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CONCEPT OF A SMALL PLASMA TUNNEL FOR CHARACTERIZATION OF HEAT SHIELD MATERIALS

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Abstract. *Small low orbit satellites experience by time an orbit decay that results in a free return to Earth surface. During the re-entry flight parts of the satellite burns due to high heat fluxes and extreme high temperatures. The surface of such satellites should be protected against heat if inboard equipment and sub-systems are intended to be recovered or reused. This fact leads to the convenience of designing a thermal shroud to protect the primary structure of the satellite and to keep an adequate temperature inside it. Due to the high heat fluxes non-conventional materials should be used and their thermal behaviour must be well determined to avoid over-sizing of the heat shield or damage of the structure. To characterize high temperature materials a device should be used which simulates the high heat fluxes. Plasma flows are in this case the most adequate energy source. For that reason a small plasma tunnel is being developed which will be applied in the development of the thermal shield of the recoverable orbital platform SARA. The paper presents the parameters that specifies plasma tunnels, discusses the basic specification for a small plasma tunnel, and concludes with comments about the preliminary results of experimental measurements concerning the characterization of the plasma tunnel system.*

Keywords*: Re-entry flow, Heat shield, Re-entry satellite, Plasma tunnel*

1. INTRODUCTION

Small low orbit satellites experience by time an orbit decay that results in a free return to Earth surface. During the non-induced re-entry flight most part of the satellite burns due to high heat fluxes and extreme high surface temperatures. The surface of such satellite should be protected with thermal insulation material if inboard equipment and sub-systems are intended to be recovered or reused. This fact leads to the convenience of designing a blunt nose shape for the satellite.

Nevertheless to well protect the primary structure of the satellite and to keep an adequate temperature inside it, high performance thermal protection material should be used. Due to the high heat fluxes and high temperature levels non-conventional materials are used to build the heat shield. During the development of such materials, their thermal behaviour must be well determined to avoid over-sizing of the heat shield or damage of the structure. To characterise high temperature materials a device should be used which simulates the high heat fluxes. Plasma flows are in this case the most adequate energy source. For that reason a small plasma tunnel is under development which will be later used to characterise the material for the thermal shield of the recoverable orbital platform SARA (Moraes, 1998).

The paper presents the parameters that specifies heat shield materials, discusses the basic specification for a small plasma tunnel, and concludes with recommendations for a cost effective and appropriate design.

2. CONCEPT OF A RE-ENTRY VEHICLE AND HEAT SHIELD

2.1. Re-entry vehicle concept

Re-entry vehicles are in general shaped by a spherical nose cap followed by a cone and, in same case, concluded by a frustum or cylindrical segment. The bluntness of the nose cap, which is defined by the ratio of nose diameter to cone base diameter should be large in order to withstand and distribute the high heat flux which will generated during the re-entry flight (Ferri & Ting, 1961). Considering an orbital vehicle performing a ballistic re-entry flight from 300 km altitude, the heat flux generated in the more dense layers of the Earth atmosphere can reach values close to 2.5 MW/m^2. Depending on the nose cap material, local temperatures of around 2500 °C can be established (Anderson, 1984).

Figure 1 shows a typical re-entry vehicle based on the concept of the Orbital Recoverable Platform SARA (Acosta & Moraes, 1999) which is under development at the Instituto de Aeronáutica e Espaço (IAE), Centro Técnico Aeroespacial.

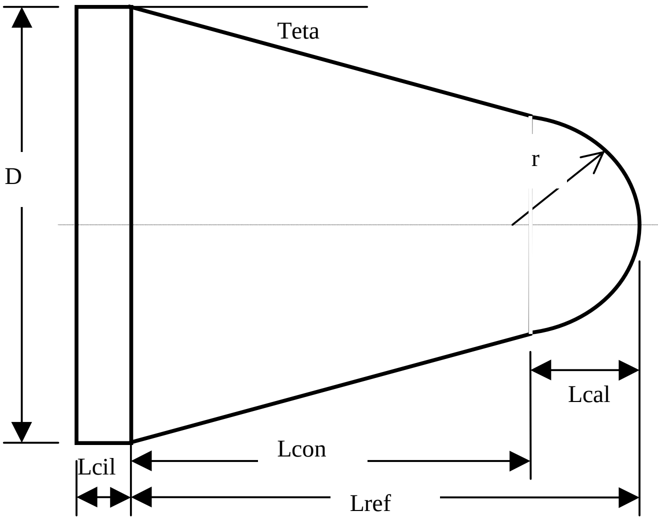

Figure 1. SARA re-entry vehicle

The de-orbiting and re-entry parameters of the SARA ballistic vehicle may lead to the expectation of a maximal heat flux of ~ 2.4 MW/m^2 at a stagnation pressure of ~ 40 kPa.

