EXPERIMENTAL PLASMA WIND TUNNEL FOR HYPERSONIC FLIGHT SIMULATING

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Abstract — **An experimental Plasma Wind Tunnel was developed at ITA (Technological Institute of Aeronautics). The setup allows simulating the hypersonic flight conditions at high altitudes using a plasma torch setup. This paper discus the particularity of the experimental setup and the methodology used to the Mach number measure in the plasma jet. The results of thermal protection system materials tested are presented. Plasma jet of about 18 mm diameter were obtained using a plasma torch of 25 kW at 300 Pa. This condition corresponds to altitude of 40 km. The plasma jet reaches an enthalpy up to 14 MJ/kg, heat fluxes up to 3 MW/m^2 and up to Mach number 3.8 .**

Key-words* — *Plasma, Plasma Wind Tunnel, Plasma Torch, hypersonic flow, atmospheric reentry.

I - INTRODUCTION

A. *Hypersonic and Atmospheric Flight Reentry*

There is a conventional rule of thumb that defines hypersonic aerodynamics as those flows where the Mach number is greater than 5 [1]. Rather, hypersonic flow is best defined as the regime where certain physical flow phenomena become progressively more important as the Mach number is increased to higher values. In some cases, one or more of these phenomena may become important above Mach number 3 [2]. Hypersonic flight simulations are important for reducing the cost of posterior flight tests. Plasma Wind Tunnel (PWT) is a facility that enable reproduce the conditions of a hypersonic flight using high power and enthalpy plasma jet. This paper concentrates on the hypersonic flight simulation, e.g., the reentry flight.

During the reentry in the Earth's atmosphere or another planet, the space apparatus, experience a sharp slowdown. This kinetic energy variation generates intense heat flows. The heating is generated at the surface of the entering apparatus due the surface friction of the atmospheric gas which required the use of a Thermal Protection Systems (TPS) to protect the apparatus from aerodynamic heating. The material used as TPS must be able to dissipate this high thermal energy. The mechanical and thermal properties of these materials are responsible for safety of crew and/or electronic equipment secure working inside the spaceship. However, large hypersonic PWT usually applied for such studies require a lot of energy and are very expensive [3]. This work presents a low cost experimental PWT that can achieve jet flow up to Mach number 5.2.

B. *Definitions and Applications of Plasmas*

The word Plasma has its origin from Greek and means something molded; Lewi Tonks and Irving Langmuir, in 1920, were the firsts to apply this definition to describe the inner region of a glow discharge [4]. Plasma is frequently cited as the fourth state of matter, it is justified because more than 99% of the known universe is in the plasma state. In general plasma contains neutral particles, electrons, ions, excited particles and photons. There is an important plasma property called quasi-neutrality, i.e., the amount of positive and negative particles are balanced [5]. Another important characteristic of plasma is the collective effects; it is due to the long range of electromagnetic forces each charged particle in the plasma interacts simultaneously with a considerable number of the other charged particle [4]. Sometimes plasmas are categorized as natural or man-made plasma. Examples of natural plasmas are stars, lightning and aurora borealis. Man-made plasmas are examples of lighting with fluorescent and neon lamps, and sparks plug used in the automotive engines [6]. Controlled thermonuclear fusion, magnetohydrodynamic generator (MHD) and plasma propulsion are some plasma applications that are currently being thoroughly studied. Plasmas are classified in thermal and nonthermal plasma. Thermal plasmas are in kinetic equilibrium, i.e., electrons and heavy particles have very close temperatures. On the other hand, plasma which contains electrons and heavy particle with very different temperatures are named nonthermal or cold plasmas [5]. Electric arc plasma torch is widely used at industry for cutting and melting as well as is the commonest plasma jet generator used in PWT around the world.

C. *PWT Structure*

To simulate the reentry phenomenon we need a hypersonic wind tunnel with high temperature flow. The conventional hypersonic wind tunnels do not work in this case [2]. A plasma jet obtained in plasma torch inside a vacuum chamber gives enough thermal energy to simulate the atmospheric reentry. Fig. 1 show a block diagram of a typical PWT [3,7]. Vacuum or test chamber is a compartment where the environment will be simulated. Pumping system is the set of pumps capable of extracting gases from inside the chamber and maintains the working pressure at appropriate level. Plasma jet generators can use two methods for generation of plasma: thermal plasma generator (TPG); and magnetoplasma-dynamic (MPG). The plasma jet generator can be powered by DC (direct current), AC (alternating

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current), RF (radio frequency) or microwave source. Data acquisition system is necessary for measuring and recording the parameters of the plasma jet, pressure in the chamber and data about samples in test. The exhaust gases from test chamber may contain substances considered harmful to the environment and equipment, and require special treatment. A cooling system is used to keep the plasma jet generator at safe temperature. Finally, the control system is responsible for driving both plasma jet generator and pumping system.

