Laser-Doppler velocimetry measurements in a plasma discharge

by

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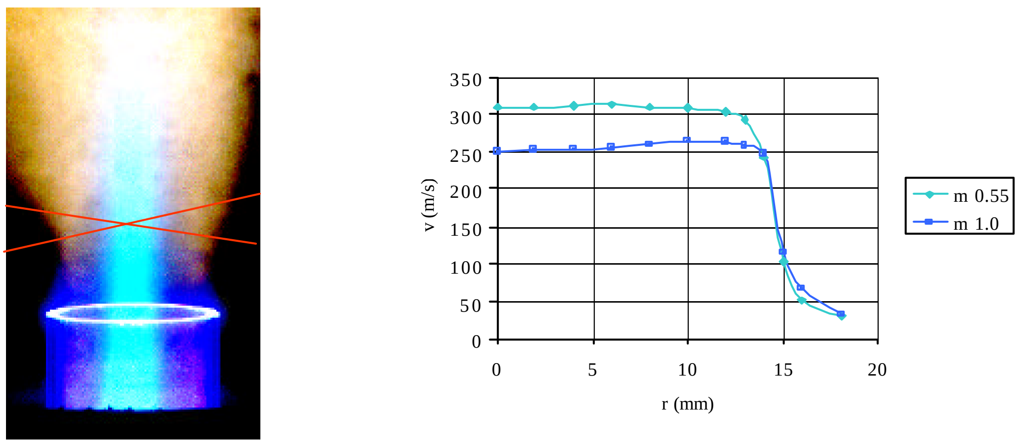
ABSTRACT

Plasmatron facilities are used to generate high enthalpy flows to test Thermal Protection System (TPS), of space vehicles, in planetary re-entry conditions. Such flow has to be accurately characterized in order to assess these tests based on the concept of local heat transfer simulation.
To this aim, the practical adaptation of laser-Doppler velocimetry has been examined for the high temperature of the plasma flow, and the severe environment of an Inductively Coupled Plasma (ICP) torch. This measurement technique has been installed on the 15 kW VKI Minitorch facility operating with air plasma. Interference filter has been placed to remove the emission of the plasma discharge. The particle behaviors in a plasma flow have been inspected in order to determine criteria to select the convenient seeding particles. The seeding generation and the transportation of solid particles have been checked for the powder used. With SiO2 and Al powder, a classical LDV set-up, used with forward scattering, appeared to be suitable for the measurements in the plasma flow conditions. Velocity measurements in the plasma jet have been performed for typical operating conditions of the VKI Minitorch facility. The velocity profiles have been measured 20 mm downstream from the torch exit, for static pressure of 50 hPa and 200 hPa in the test chamber. The characterization of the flow field in the discharge region, for the same plasma conditions, is also presented.



(a) (b)

Fig.1. LDV measurement in an air plasma jet

a) Picture of an air plasma jet seeded with Al particles (F ~ 1mm)

(The traces of the laser beams have been artificially intensified for their visibility on the picture)

b) Velocity profiles of an air plasma jet 20 mm downstream from the torch exit

(Power: 3.6 kW, static pressure: 50 hPa, mass flow: 0.55 g/s and 1.0 g/s)

