CHARACTERIZATION OF ARC-HEATED EXPERIMENTAL SETUP TO PRODUCE HYPERSONIC PLASMA JET FOR THERMAL PROTECTION MATERIAL TEST

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***Abstract**. Arc-heated facilities are the key tools for the qualification of hot components of re-entry vehicles in realistic aero-thermodynamic environment because it makes possible to control some gas-dynamic variables, such as the enthalpy of plasma simulated. This paper presents some results of characterization of an arc-heated experimental setup for producing hypersonic plasma jet developed in Instituto Tecnológico de Aeronáutica (ITA). The main parameters measured in the setup used in this work are: arc current and arc voltage; air flow rate through heater and nozzle; pressure in the heater discharge chamber and in vacuum chamber; total gas enthalpy, calculated by means of energy balance in electric-arc-heater; heat flux, measured from transient calorimeter; Mach number calculated by parameters of plasma in heater and ratio of pressures in heater and vacuum chamber. The results showed that it is possible to produce Mach numbers up to 5, enthalpy from 1 MJ/kg to 13 MJ/kg, heat fluxes up to 3 MW/m^2 and stagnation pressures in the range of 1.0 atm to 0.01 atm. By considering the levels of heat fluxes, enthalpy and stagnation pressure, the setup is able of modeling some conditions of re-entry of Brazilian satellite SARA (satellite of atmospheric re-entry) for the most crucial part of trajectory - for altitudes approximately from 42 km to 34 km.*

***Keywords**: arc-heated, reentry, plasma torch, plasma jet, thermal protection system.*

1. INTRODUCTION

Upon reentering the Earth's atmosphere an orbital vehicle encounters gases at velocities of more than 7 km/s thereby being subjected to great heat loads. For the development of thermal protection systems for reentry bodies are needed to simulate in steady state conditions the required surface temperature on the material, pressure, specific enthalpy and mass flow rate. The simulation of a spacecraft entering a planetary atmosphere in the hypersonic flight regime requires the knowledge of dissociation, ionization and chemical processes, radiative gas phenomena, and nonequilibrium effects on the internal modes. The physical properties of the gas flow surrounding a spacecraft during a planetary entering atmosphere depend on the chosen spacecraft trajectory. Different ground test facilities are available today to simulate such entry conditions (low-pressure hyperenthalpic gas flows): shock tubes, inductive plasma torches, radio-frequency sources, and arcjet.

Arcjet facilities present the advantage of providing long test runs, performed with stable operating conditions and with appropriate values for several plasma conditions, and are currently used to produce the heating environment of high-speed planetary entry flights, for the simulation of planetary entry conditions, for carrying heat flux tests on materials for spacecraft protections and for a detailed analysis of the plasma flow. One important parameter that such tests must simulate is the flow enthalpy, "Raiche *et al.* (2006)". The average specific enthalpy of the flow in exit plane of the arcjet jet nozzle can be derived for all kinds of plasma wind tunnels by an energy balance. Therefore the electric power consumed by the plasma source the mass flow rate and the heat losses within the plasma generator are measured. The average specific enthalpy at the end of the plasma generator is then derived as the difference of the electrical power and the total heat loss related to the mass flow rate. This result is very important for an initial estimation of flow situation and even more so for assessment of the plasma source condition and reproducibility of a test series.

An arcjet facility is being constructed at Instituto Tecnológico de Aeronáutica (ITA) (Fig. 1 and 2), with the purpose to produce an intense thermal flow, like those that are necessary in thermal protection materials test, was reported in "recent work (Barros, E.A and Petraconi. G., 2005)". In a first stage, it will only serve as the heat source, having the capacity to generate plasma jet with great enthalpy. And later, the vacuum system will be improved to simulate the aerodynamic ballistic reentry conditions.