2.2. Heat shield concept

The thermal protection system (TPS) development for the recovery platform SARA takes into account two different approaches:

1) An ablative approach;
2) A reusable approach.

The two-approach philosophy relies on the different development stages of the technology to be used in the platform project. The ablative technology has been used in IAE during the last 15 years for nose cones and divergent throats of rocket motors and the possibility of a rapid development to match the thermal protection requirements of a re-entry platform seems to be very high. The problem here would be a precise property evaluation (conductivity, CTE, etc) for the new ablative systems subjected to the re-entry environment (recession rate, back face temperature, etc) since the mass and reliability requirements are stronger than in the nozzle case. A reusable approach on the other hand needs another class of materials. These materials are the subject of a new research and a complete investigation of the properties and manufacturing methods must be made to assure the required reliability the program demands. Since the other technologies involved in the platform development like aerodynamic and thermodynamic calculations, structural design, on board electronics, etc, could be available in the next two years, IAE decided to use an ablative thermal protection to test the whole system before going further. A reusable approach can be introduced after the new materials development is completed.

In the ablative approach the nose cap of the platform will be made of 2D or 2,5D carbon/carbon (C/C), while the conical part will rely on a sandwich construction, with a carbon/phenolic resin face sheet and a carbon honeycomb, filled with low density ablative material, like phenolic microbaloons. The development process of the C/C material achieved already its end phase and although the properties are lower than the international standards, this can be reached in the years to come. The carbon/phenolic material is completely well developed and flight qualified; nevertheless the carbon honeycomb ablative material needs some further improvements.

The reusable approach intends to use a carbon/silicon carbide (C/SiC) or a carbon/carbon-silicon carbide (C/C-SiC) nose cap, with a conical part made of a defined number of plates from the same material and an isolation sheet consisting of a ceramic fibre felt. The ceramic fibre type will be defined later but some possible materials would be alumina or silica fibres. The panels will be attached to the cold substructure with C/C screws. IAE in co-operation with UNICAMP had already begun the development of C/SiC and C/C-SiC and the feasibility of the process was proved. Now, the task will be to achieve the correct process adjustment to reach the desired properties and initiate the manufacture of big components. IAE intends also to begin with the ceramic fibre felt development in the next months. Carbon fibre felts are already available.

During all the development phase, samples will be made to test and evaluate their performance in a plasma chamber before the final component qualification in a plasma wind tunnel occurs. The oxyacetylene ablation test could allow a comparative study about different types of ablative materials, but would not simulate the re-entry environment, an indispensable step to reach a reliable design. It is expected that the solution of the inverse heat and mass transfer problem in a plasma chamber experiment will provide the material properties within the reliability level required. These properties can be used subsequently to calculate the direct ablative problem of a heat shield subjected to a high heat flux due to re-entry.

3. PLASMA WIND TUNNEL

3.1 The plasma wind tunnel concept

A plasma tunnel is a special type of plasma machine where a subsonic or supersonic jet of a rarefied gas is heated to high temperature by means of an electrical discharge that can be ignited trough electrical induction coupling with a high-frequency generator or, as most usual, by a high current DC arc-jet type discharge. The gas, which has reached a dissociated and ionized plasma state, is directed onto a target, primarily for the purpose of testing the resistance of material to the thermal loads encountered by space vehicles during the re-entry phase. The system is comprised of three major components, namely, the plasma source, the vacuum chamber (test camber) and the pumping system, as shown schematically in Figure 2. The gas is injected into the plasma chamber where the electrical discharge is produced. The plasma flows trough a nozzle towards the vacuum chamber, driven by gas pressure gradient and electrical acceleration of the charged particles. A plasma jet emerges from the nozzle exit into the vacuum region and expands naturally, driven by its internal pressure. The pumping system must be robust enough to assure the differential pumping of the plasma source and the desired flow regime in the test chamber.