1. INTRODUCTION

Re-entry flight paths followed by space vehicles as they descend into planetary atmospheres lie in the hypersonic regime, characterised by the presence of very strong shock waves. The deceleration of the flow produces tremendous heating, mainly to the leading edge and nose regions of the vehicle. Simple calculations easily show that the temperature behind the shock can be as high as 6000 K for Earth re-entry from orbit (Bottin and Carbonaro, 1997). This goes to 10000 K for lunar retum paths. As a result, very high heat flux rates are experienced by the spacecraft and suitable Thermal Protection Systems (TPS) must be used to protect the vehicle and its crew from certain destruction. In order to reliably assess the performance of TPS materials, testing must be done on Earth in high-enthalpy facilities capable of reproducing the severe heat conditions of reentry, with run times of the order of half an hour or more. A numbers of plasma test facilities, in which the temperature of the flow reaches typically 10,000 K, have been built over the past three decades for such aerospace applications (Smith et al., 1998). From 1995 to 1998, the European Space Agency together with the Belgium Federal Office for Scientific, Technical and Cultural Affairs sponsored the construction of a 1,2 MW plasmatron at the Von Karman Institute (Bottin et al., 1997). It combines the advantages of Inductively Coupled Plasma (ICP) torches, for high purity flow, with those of a new generation of high frequency generators including a solid state MOS inverter oscillator, for high generator efficiency. This facility is designed to test thermal resistance and catalycity effect of TPS samples which are placed in the plasma jet (figure 2). The goal of such tests is to simulate the local heat transfer of the re-entry conditions in order to allow an extrapolation to real flight conditions. Several measurements techniques have been developed for the characterization of the high enthalpy flow (Chazot et al., 2000). Intrusive measurement techniques allow to select the range of test operating conditions. Non-intrusive measurement techniques, based on emission spectroscopy, permit a diagnostic of the plasma flow. Typical TPS tests, as defined in plasmatron facilities, fully depend on the characteristics of the incoming flow on the sample. It appears to be of first importance to determine the flow field in the ICP torch to define accurate test conditions for the materials. To investigate this problem we propose to adapt LDV measurements for the plasma jet and the discharge region of an ICP torch.

In order to have a complete and more detailed characterization of the flow we use a smaller facility denominated "Minitorch" designed in parallel to the bigger plasmatron, and working in similar conditions. This pilot facility serves to test measurement techniques in air plasma environment and to investigate ICP torch behavior for specific working conditions. The present study will focus on this minitorch which allows a very large optical access, and is easier to handle.

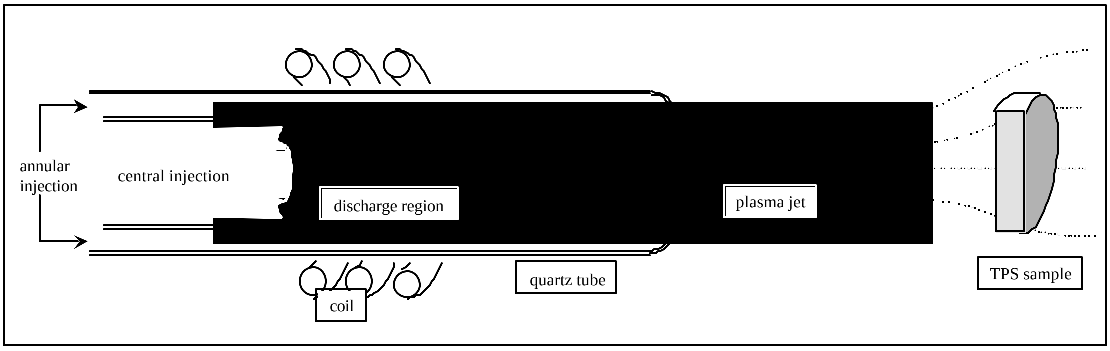


Fig. 2. Sketch of an ICP torch for plasmatron facility for TPS test

2. PLASMA DISCHARGE IN THE ICP TORCHES USED FOR TPS TESTING

It is well known that the complete simulation of the aerodynamic and thermal loads encountered during re-entry flight is impossible within a single facility. New concepts of high-enthalpy facilities are being studied, such as the radiatively-driven hypersonic wind tunnel using non-isentropic heating processes (Miles et al., 1995), but the large-scale technology required is still mostly unavailable and it is unlikely that any such facility will be operational in the short future. Plasmatron-type facilities use an ICP torch which present the main advantages of high purity and high energy density for the plasma flow generated. They allow to test TPS in a complete simulation of the local flight conditions at the stagnation point (Kolesnikov, 1993).