2. EXPERIMENTAL APPARATUS

The experimental apparatus (Fig. 1 and 2) is composed by: a stainless steel vacuum chamber (3m^3); vacuum system with two stage rotary pumps (160m^3/h) connected to a booster roots (500m^3/h); pressure sensors and gas lines (oxygen, nitrogen, argon, hydrogen) with mass flow. Through a programmable controller connected to a butterfly valve it is possible to automatically adjust the pumping speed, keeping the constant pressure inside of the vacuum chamber, for small variations in the injected gas flow. The arc-heater is constituted by plasma torch with a exit Laval nozzle, cooled internally through the forced water circulation and two electrodes electrically separated by an electric insulator (Fig. 3). The gas injected in the plasma torch is ionized and heated by the arc between the electrodes, producing a plasma jet accelerated in the exit Laval nozzle.

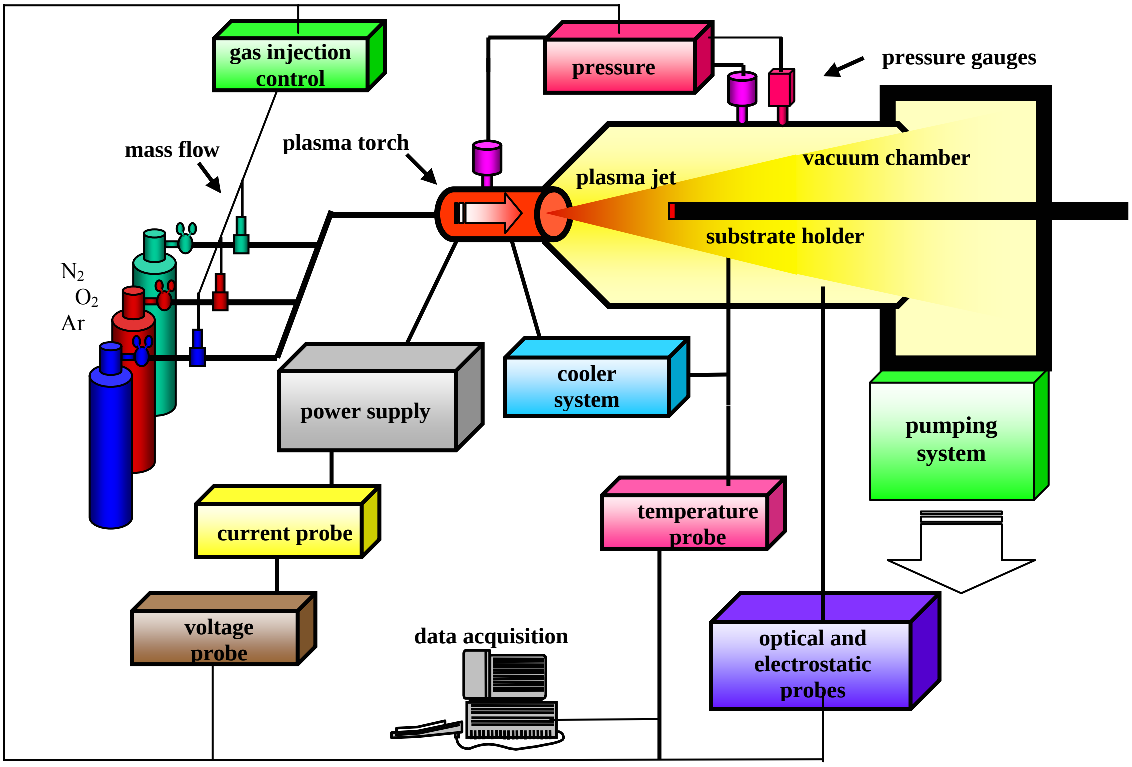


Figure 1. Diagram of experimental apparatus

Figure 3 shows the plasma torch build with a geometric configuration for the electrodes to improve the vortex generation, to minimize the premature consuming of the electrodes and copper vapor problems in first version, reported in “Barros, E.A. *et al.* (2005)” and “Charakhovski, L.I. *et al.* (2006a)”. This setup permits gas-dynamic control of enthalpy of plasma jet in addition to common control of the regimes of plasma heater. This makes it possible variation of the main parameters including enthalpy of plasma jet within wider range than during changing only the regime of plasma heater. In addition this allows adjust better characteristics of vacuum system to the regimes of operation of plasma heater. The method is based on the controlled outflow upstream the nozzle of the part of vortex flow from colder boundary layer at the walls of arc stabilizing channel into atmosphere with minimal heating, reported in “Charakhovski, L.I. *et al.* (2006b)”. There flow rate for arc stabilizing much higher than for generation of plasma jet was also used for testing heat shielding materials aiming increasing of operational pressure of plasma heater for increasing of heat flux to material tested.