A variety of such plasma wind tunnel facilities have been used for ground-based simulation of re-entry phenomena to acquire the understanding necessary for the design of modern reusable re-entry vehicles and space probes, and for qualification of thermal protection systems (M. Auweter-Kurtz et al., 1996). The full laboratory characterization of re-entry environment is laborious and costly. For that reason plasma tunnels of different sizes and operation purposes are, more often, in use in many countries. Large plasma facilities with power level up to 0.5 MW and for specific enthalpies ranging from 5 MJ/Kg up to more than 150 MJ/Kg are used to simulate the first phase of the re-entry where the specific enthalpy is high and the temperature is at its maximum; the stagnation pressure reaches 0.1 mbar up to 50 mbar and the maximum mass flow with air is about 30 g/s. On the other hand smaller devices are readily available world-wide, which can operate continuously to investigate the thermal load and surface chemistry associated with the erosion or ablation mechanism of TPS. In this case the emphasis is placed on simulating thermophysical and chemical conditions on the surface os the TPS specimen rather than reproducing aerothermodynamics conditions of re-entry. A different approach to sep up experimental facilities for re-entry environment simulation relies on the concept of shock-tunnel(K. M. Chadwick, 1997). In this case a plasma source is not a primary component of the system.

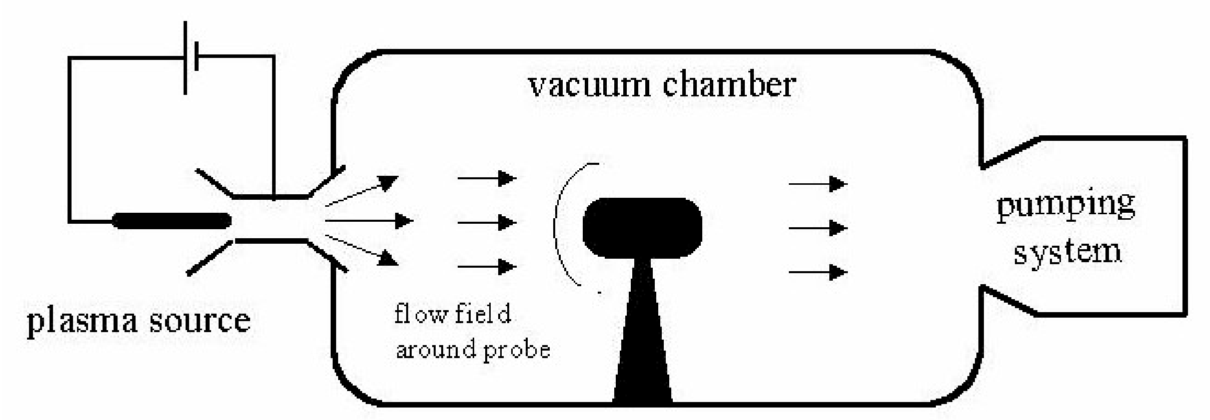

Figure 2. Schematic diagram showing the major components of a Plasma Wind Tunnel

3.2 Concept of a small plasma tunnel for characterization of TPS material

In this section the concept of a small plasma tunnel is described, which is primarily aimed to implement plasma facility of low cost but nevertheless adequate for the investigation and qualification of thermal protection system material. It should simulate the condition of heat flux about (50-100) W/cm2 over TPS material samples exposed to the plasma flow as well as the chemistry similarities of re-entry environment. The schematic diagram of the plasma tunnel is shown in Figure 3. The novelty in the design of the system is related to the use of a plasma source, which is based in a low-pressure arc discharge instead of a conventional plasmatron, or a thermal plasma source. As a whole the tunnel has a triple-plasma structure, namely a low-pressure positive column, constriction plasma and the plasma jet. The constriction plasma is governed by electrostatic double-layers, one at each side of the constriction. The double layer between the positive column and the constriction plasma acts as a localized absorber of electrical power, which is transferred to the ions and electrons, increasing in this way their kinetic energies (Maciel and Allen, 1989). The constriction plasma is strongly heated by the double-layers giving rise, at the nozzle exit, to an emerging plasma jet of high specific enthalpy. The plasma source has a mercury pool as cathode and a liquid nitrogen trap that can be used to prevent Hg vapour to reach the cylindrical discharge tube when a plasma jet, based on another gas (argon, nitrogen or oxygen), is intended to be produced in the test chamber. In any case, the Hg vapour dominates the plasma near the cathode and there will be effectively a mercury plasma cathode anchoring distinct positive column plasma. The arc discharge operates at low pressure, about 0.1 Pa, with at least ten times lower pressure in the test chamber. The current is in the range of 5-12 A, and discharge voltage between 100 V and 200 V. The power dissipated at the constriction double-layer, in the range of kW, is most transferred to the enthalpy of the emerging plasma jet. Accordingly, an estimated heat flux of more than 100 W/m2, transported mainly by the charged particles, can be provided for thermal loading of material samples, placed to intercept the plasma jet at a distance of 5 to 10 cm from the constriction exit.