The basic scheme of an ICP torch consist of a coil with a few turns, connected to a high-frequency generator, surrounding a quartz tube where gas is injected. Once an initial ionization is created by suitable means, the coil induces eddy currents in the conducting gas, transferring energy and maintaining it into a plasma state (~ 10000 K). Classically a plasma torch is designed with two co-axial flows: an annular flow called plasma gas and a central one called auxiliary gas. It is known that the annular gas plays a major role and the central one serves only to prevent the inner tube from melting and has not a significant influence on the plasma jet (Chazot et al., 1998). Therefore we have chosen to work with a simpler torch design. The plasma charge is fed only by one annular flow which can have different injection modes (swirling and straight). The center body, which serves to form the annular nozzle, is cooled by an internal water circuit. This new design allows a better accuracy in manufacturing and adjusting the torch geometry. It reduces the uncertainty due to the diameter and the alignment of the inner quartz tube. One can also assume that it yields a less complex flow pattern in the discharge region, because it avoids the interaction of two coaxial jets. It also prevents the inevitable separated flow zones at the end of the inner quartz tube and around the injection inside it. Figure 3 shows a sketch of the ICP torch and gives the torch geometry used in the numerical model. The plasma discharge in the torch can be divided in two parts, the most sensitive part in the coil region called the discharge region characterized by a strong interaction of all the parameters such as gas flow, temperature and electromagnetic fields, and the downstream part named the plasma jet. It may be reasonably assumed that electromagnetic effects are negligible at this position. Due to their high temperature such flows manifest high velocities associated with low Mach and Reynolds numbers. The classical LDV measurements have to be adapted to the particularities of plasma flows to be used as a method of characterization for the high enthalpy flow of an ICP torch.

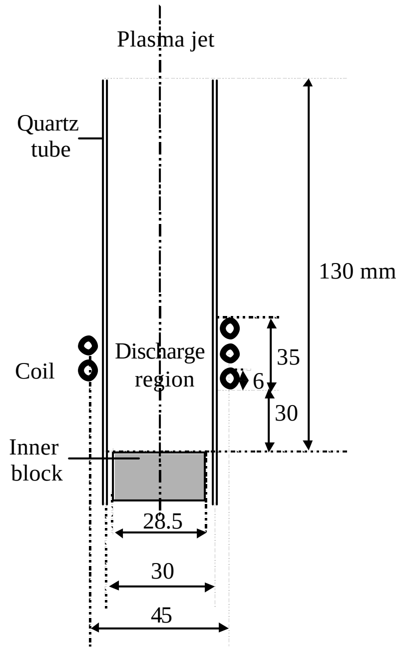
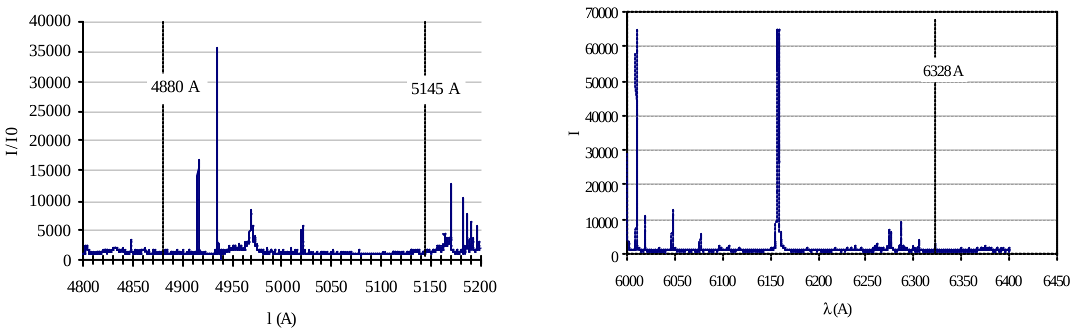


Fig. 3. Sketch of the ICP torch

3. LDV MEASUREMENTS IN PLASMA FLOWS

3.1 Optics

The plasma discharge is a very bright source which emits on a large wavelength spectrum. One have to check if the wavelengths of the laser beam used for the measurement are not corresponding with a peak of the plasma spectrum. When working with an air plasma, we can avoid overlaps of the LDV signal by using an Argon laser or a classical He-Ne laser of 17 mW (figure 4). Nevertheless one have to use an interference filter because the plasma is an intense source of light and leads to a saturation of the photo-multiplier.