Figure 2. ITA experimental apparatus

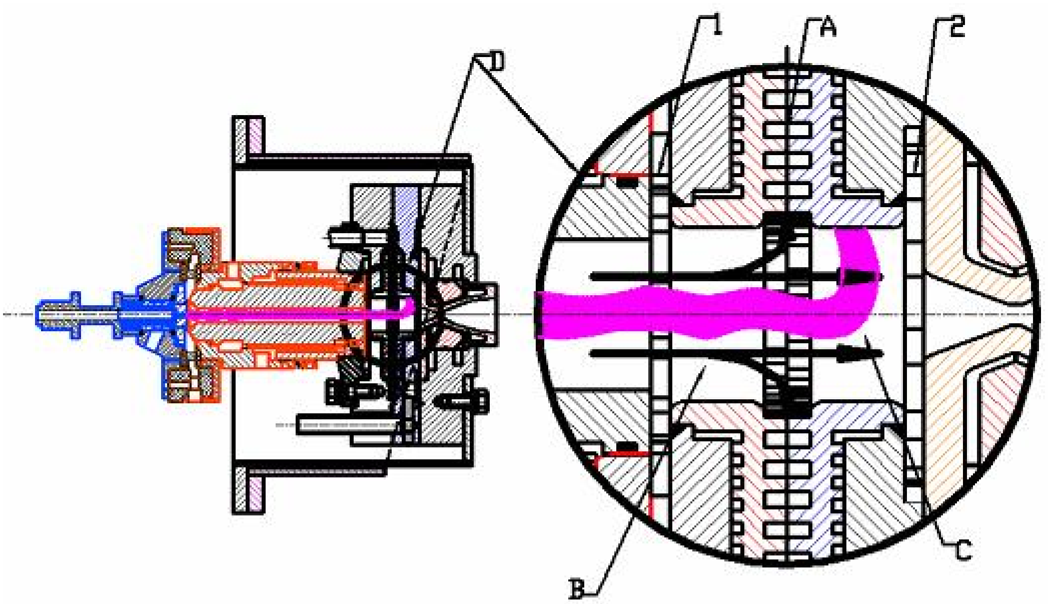


Figure 3. ITA plasma torch experimental setup. High-enthalpy plasma heater using pre-nozzle insertion as anode and the scheme of gas flows for the regime of elevated enthalpy. 1,2 – gas supplying vortex chambers; A –suction gap between water-cooled sections B and C. Flows are shown with arrows

Setup shown in Fig. 3 was tested using nozzles with the diameter of throat 2.7 mm and 1.9 mm. Diameter of nozzle exit was 22mm and hypersonic plasma jet obtained. Air was supplied from commercial manifold in ITA with the maximum pressure about 5 atm. Due to limited capacity of air system maximum pressure 2.5 atm in discharge chamber was used. The electric power source used in early experiments was capable to supply a tension of 120V, without load, and around 70V, with load, keeping voltaic arcs with current until 400A. Due to the low value of maximum tension that this source is capable to supply, it is only possible to carry through tests with argon. That is an easy gas of being ionized, with low electric breaking strength. To solve this problem its is being constructed a new power source, capable to supply tension higher (600V), that it will allow to the accomplishment of experiments injecting itself other gases in the plasma torch. The case of special interest is dry air or nitrogen and oxygen mixture similar to the atmosphere. Setup was fed from the same power supply made on the base of 6 welding rectifiers with the open circuit voltage 675 V and maximum current 140 A. Power supply volt-ampere characteristic is shown in Fig. 4.