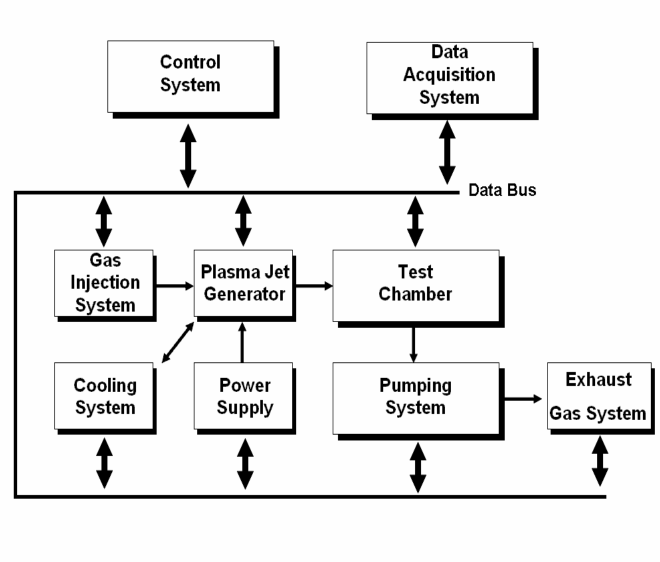

Fig. 1. Typical Plasma Wind Tunnel Structure

There are several PWT around the world. The largest one is the SCIROCCO PWT, constructed at CIRA, the Italian Aerospace Research Center in Capua, Italy. This test facility uses two conical nozzle configurations with exit diameters of 1150 and 1950 mm and heater by an electric arc of 70 MW. The tests may last up to 30 minutes [8]. However due of the very high operation costs, CIRA has developed a smaller PWT called GHIBLI, this new facility operates with 2 MW and enables testing models up to 80 mm [3].

II - THE EXPERIMENTAL PWT SETUP AT ITA

The experimental PWT setup constructed at the ITA (see Fig. 2) is a low-cost hypersonic plasma apparatus for reentry simulation. It was made on the basis of thermal plasma generator using a plasma torch with an especial pre-nozzle gas-dynamic insertion. Plasma torch has hafnium thermionic cathode and copper tubular anode. The plasma torch is mounted on a 1.5 m diameter, 1,8 m long, water-cooled test chamber; the vacuum system consists of two mechanical vacuum pumps and one Roots pump, which are capable of extracting 660 m^3/h. Usually the plasma jet is generated using air, but is possible generate plasma using Ar, N_2, CH_4, H_2 or any other gas mixture. In the experiments it was used two different convergent-divergent conical nozzles with the throat diameters of 3 and 1.8 mm, reaching Mach number 3.8 and 5.2, respectively. During this experiment the power supply reaches 160 V and 125 A. Using an air flow rate of the 7000 l/h the vacuum chamber was kept at P_v about 2.15 Torr which corresponding at an altitude of 40 km and are in good agreement with the exponential atmospheric model, usually used for aeronautics calculus [7]. Altitudes only up to 40 km can be simulated in this system because of the limited capability of the vacuum pumping system. The plasma torch generates a high enthalpy jet up to 14 MJ/kg that corresponds to about 5000 K. The diameter of the plasma jet is in the range 15-20 mm.

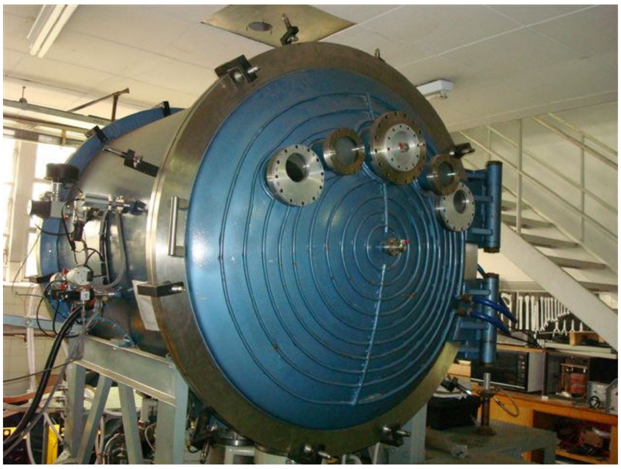

Fig. 2. Experimental Plasma Wind Tunnel at ITA, chamber test view.