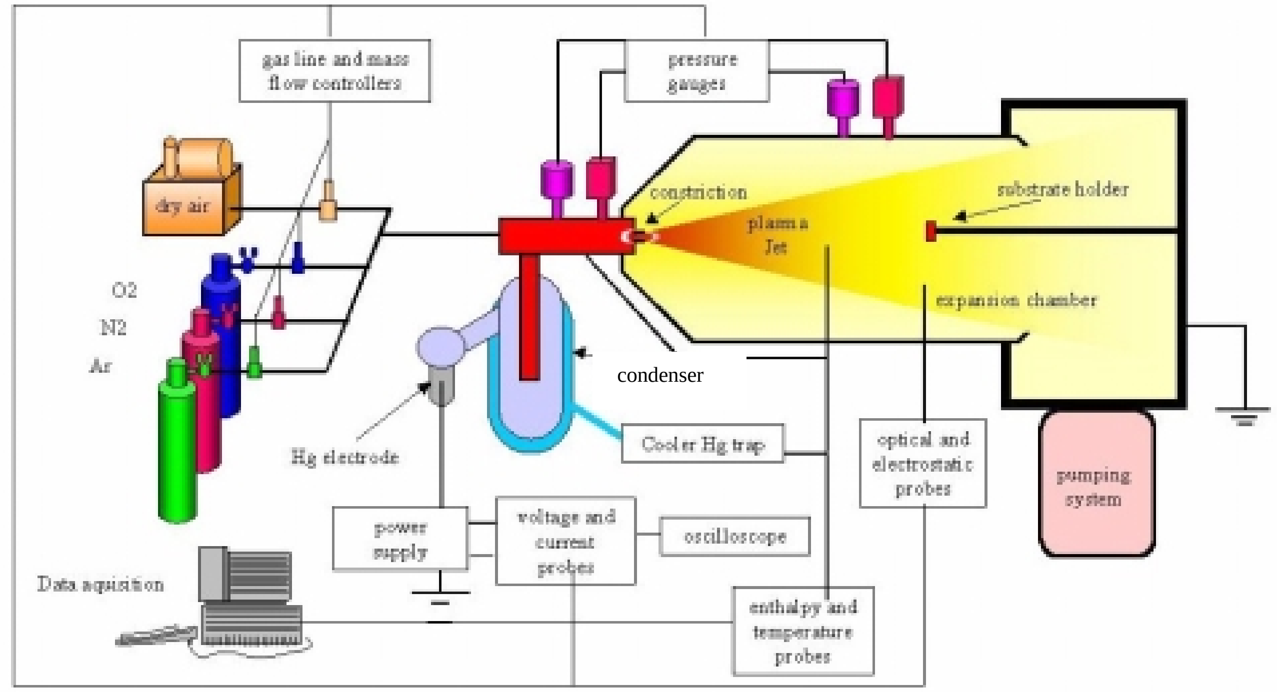

Figure 3- A schematic diagram of the plasma tunnel

3.3 **Specification of the main parts of the plasma tunnel**

The worked out concept of the plasma tunnel should be built of the following main parts:

Vacuum chamber-as shown in figure 4, made of stainless-steal with various quartz windows. Cylindrical shape, 200 cm long and 95 cm diameter. Water cooling of the walls. Movable back-plate with feedthroughs for electrical current, optical and electrostatic probes, enthalpy probe and other diagnostic tools. Movable substrate holder.

Pumping system- two rotary pumps Edwards-E2M-80 and a root pump EH-500, capable of 500 m3/h. pumping speed. Three oil diffusion pumps(20000l/s each) connected in parallel and pumped by the roots, see figure 5.