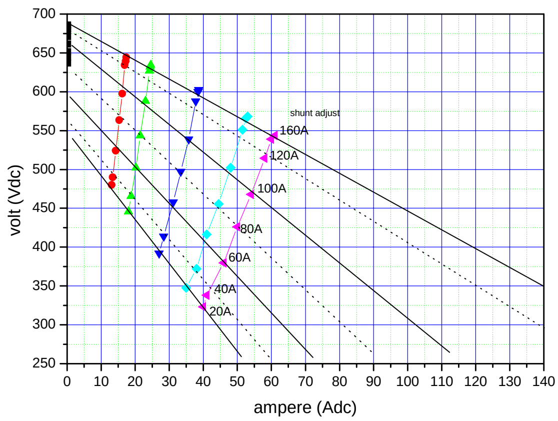


Figure 4. Power supply volt-ampere characteristic

The main parameter gotten in the characterization of this plasma torch is the enthalpy of the plasma jet generated in the torch through the voltaic arc in the gas. The measure of the enthalpy was gotten by stipulated in "ASTM E 341-81 (1996)". The temperatures of water refrigeration in the input and output of the plasma torch had been monitored with thermocouples, and the temperature gain is multiplied by water flow to obtain the lost power. The arc electric current was measured through a hall-effect sensor, and multiplied by a voltage measured with a digital voltmeter, to obtain the input electric power. The difference between input electric power and refrigeration lost power give the transferred power. For calculation of heat flux to calorimeter we used well known simplified version of the "Fay and Riddell (1958)" relation presented by "Sergeev *et al*. (1971)":

$$q = 0.45 R^{-0.5} P_{st}^{0.5} h \tag{1}$$

Here q – heat flux density. W/m^2; P_{st} – pressure at stagnation point. Pa; R – the radius of curvature of the front surface of calorimeter. m; h – enthalpy. J/kg. Equivalent radius of the flat end surface of cylindrical calorimeter (R_{cyl}) was taken as according to "Mezines and Masek (1979)":

$$R_{eq} = 3{,}33 R_{cyl} \tag{2}$$

Measuring of heat fluxes was made by well-known transient calorimeter. Calorimeter (Fig. 5) constitutes copper round disc by thickness 1.3 mm and diameter 10 mm placed to the face flat surface of cylinder by diameter of 12mm. This cylinder was made from carbon plastic material with low heat conductivity in comparison with copper. Copper disc was supplied by thermocouple at rear surface. Calorimeter was introduced to plasma jet (Fig. 6 and Fig. 7) to the time of 1-2 s and heating of copper disc was recorded by the data acquisition system. The examples of recording of the parameters of experiment we show in Fig. 8. At thickness of 1.3mm of the copper disc regular regime of heating was attained at the time less than 0.1 s and heat flux was calculated by well-known formula for such calorimeter:

$$q = \frac{a}{\lambda} \delta \frac{dT}{d\tau} \tag{3}$$

Here: a and λ – copper diffusivity and conductivity. respectively; δ – the thickness of plate; T – temperature; τ – time.

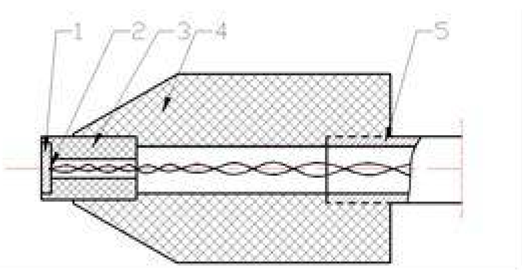


Figure 5. Schematic drawing of calorimeter. 1-sensor – copper disc by thickness of 1.3mm; 2 – thermocouple; 3, 4 – body made from heat insulating material; 5 – tubular holder

