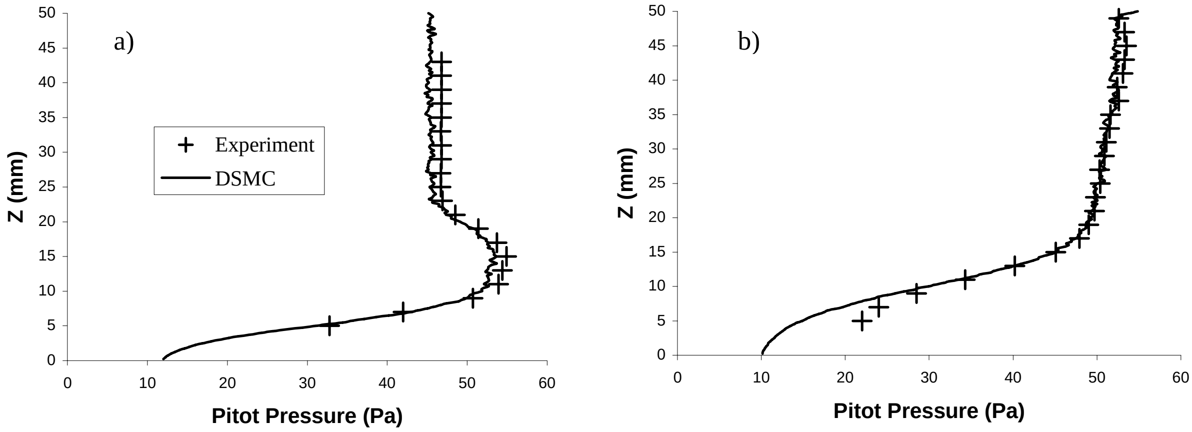

FIGURE 3. Pitot probe measurements compared to simulation a) at 2 cm from the leading edge, b) at 6 cm.

The time response of the probe is not null, especially close to the plate. Figure 4 shows the Pitot pressure versus time. The tube moves and in the same time, acquisition of the pressure is done at 1 Hz. The first part of the curve represents the pressure when the tube is at 5 mm above the plate (Oz axis), it stands there since a long time and the pressure is well established, then the displacement starts and takes the tube at 10 mm. After the probe is arrived at this location, the pressure still takes time to stabilize; about 20 seconds have to be waited before the measure to be acquired.

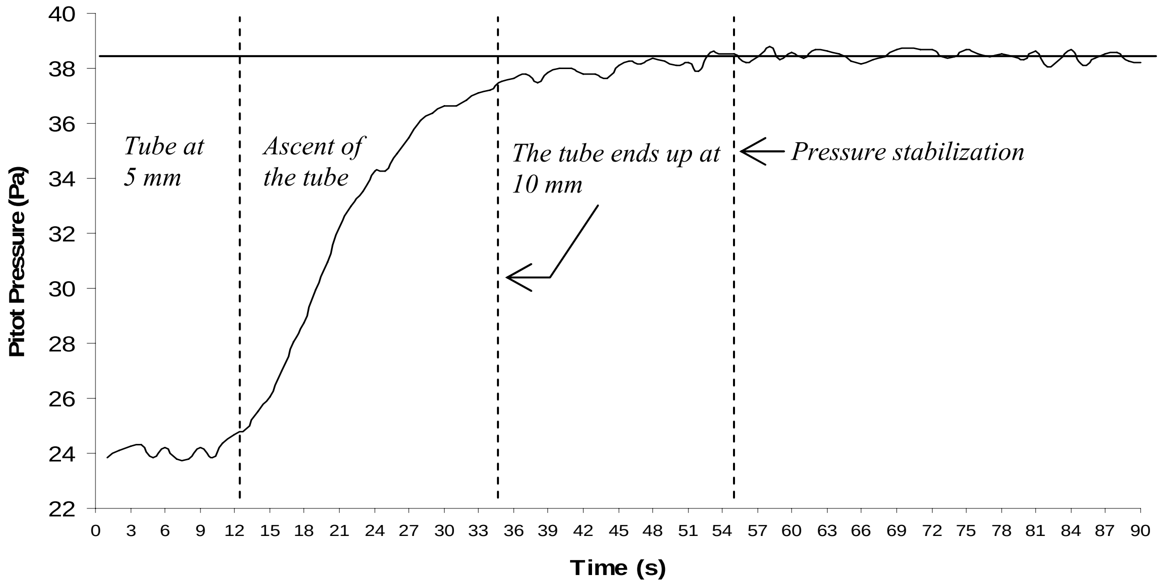

FIGURE 4. Pitot pressure versus time. The displacement takes the tube from its initial position (5 mm above the plate) to its final position (10 mm above the plate).

Measurements with Discharge

The model described in the first part is used. The first important result is that when a positive voltage is applied to one or the other electrode, the discharge is completely unstable, sparks appear everywhere in the wind tunnel and the mean current delivered by the power supply varies a lot. Thus a negative potential is applied, the discharge is then stable, homogeneous above the active electrode, the dominant color is violet. The Pitot tube is positioned at 10 mm above the plate and 48 mm from the leading edge, in the middle of the inter electrodes space. The discharge is switched on, as time goes on, temperatures of the Pitot probe's thermocouple, of the plate's thermocouple and the

Pitot pressure are recorded and given in figure 5. Potential is applied to the upstream electrode and time t=0s corresponds to the discharge ignition. Voltage applied is -1000 V and the mean current is 25 mA.