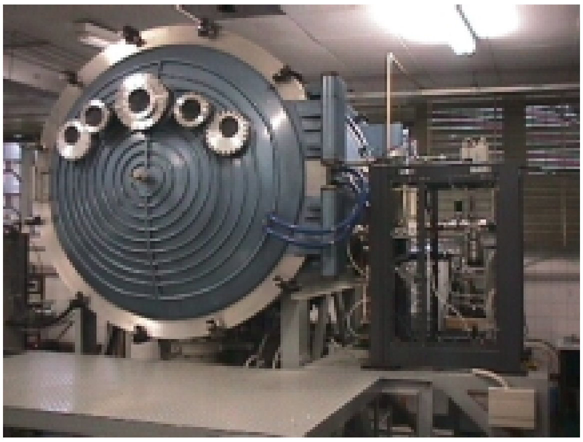

Fig. 4 – Photography of the vacuum chamber apparatus

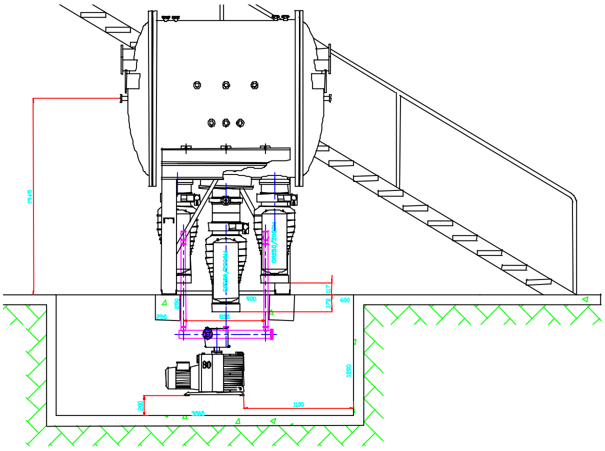

Fig. 5 –Schematic drawing of the vacuum apparatus showing the pumping system

Plasma source- made of pyrex tubing, 1.0 m in length. Central cylindrical column of 30 mm internal diameter and 40 cm in length. Constriction nozzle made of ceramics, 20 mm long and 3 mm internal diameter. Mercury cathode pool with water-cooling jacket. Liquid nitrogen trap for condensation of Hg vapour. Tungsten pin connection of cathode pool with the external electrical circuit. Auxiliary tungsten anodes and entrances for electrostatic probes, in the central column. Connections for pirani gauge and ion gauge. Connections for the gas supply. DC power supply with current up to 20 A and variable voltage up to 3000 V, see figure 6.

Gas supply- connections of the plasma chamber to a gas line of nitrogen, argon, oxygen, dry air and methane, via mass flow controllers. Connections for pressure gauges.

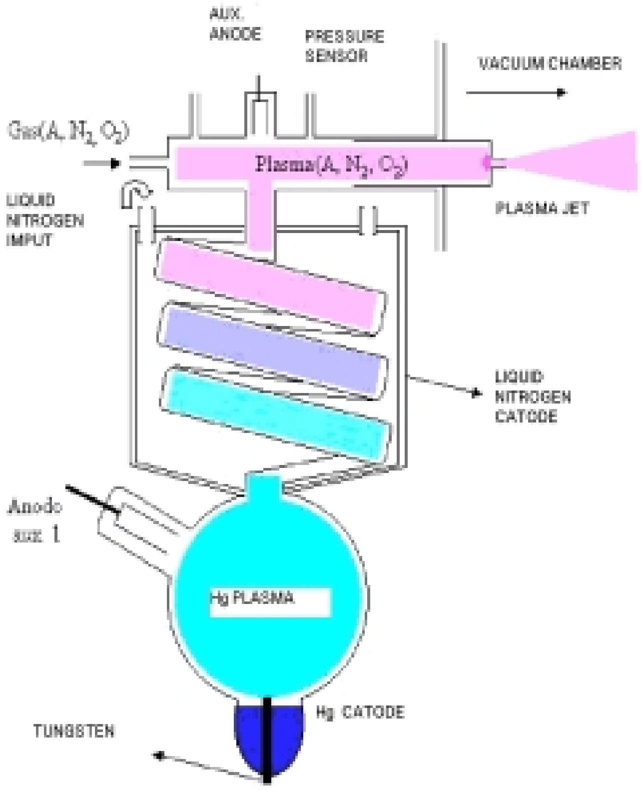

Fig. 6a – Schematic diagram of the plasma source based on a cathode plasma arc discharge in mercury