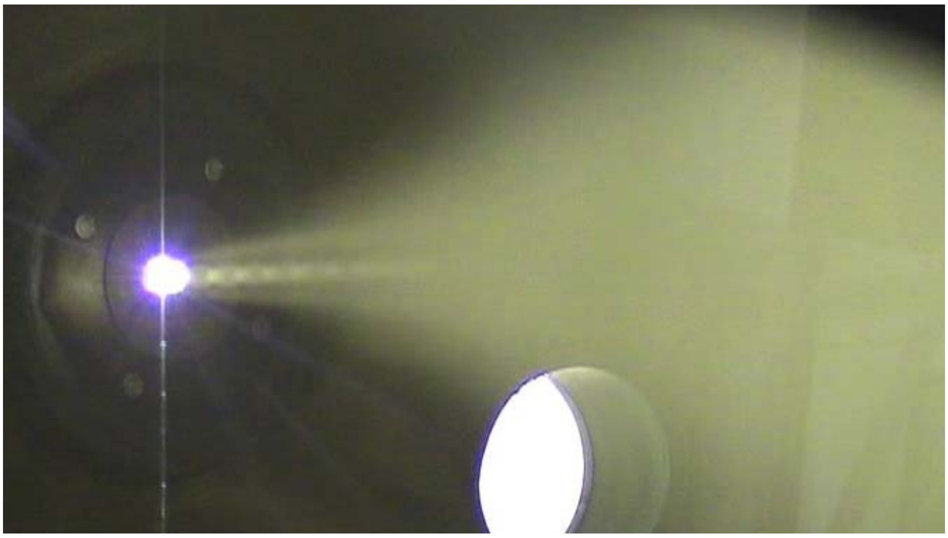


Figure 6. General view of the hypersonic plasma jet inside the vacuum chamber

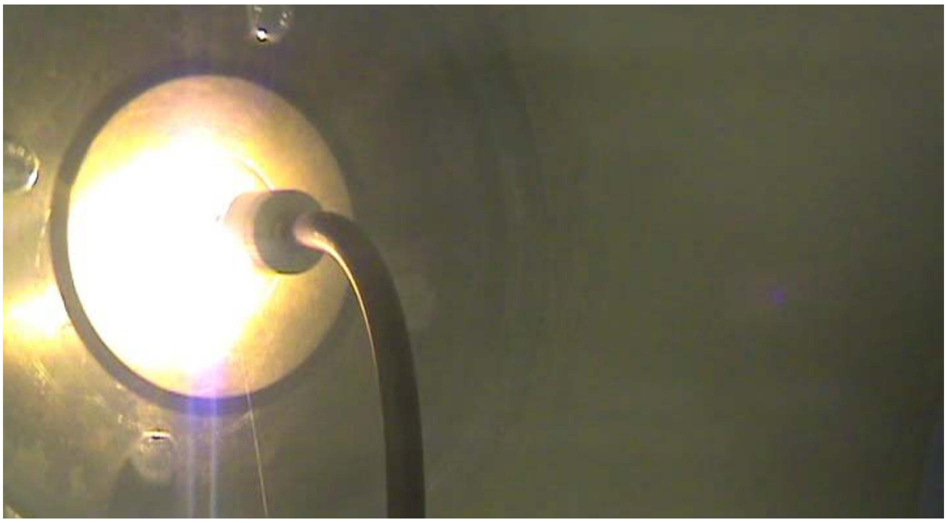


Figure 7. The view of calorimeter being streamed with hypersonic plasma jet

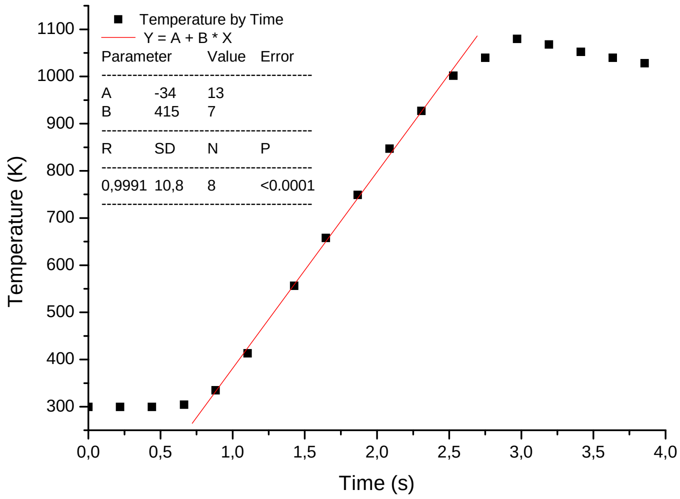


Figure 8. Example of record of temperature of sensor (copper disc) at calorimeter shown in the Fig. 5 and Fig. 7