III – RESULTS

The results of this experiment can be grouped in two blocks: plasma jet characterization and material tests. The plasma jet Mach number measurements is important to reproduces the closer reentry environment and the sample characterization is necessary for ensure the correct choice and dimension of the thermal protection system to a future spatial vehicle.

A. *Plasma Jet Characterization*

The key parameters for a plasma jet characterization are: a) measurements of Mach number; b) heat flux; and c) jet enthalpy. The Fig. 3 shows the shape of the plasma jet, where it is possible to view the successive diamond shapes. This phenomenon is observed at supersonic and hypersonic flow where formation of shock waves occurs. It means that the pressure of the gases exiting the nozzle is different from the ambient pressure and this difference causes successive compressions and expansions that result in this characteristics diamond shape pattern also known as Mach diamond or Mach disks.

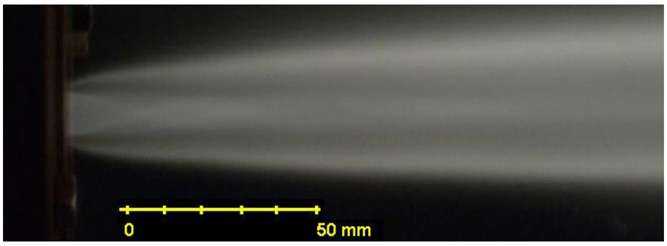

Fig. 3. Shock diamond effect at plasma jet of the Experimental ITA PWT.

Due the diamond shock wave effect, the plasma jet presents a non uniform flow. The most adequate position for the sample is very close to the nozzle exit, because in this point the flow is approximately uniform.

The Mach number of hypersonic flow can be evaluated from measurement of the ratio between the stagnation P_0 and static P_v pressure. The pressure within the flow can be measured using a Pitot tube, but in supersonic and hypersonic flow the introduction of an object causes a perturbation in the flow and a shock wave formation. Usually supersonic Pitot tube is supplied by orifice for measuring static pressure disposed at distance about 10D, here D is Pitot tube diameter. However we did not have this equipment.

That means we must apply very compact Pitot tube if we want to measure Mach number in non-uniform jet likely diamond jet. To make such tube is practically impossible for our plasma jet. Therefore we have really measured static pressure in vacuum chamber outside of jet using a pressure sensor. This pressure corresponds better to static pressure at the exit of nozzle. The static pressure was measured about 2.15 Torr which corresponding at an altitude of 40 km according with the exponential atmospheric model, see Fig. 6. At the remaining points static pressure in plasma jet can be much more different from the pressure in vacuum chamber. Then we can come to conclusion that Mach number about 3.8, which was measured close to the nozzle exit, is the truest. The Mach number, for pressure measured close to the nozzle, must to be evaluated using the (1) [9], where P_1 is the stagnation pressure in Pitot tube and P_v is static pressure at chamber.

$$\frac{P_1}{P_v}=\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{\gamma-1}}\left(\frac{2}{\gamma-1}\right)^{\frac{1}{\gamma-1}}\frac{M^{\frac{2\gamma}{\gamma-1}}}{\left(\frac{2\gamma}{\gamma-1}M^2-1\right)^{\frac{1}{\gamma-1}}} \qquad (1)$$

Here $\gamma=c_p/c_v$ = 1.194 is specific heat ratio according [10].