(a) (b)

Fig. 4. Air plasma wavelength spectrum, a) $4800 < l < 5200$ Å, b) $6000 < l < 6400$ Å

The filter allows to reduce the perturbation due to the thermal emission of the particle heated in the high enthalpy flow which can lead to noisy signal. Another problem concerns the presence of the temperature gradients which can introduce variations of refraction index and disturb the interference pattern in the probing volume. From experiments with schlieren photography in plasma jet at low pressure and from literature about LDV measurement in hot gases one can consider this effect as negligible for plasma at sub-atmospheric pressure (Chazot, 1999; Pfeifer, 1981). On the other hand one have to worry about the accessibility of the plasma flow and to realize a good optical alignment. For measurements in the plasma jet no problem arise since the optical access is made through two parallel flat windows. However for the measurements in the discharge region the refraction of the laser beams on the round surface of the quartz tube cannot be avoided. A correction of the probe volume location must be taken into account in that case.

3.2 Seeding and particle behaviour

The seeding conditions in plasma flows are one of the worst that can be accounted as they concern a gas at high temperature under low pressure. Previous experiments in combustion (Melling, 1981) and in argon plasma (Gouesbet and Trinite, 1977) guided us to choose a convenient apparatus. A cyclone aerosol generator has been built based on a model already used successfully for Al_2O_3 particles to seed flames (Glass and Kennedy, 1977). It has to be noticed that seeding problem can appear before reaching the plasma discharge. Actually, during the process of particle transportation in pipes, the seeding can decrease drastically because of particle deposition on the tube wall. The powder has to be in good condition to be injected in the flow. Possible electrostatic charge or humidity have to be removed.

It is out of the scope of this report to study in detail the behavior of particles in a high enthalpy flow. We just mention the relevant parameters that have to be checked to be in good conditions for LDV measurements in plasma flows. The particles are exposed to a low-density fluid with high temperature. They have to be small enough to follow the fluid, but big enough to resist to the strong heat transfer at which they are exposed. So we have to inspect the motion of the particles and their thermal resistance.
The ability of a particle to follow the flow depends on its shape, size, relative density with respect to the density of the fluid and particle concentration. An easy way of characterizing particle dynamics effects is to examine the Stokes number.

$$St = \frac{t_p}{t_f}$$

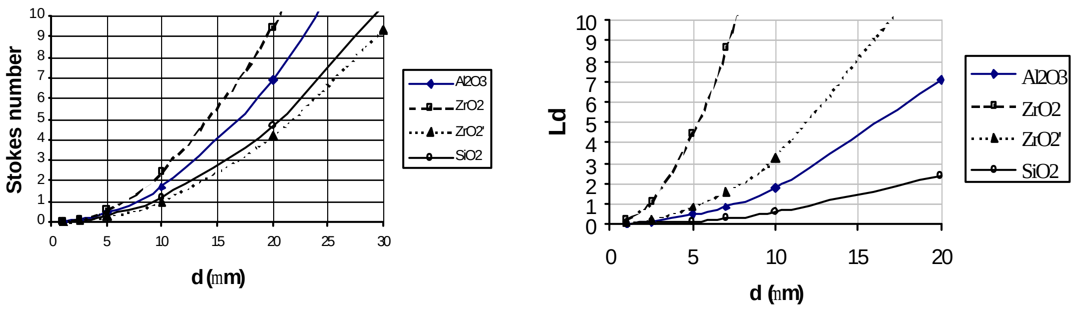
Where τ_p is the characteristic particle response time and τ_f is the time scale of the flow variations. For $St \ll 1$, the particles will effectively follow the fluid motions to be measured. τ_f is evaluated as the diameter of the torch over the mean velocity of the flow for the working condition of the torch. The particle time τ_p is defined by:

$$t_p = \frac{r_p d_p^2}{18m}$$

In order to check their ability to support the heating from the plasma flow during their flight we have to estimate their total evaporation time. The complete solution of the evaporation of a material in a plasma discharge has been already examined (Bonet et al., 1974). This unsteady problem is not trivial and takes into account many effects of heat and mass transfer phenomena. A rough calculation of this consumption time τ_c can be consider assuming a pure heat transfer conduction to the particle (Chazot, 1999). A non-dimensional life duration number can be defined by the ratio between the consumption time and the time of flight of the particle in the discharge (τ_r).

$$L_d = \frac{t_c}{t_r}$$

From the literature, Alumina (Al_2O_3), Zirconium oxide (ZrO_2) and porous Zirconium oxide (ZrO_2') appear to be adapted for LDV measurements in high enthalpy flow (Gouesbet, 1985; Moreau and Labbe 1978). ZrO_2' presents the advantage to be lighter with a good thermal resistance. SiO_2 particles, which can be found with a spherical shape, have the advantage to be easy to inject. As an example, the Stokes number and life duration number for Al_2O_3, ZrO_2, ZrO_2' and SiO_2 are calculated for typical plasma conditions (T = 6000 K, $\dot{m}$ = 0.5 g/s) (figure 5).