2.1. Results and Comments

In accord with the project there was created hypersonic plasma wind setup based on available today in ITA energetic base and supporting systems. This setup showed during testing an ability obtaining Mach numbers up to 5, enthalpy from 1 MJ/kg to 13 MJ/kg, heat fluxes up to 3.4 MW/m^2 and stagnation pressures from 1 atm to 0.01 atm. By the level of heat fluxes, enthalpy and stagnation pressure setup is able modeling of the expected conditions of reentry of Brazilian satellite SARA for part of trajectory between altitudes approximately from 42km to 34 km, which was considered as the main task of this study. The lack of enthalpy in the form of kinetic energy is compensated in this setup by the enthalpy in the form of thermal energy for correct modeling thermal conditions at Mach > 5. So this method can supplement another methods applied today for reentry simulation.

Perspective appreciations were made and presented here for the possible further development of the hypersonic plasma wind setup by using the results of this work and available improvement of the supporting systems in ITA. Application of transonic blowing arc in created setup was also proposed for the further perspective elevating enthalpy.

Several types of plasma heaters were developed for testing materials. They include besides traditional plasma heater with the flat end thermo-ionic cathode also plasma heater with thermo-ionic insert deepened at tubular cathode and reverse vortex flow. Besides plasma heater was designed for especial applications with the flat plasma jet out-flowing transversally to the vortex axis with no twist.

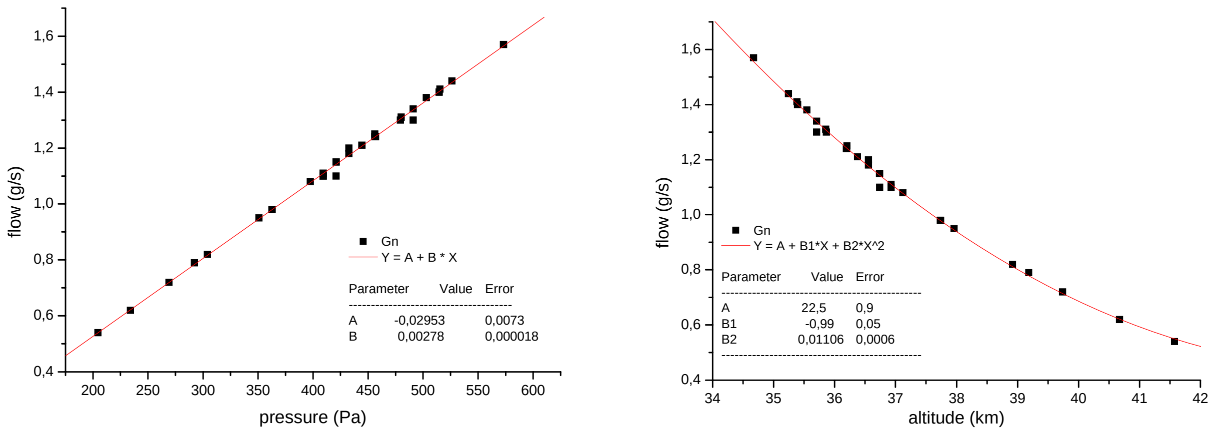
Plasma heater with the reverse vortex flow allows increasing thermal efficiency up to 10-20% depending on the regime. This can be significant during using experimental base with the limited electric power. Plasma heater with the flat plasma jet makes it also possible better using of electric power for testing of flat panels of heat shielding materials. This heater can also find collateral technological application for the kinetic plasma spray of refractory coatings with the improved density and lowered porosity due to elevated operational pressure high-temperature refractory mixing chamber and effective coaxial injection of material to plasma jet. These features have to improve the quality of coatings in comparison with the traditional kinetic spray with no plasma heating and traditional plasma spray with injection of material downstream the nozzle.