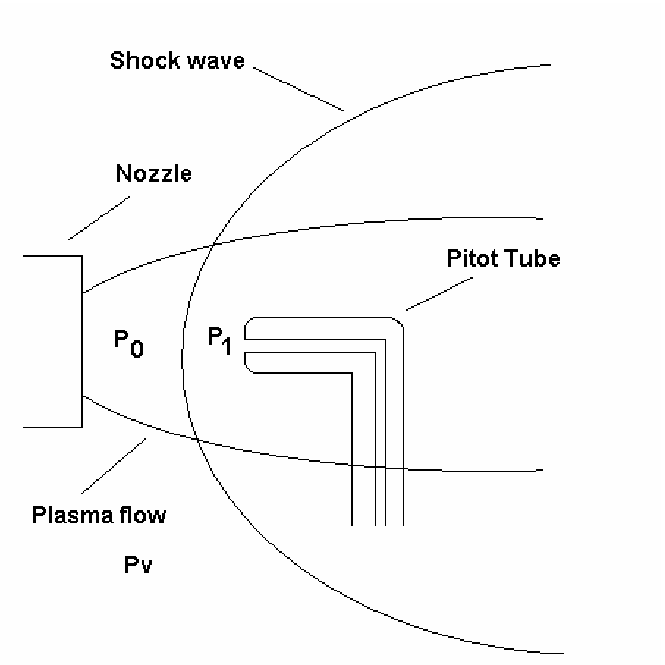

Fig. 4. Shock wave formation due the insertion of the Pitot tube.

The Fig. 5 presents distribution of the stagnation pressure P_1, along of the longitudinal axis of the plasma jet; where it is possible observe the pressure variation due to the Mach disc presence. The sample must be inserted in a uniform region of the jet to avoid changes in the parameters that would invalidate the experiment. Thus the material samples were placed at 5 mm distance to the nozzle exit.

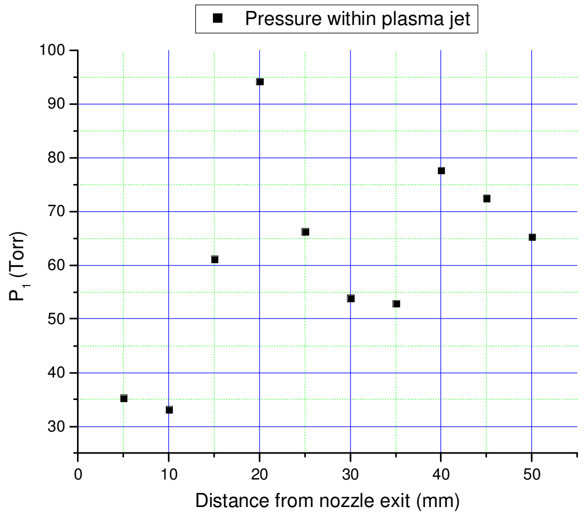

Fig. 5. Stagnation pressure P_1 along of the longitudinal axis of the plasma jet measured by Pitot tube.

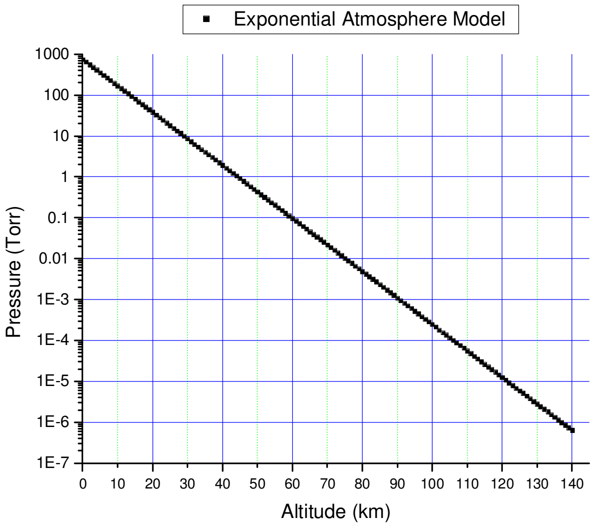

Fig. 6. Exponential Atmosphere Model.

B. *Material Testing*

In this block of experiment the ablation characteristics of quartz phenolic samples were studied. Quartz phenolic is a material typically used as TPS in space vehicle. Such materials are a phenolic-based material composed of quartz impregnated with a phenolic resin. Testing was carried out on seven disks of 6 mm thick and 11 mm diameter. Samples were exposed to the plasma jet during 60 seconds. An optical pyrometer was used for measure of the temperature of the sample surface subjected to the plasma flow and the temperature at rear surface was measured by thermocouple of type K. A water cooled support was constructed and a ceramics bushing was used for protect the side wall of the sample from thermal impact, according Fig. 7. This permits to apply one dimensional approach in sample heating. Before and after experiment the mass of the samples were measured by a precision balance to determine the mass loss. Thermal diffusivity, thermal conductivity and specific heat, are the three most important thermo physical properties of a sample material that are indispensable for heat transfer calculations [12].