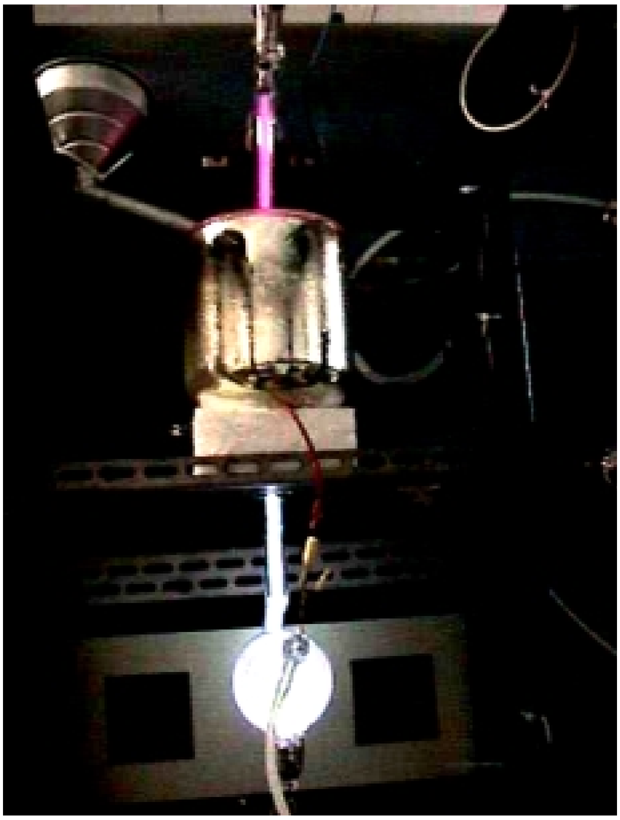

Fig. 6b – Photography of the cathode region of the plasma source

4 CHARACTERIZATION OF THE SYSTEM

4.1 Vacuum characteristics

In figure 7 the plots of the residual pressure indicate that a residual pressure of magnitude about 10E-5 torr could be attained in the chamber after 15 minutes pumping time. As shown in fig.8, flow rates of argon in the range of 10 to1000 sccm lead to equilibrium pressures corresponding to altitudes of interest for re-entry studies.

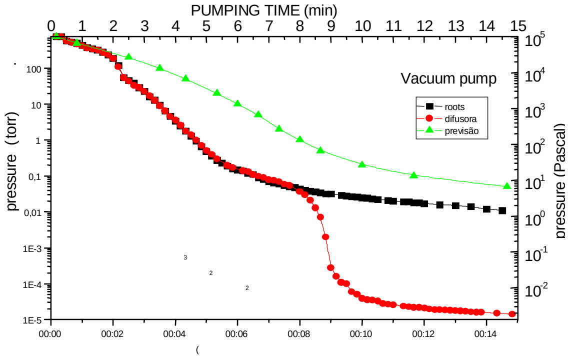

Fig. 7 –Variation of the residual pressure in the vacuum chamber with the pumping time

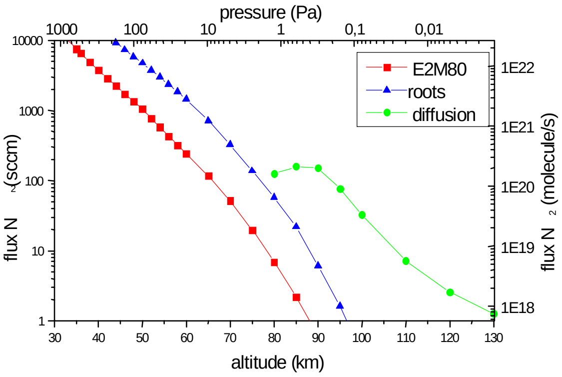

Fig. 8 –Plot of the gas flow rate into the vacuum chamber corresponding to a stationary pressure or equivalent altitude

4.2 Arc discharge characteristics

Preliminary measurements of voltage and current of the arc discharge were recorded and presented in the plots below. We can observe from fig. 12 that a higher discharge voltage is demanded when oxygen is added to a nitrogen discharge.