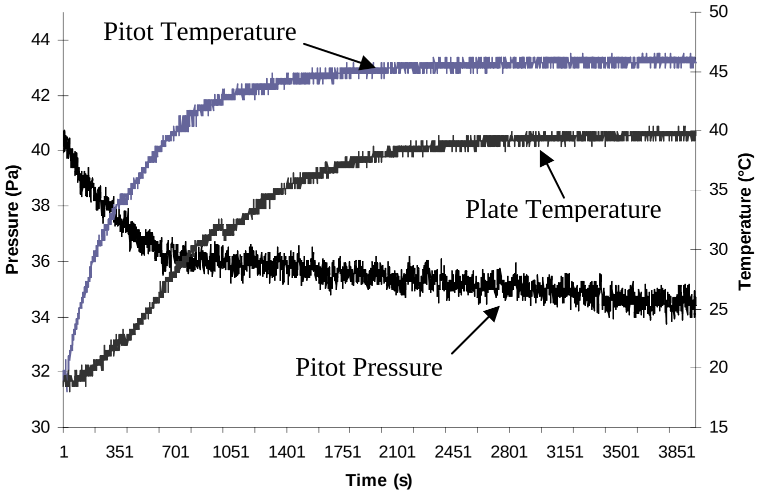

FIGURE 5. Recordings in time of the Pitot sensor, of the thermocouple glued on the Pitot tube and of the thermocouple which lies 1 mm under the plate.

Heating of the plate and of the probe occurs, in the same time, Pitot pressure is decreasing. A change in the Pitot pressure is observed. Another measurement is done in order to check if the temperature of the tube influences its pressure: Pitot probe is moved at 20mm above the plate, the discharge being still on, after equilibrium in temperature of the tube is reach at this location, discharged is switched off. The Pitot pressure and temperature are still recorded as time runs. Figure 6 shows that the Pitot pressure increases quasi instantaneously and remains constant as the Pitot temperature is decreasing. Thus Pitot pressure does not seem related directly with the temperature of the probe itself.

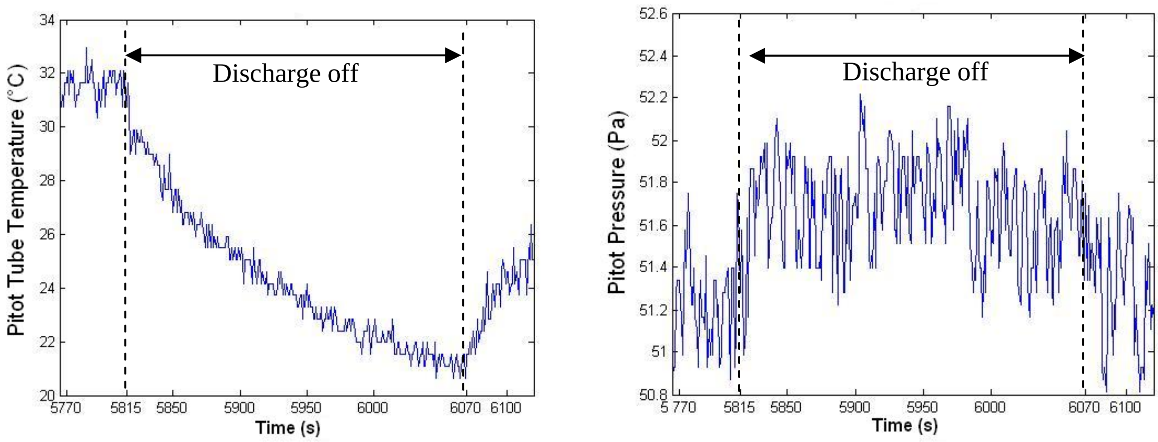

FIGURE 6 . Recording of the Pitot temperature (left) and pressure (right) in time. First the discharge is on, it is turned off at t=5815 s and switch on again at t=6070 s.

The next measurements presented are complete Pitot vertical profiles at 48 mm from the leading edge, that is to say in the middle of the inter electrodes space. First a profile without discharge is assessed, the Pitot starts at five 5mm above the plate, it is moved 5 by 5 mm; each time equilibrium in pressure is waited and the measure is acquired. Then the tube is taken back at its initial position and the discharge is switched on, equilibrium in temperature is waited for (like in figure 5). Then the same process as before is repeated, measurement are taken every 5 mm. This experiment was first performed for a potential applied upstream (U=-1060V, I=27 mA) and then for a potential applied downstream (U=-1240V,I=23mA). That is to say the two experiments are done with the same power of 28.5 W. Results are drown in figure 7. A change is seen in the Pitot pressure profiles. It is clear in the case when the upstream electrode is active, less evident in the other case.