(a) (b)

Fig. 5. Characteristic non-dimensional numbers for different size of Al_2O_3, ZrO_2, ZrO_2' and SiO_2 particles in a plasma flow

a) Stokes number

b) Life duration number

These graphs give rough ideas for a preliminary selection of particles, in any case a test in real condition has been done for the final choice. Al powder has also been used in the ICP torch. This experience leads to a general remark concerning seeding realized with metallic powders. When the time residence of the powder become larger and the evaporation rate increases, the presence of the metallic vapor in the coil region changes a lot the electrical properties of the discharge. This change of impedance leads to electrical instabilities and it becomes difficult to control the power transferred to the plasma charge.

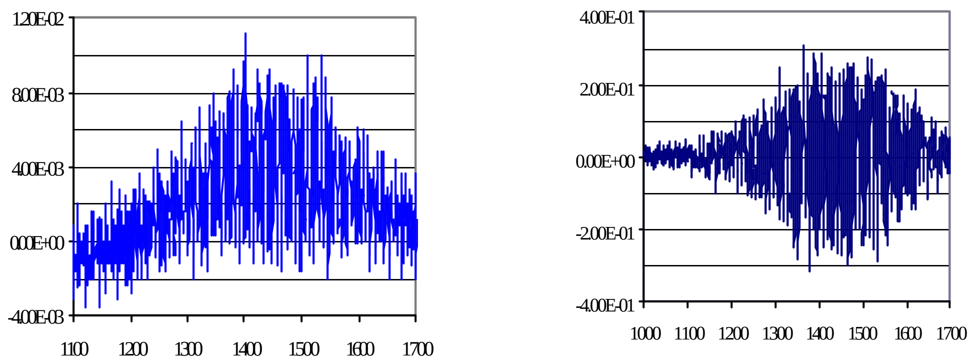
3.3 Signal processing

Considering a good optical adjustment and a regular seeding the signal scatter by the particles is firstly collected in a pinhole through an objective and guided by an optic fiber to a photo-multiplier. The electrical signal is filtered and analyzed in the signal processor device. Its role is to select the valid signal which contain relevant information to deduce the flow velocity. The main parameter to measure is the signal frequency ($f_{Doppler}$) since the particle velocity (V) is given by:

$$V = f_{Doppler} * i$$

(i : fringe spacing)

In many case the signal to measure, usually call “Doppler burst”, can easily be affected by several sources of disturbances. A faraday cage has to be placed around the torch to limit its electro-magnetic radiation to the surrounding, since the radiation frequency is in the same range of that the Doppler frequency measured. The disturbance coming from the particles are more difficult to control. Actually the dispersion in particle diameter introduce big differences in light scattering. The thermal emission of the particles, heated in the high enthalpy flow, can induce noise in the measurements and lead to a poor modulation of the Doppler signal. Moreover the particles which cross the control volume partially or in a bad way have to be remove in order to process a real value for the velocity. Since we measure relatively high velocities, little light is scattered and the voltage of the photomultiplier has to be increased. This amplifies the noise level as well. Figure 6 shows typical non-filtered and filtered signals from SiO_2 particles in the plasma jet of the Minitorch facility. The adaptation of the pass-band filter is made with an estimation of the velocity range based on preliminary Pitot probe measurements assuming a mean temperature of 5000 K for the plasma jet.



(a) (b)

Fig. 6. Typical Doppler signals from SiO_2 particles in an air plasma jet

a) Non-filtered signal

b) Filtered signal

4. MEASUREMENTS IN THE PLASMA JET

The measurements have been done for two static pressures in the test chamber and two mass flow rates keeping the same value of the anode power. This represents four working conditions for the ICP torch reported in table I.