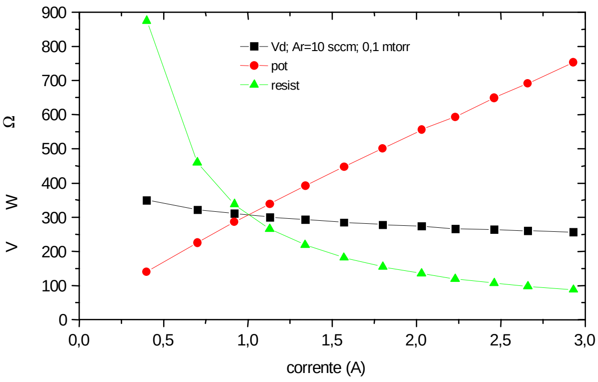

Fig. 9 –Dependence of voltage, resistance and power of the arc discharge on the current.

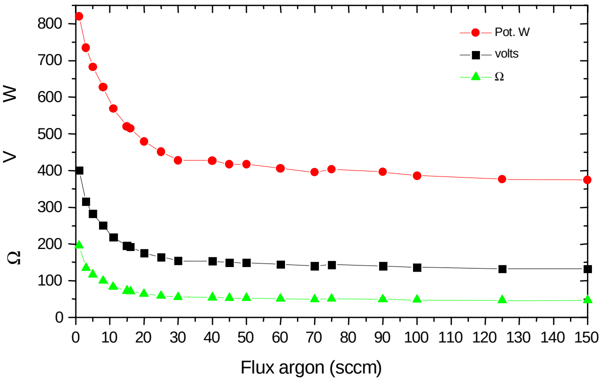

Fig. 10 – Dependence of the discharge voltage, resistance and power on the argon flow rate

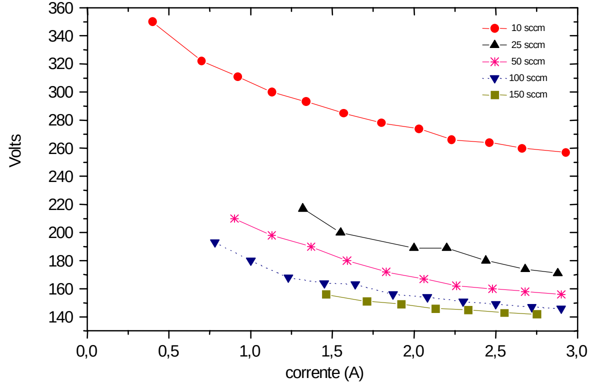

Fig. 11 –Current-voltage characteristics of the arc discharge at various gas flow rates

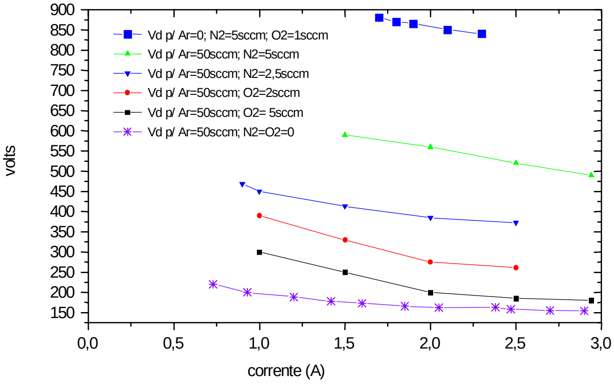

Fig. 12 – Voltage, resistance and power of the arc as function of the discharge current at various gas mixtures flow rate

Fig. 13 – Photography of the plasma source in operation illustrating its capability to heat and to melt a titanium sample.

5. CONCLUSIONS

Recoverable and reusable small satellites need a safe and reliable heat shield in order to prevent damage of their structures during the re-entry flight. If the thermal behaviour of the heat shield materials is not known, a thermal characterization should be done with appropriate devices as for instance plasma tunnels. The present article describes a concept for a small plasma tunnel to be applied for the thermal characterization of ablative and non-ablative heat shield materials embedded in a high heat flux environment, typical of a re-entry flight. Some features of the proposed plasma tunnel have been discussed and preliminary measurements are presented within an approach of designing a low cost and effective facility. The plasma jet produced was tested to successfully demonstrate its capability to heat and melt a titanium sample Additionally the article presented and discussed the shape of the recoverable satellite as well as the typical materials, which could be used to manufacture the heat shield.

6. ACKNOWLEDGEMENTS

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