We show in Table 1 the main regimes of setup implemented during testing. Here I – arc current; U –arc voltage; N – arc power; G_h – integral air flow rate through heater; G_n – air flow rate through the nozzle; P_h – pressure in the heater discharge chamber; P_v – pressure in vacuum chamber, h – enthalpy of plasma jet; q_{th} – calculated theoretically heat flux to the front flat surface cylindrical body with the diameter 12 mm; q_{th} – the same heat flux measured experimentally; Mach number calculated by parameters of plasma in heater and ratio of pressures in heater and vacuum chamber; a – the distance from the nozzle to calorimeter during measuring heat flux. Enthalpy of plasma jet was calculated from the heat balance of plasma heater taking account also heat losses with the air deleted upstream the nozzle through control device for adjusting the regimes of plasma heater. The typical temperature of the gas out-flowing upstream the nozzle was about 200 ^{0}C.

Table 1. Experimental results of the characterization of plasma jet and plasma heater.

I, A	U, V	N, kVA	G_h g/s	G_n g/s	P_h atm	P_v Pa	h MJ/kg	q_{th} MW/m^2	q_m MW/m^2	*Mach*
97.6	351	34.2	8.18	1.57	2.22	573.2	7.39	2.59	1.80	4.2
98.2	345	33.9	8.18	1.24	2.02	456.2	8.50	2.76	2.00	4.3
99.0	343	34.0	8.18	1.15	1.91	421.1	9.07	2.84	2.50	4.3
99.5	342	34.0	8.18	1.08	1.80	397.7	9.42	2.83	2.45	4.3
99.7	340	33.9	8.18	0.98	1.70	362.6	10.00	2.85	2.30	4.2
99.9	339	33.9	8.18	0.95	1.60	350.9	10.40	2.83	2.40	4.2
100.3	340	34.1	8.18	0.82	1.50	304.1	12.95	2.83	2.20	4.2
112.0	349	39.1	10.43	0.98	1.50	363.0	11.10	2.73	2.15	4.2
110.8	354	39.3	9.65	1.41	2.40	515.4	10.00	3.83	3.38	4.2
109.7	358	39.2	9.27	1.31	2.35	480.3	10.00	3.31	2.46	4.3
109.1	361	39.4	8.89	1.24	2.30	456.8	9.90	3.18	2.57	4.3
100.6	346	34.9	10.50	1.40	2.10	514.6	8.12	2.25	1.80	4.2
114.4	350	40.0	10.10	0.72	1.30	269.0	13.73	2.64	2.40	4.3
119.8	329	39.4	7.25	0.54	1.15	204.6	15.80	2.78	2.30	4.3
79.0	364	28.7	7.7	0.72	2.5	234.0	7.3	1.46	1.36	4.8
75.6	376	28.4	7.00	0.62	2.5	234.0	7.9	1.54	1.46	5.0

The first parameter necessary to characterize the vacuum system is measure the mass flow of plasma jet versus static pressure inside vacuum chamber with stable operating conditions (Fig. 9 a). Then, using this static pressure with the atmosphere standard model is possible plot the simulated altitude versus mass flow through the Laval nozzle (Fig. 9 b). In the actual use vacuum system was possible operate with injected mass flow form 0.4 g/s to 1.6 g/s, and maintain a respective stable static pressure between 200 Pascal and 600 Pascal, that correspond to simulate altitude between 34 km and 42 km.



(a) (b)

Figure 9. Mass flow plasma jet versus (a) static pressure inside vacuum chamber, or (b) converted to simulate altitude

The mass flow through the Laval nozzle is function of many parameters like throat nozzle, gas temperature and pressure. In Fig. 10 we present the obtained relation for mass flow though the Laval nozzle versus pressure inside plasma torch discharge chamber. The average specific enthalpy of the flow, in exit plane of the arcjet nozzle, can be derived by energy balance. Therefore the electric power consumed by the plasma source the mass flow rate and the heat losses within the plasma generator are measured. The average specific enthalpy at the end of the plasma generator is then derived as the difference of the electrical power and the total heat loss related to the mass flow rate. This result is very important for an initial estimation of flow situation and even more so for assessment of the plasma source condition and reproducibility of a test series. In Fig. 11 we present the arc current versus pressure inside plasma torch discharge chamber and in Fig. 12 we present the enthalpy versus pressure inside plasma torch discharge chamber.