Table I: Working conditions

Mass flow	Anode power	Pressure	Experiment N°
0.55 g/s	3.6 kW	50 hPa	N°1
1.0 g/s	3.6 kW	50 hPa	N°2
0.55 g/s	3.6 kW	200 hPa	N°3
1.0 g/s	3.6 kW	200 hPa	N°4

The torch works with a straight annular injection. The axisymmetry of its configuration has been checked by preliminary Pitot probe measurements.

The LDV measurements have been implemented in the plasma jet, 20 mm downstream of the torch exit. They are taken along the radius since the axisymmetry of the jet has been checked. All the optical set-up of the LDV system is fixed to a table that can move in the three directions. In our case, the intersection of the laser beams is located on the axis of the jet (figure 7). This point is taken as a reference mark and only the traversing direction is used. The position of the table is checked by a ruler which allows an accuracy of half a millimeter for each displacement.

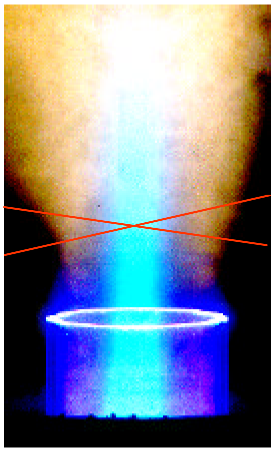


Fig. 7. Crossing laser beams in an air plasma jet seeded with Al particles

The two ranges of pressure lead to two velocity ranges and two different signal processor devices were used. The TSI counter, used for the low pressure cases, allows us to visualize, on a chart, the velocity histogram in real time (figure 8). Each measurement corresponds to a recording of an average of one thousand valid signals. The velocity profiles of the plasma jet are shown in figure 9 and 10. The seeding of the plasma was performed at 200 hPa with particles of silica, less than 1µm in diameter, and at 50 hPa, with particles of aluminium with a diameter of 5 to 10 µm.

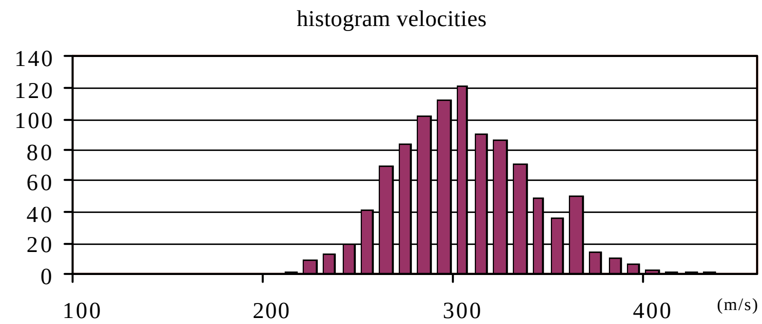


Fig. 8. Velocity histogram on the axis of the plasma jet (exp. N°1)

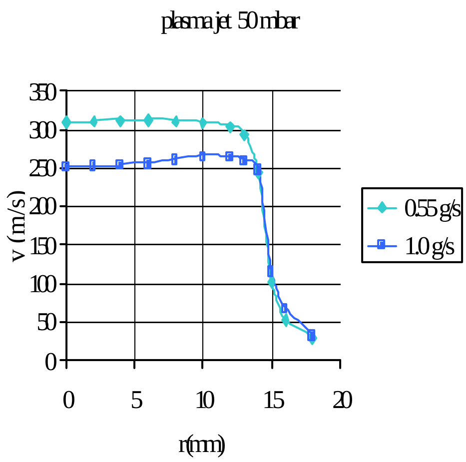


Fig. 9. Velocity profiles in the plasma jet (exp. N°1, 2)

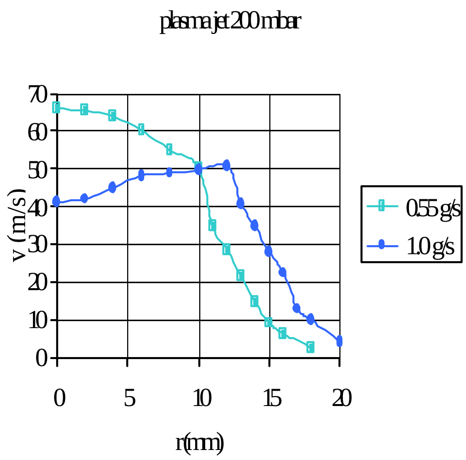


Fig. 10. Velocity profiles in the plasma jet (exp. N°3, 4)