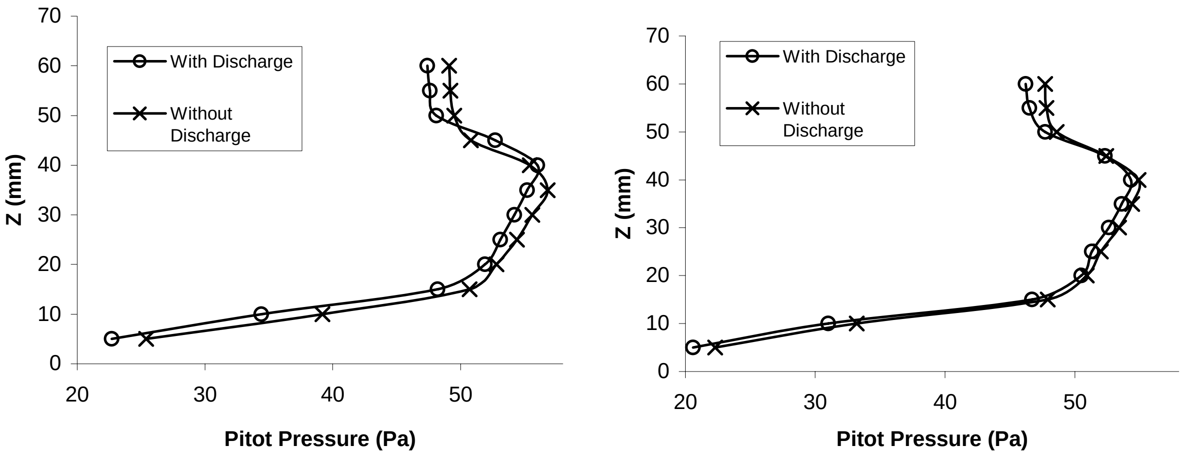

FIGURE 7. Pitot pressure versus distance above the plate. On the left: upstream electrode active, on the right: downstream electrode active.

CONCLUSION

The influence of an electrical discharge created above a flat plate on a supersonic rarefied flow is studied. The experimental configuration as well as first results has been presented. The discharge is stable, luminous and glows above the active electrode. It was checked that the heating of the Pitot tube by the discharge does not disturb the measurement of the stagnation pressure. Heating of the plate occurs as runs the discharge and in the same time, Pitot pressure decreases – at least when it is positioned at 10 mm above the plate. These two events could be linked. Full vertical Pitot tube profiles above the plate have then been presented. When the voltage is applied on the upstream electrode, a thickening of the boundary layer is clearly observed compare to a non discharge configuration. When the potential is applied downstream, the effect is less pronounced, there is a decreasing of the Pitot pressure at every location. Additional measurements involving more power are in progress. It has to be confirmed but the strain gauge seems to measure either an effect of drag reduction or increase depending on the polarity.

ACKNOWLEDGMENTS

This work was supported by the Region Centre.

REFERENCES

1. E. Moreau, L. Leger and G. Touchard, “Effect of a DC surface corona discharge on a flat plate boundary layer for air flow velocity up to 25 m/s” *Journal of electrostatics* **Vol 64**, pp 215-225, 2006.
2. P. Bletzinger, B.N. Gangly, D. Van Wie, A. Garscdden, “Plasma in high speed aerodynamics” *J. Phys.D: Appl. Phys.***Vol 38**, 2005.
3. S. Leonov, V. Bityurin, N. Savischenko, A. Yuriev, V. Gromov, “ Influence of surface electrical discharge on friction of plate in subsonic and transonic airflow” *AIAA paper n°2001-0640, 2001*.
4. D. Bivolaru, S.P. Kuo, “Aerodynamic modification of supersonic flow around truncated cone using pulsed electrical discharges” *AIAA J.* **Vol 43**, N°7, July 2005.
5. D.F. Opaits, D.V. Roupassov, S.M. Starikovskaia, A. Yu. Starikovski, I.N. Zavialov, S.G. Saddoughi, “Plasma control of boundary layer using low temperature non equilibrium plasma of gas discharge” *AIAA paper n°2005-1180*, 2005.
6. R.B. Miles, S.O. Macheret, L. Martinelli, R. Murray, M. Shneider, Yu.Z. Ionikh, " Plasma control of shock waves in aerodynamics and sonic boom mitigation” *AIAA paper n°2001-3062*, 2001.
7. V.A. Bityurin, A.I. Klimov, “Non-thermal approach in plasma aerodynamics” *AIAA paper n°2001-0348*, 2001.
8. V. Lago, E. Depussay, P. Lasgorceix, A. Lebehot, J.P. Martin, “The experimental facilities at Laboratoire d’Aerothermique” *24th International Symposium on Rarefied Gas Dynamics, edited by M. Capitelli, American Institute of Physics, 2005, pp.1337-1340*

9 J. allegre, M. Raffin, “Techniques expérimentales liées à l’aérodynamique à basse densité” *AGARDographie N° 318(Fr).*

10 E. Menier, J.C. Lengrand, E. Depussay, V. Lago, L. Leger, “Direct Simulation Monte Carlo Method Applied to the Ionic Wind in Supersonic Rarefied Conditions *AIAA paper n°20061-3343*, 2006.