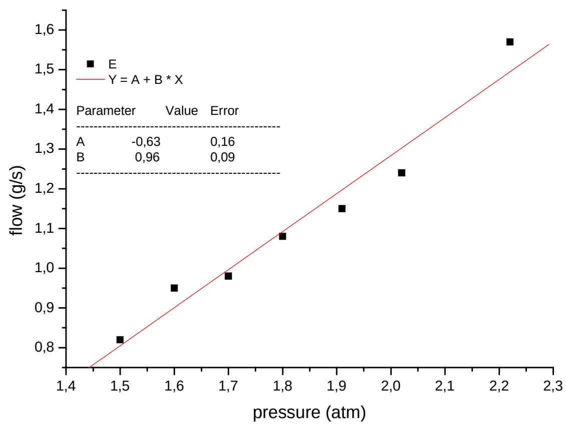


Figure 10. Mass flow of plasma jet versus pressure inside plasma torch

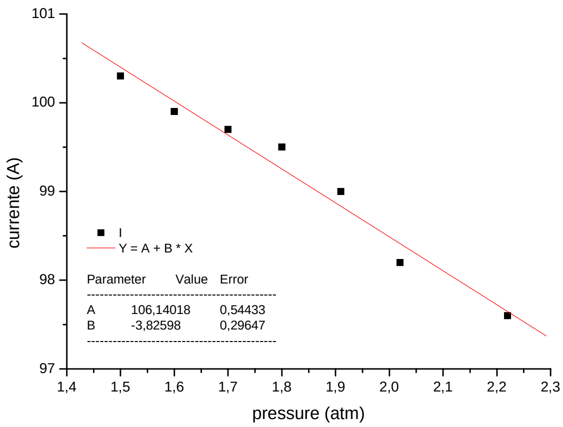


Figure 11. Current versus pressure inside plasma torch

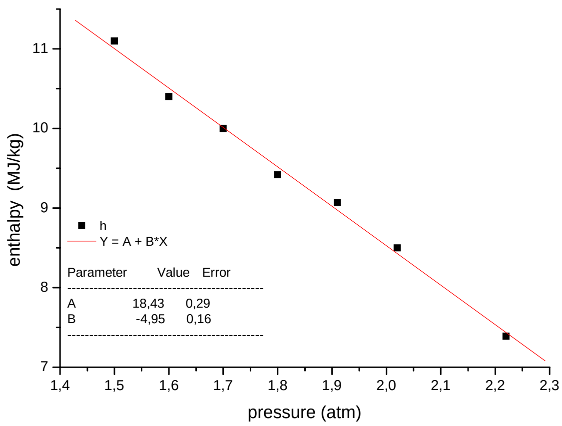


Figure 12. Enthalpy versus pressure inside plasma torch

2.2 Conclusion

This study confirmed that is possible simulate in steady state conditions some atmosphere reentry conditions required for the development of materials of thermal protection systems. The electric power consumed by the plasma source, the mass flow rate and the heat losses within the plasma generator are measured to determine the average specific enthalpy of the flow in exit plane of the plasma generator nozzle. Performance of the facilities during testing showed an ability to produce Mach numbers up to 5, enthalpy from 1 MJ/kg to 13 MJ/kg, heat fluxes up to 3 MW/m^2 and stagnation pressures in the range of 1.0 atm to 0.01 atm. This result is very important for an initial estimation of flow situation and even more so for assessment of the plasma source condition and reproducibility of a test series. By considering the levels of heat fluxes, enthalpy and stagnation pressure, the setup is able of modeling some conditions of reentry of Brazilian satellite SARA (satellite of atmospheric reentry) for the most crucial part of trajectory, for altitudes approximately from 42 km to 34 km.

3. ACKNOWLEDGEMENTS

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