The trends of the velocity profile for the two ranges of pressure are similar. The differences between the curves are more pronounced for the higher pressure. The velocity profiles measured for the higher mass flow rate exhibit a slight “M” shape. As a result of the coupling between the temperature and the velocity profiles in the plasma jet, the maximum velocity is decreasing when increasing the mass flow. For the higher pressure ranges the velocity gradient at the border of the jet is smaller than for the lower pressure cases. This is coherent with the visual inspection of the jet which appear more open at higher pressure. This corresponds to a more extended mixing layer.

5. MEASUREMENTS IN THE DISCHARGE REGION

Measurements in the discharge region intend to characterize the recirculating zone above the inner block. The brightness is much higher than it is in the plasma jet, but the seeding is better since the particles have not yet disappeared by evaporation. The injected particles are heated in the plasma and become visible because of their thermal emission. It allows some flow visualizations in the discharge region of the torch. A band-pass filter has been placed in front of the camera in order to reduce the light emitted by the plasma to distinguish the particles. By adapting the time exposure of the camera we could record bright traces corresponding to the particles path (figure 11). These pictures correspond to working condition similar to exp. N° 3. Actually, the main emission comes from the largest particles. We have to consider that these ones follow only roughly the streamlines of the flow. Nevertheless we could recognize the main structure of the flow field. The particles are trapped in the vortex and roll-up above the inner block. These big particles go slower than the flow. Consequently on the picture (figure 11), if we consider the flow as a reference for the motion, the wakes of the particles, made of silica vapor, are ahead of the particle in fusion. These preliminary tests allow to check that there is no influence of the vapor of the particles on the electrical characteristics of the discharge.
LDV measurements in the discharge region will be performed in the near future to be included in the final version of this paper.

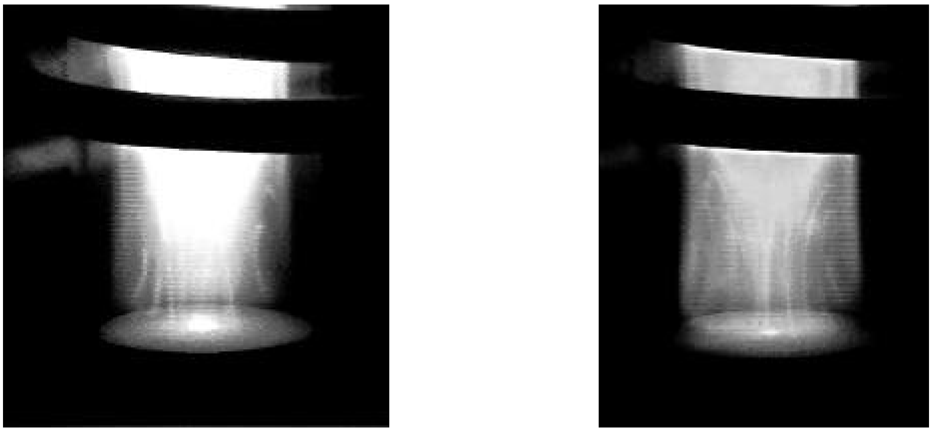


Fig. 11. Pictures of the discharge region seeded with SiO_2 particles (F < 10 mm), exp. N° 3

6. CONCLUSION

LDV measurements can be realized with a classical set up using adapted interference filters. The seeding appears as the most important problem since it has to satisfy many criteria which have to be carefully examined to achieve accurate measurements. Spheroid SiO_2 particles with typical diameter of 1µm have been selected and tested for the plasma conditions investigated (3.6 kW, 0.55 g/s, 50 hPa). As a non-intrusive and space resolved technique LDV measurements bring detailed information about the plasma flow. They allow the characterization of the plasma jet and can be extended to the discharge region as well. These measurements provide precise results to assess the accuracy of more global high enthalpy measurement techniques used for TPS tests.

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