The Table I shows initial mass m_i, final m_f and mean mass loss $\dot{m}$ of the sample. The mass loss was evaluated according (2) [11].

$$\dot{m} = \frac{m_i - m_f}{\pi r^2 \Delta t} \qquad (2)$$

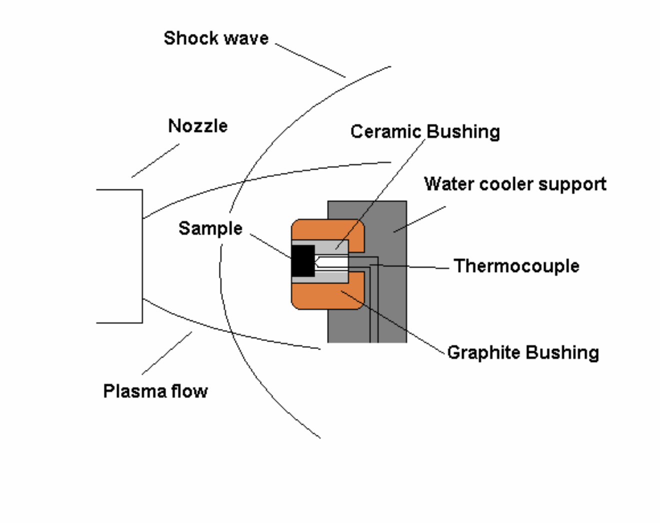

Fig. 7. The setup with sample of material in protecting bushing and water cooler support for testing in vacuum chamber.

The average mass loss and mass density were evaluated as 0.0298 kg/m^{2}s and 2.56 g/cm^3, respectively. According to Fig. 5, the front temperature measured by pyrometer increases rapidly and after stabilizes about 1550 K, while the rear surface temperature of the sample slightly increase up to 770 K. The data acquisition was started at t=0s and the sample was inserted at t=10s. The front surface temperature reaches the maximum temperature of 1580 K at t=22.25s. The rear surface temperature grows linearly and attains 823 K at t=72.48s, when the plasma torch was turn off. The heat flux 2.5 MW/m^2 was measured by a calorimeter at the same position where the samples were inserted.

TABLE I – MASS LOSS OF QUARTZ PHENOLIC SAMPLES.

Sample #	m_i (g)	m_f (g)	$\dot{m}$ (Kg/m^{2}s)
1	1.4719	1.3138	0.0277
2	1.4551	1.2652	0.0333
3	1.4868	1.2992	0.0329
4	1.4389	1.2797	0.0279
5	1.4308	1.2682	0.0285
6	1.2222	1.0611	0.0283
7	1.2008	1.0371	0.0287

The dimensions of the sample permit to apply one dimensional approach in sample heating. Using data from Fig. 8 and solving (3) was possible evaluating thermal diffusivity a=2,13 x 10^{-7} m^2/s.

$$\frac{\partial T}{d\tau} = a\frac{\partial^2 T}{dx^2} \qquad (3)$$

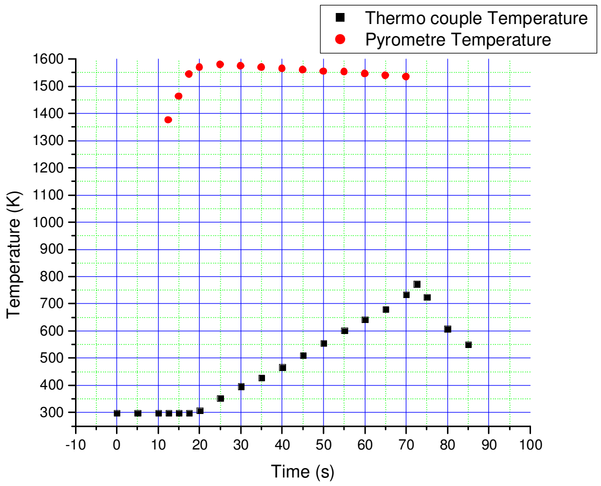

Fig. 8. Temperature at front and rear surface of the quartz phenolic sample #1 during a 60 seconds testing.

IV - CONCLUSIONS

Despite the modest characteristics of this experimental system, key parameters of the atmospheric reentry were satisfactorily simulated. Mach number up to 3.8 was attained. Samples of quartz phenolic material, used as thermal shield, were subjected to testing. News studies and implementations are necessary for constructing an operational plasma wind tunnel.

REFERENCES

[1] John J. Bertin, Russell M. Cummings; Fifty years of hypersonics: where we've been, where we're going; United States Air Force Academy, USAF Academy, 2003, USA.

[2] Anderson, John D., Jr.: Hypersonic and High Temperatures Gas Dynamics, 1 ed, McGraw-Hill Book Co., New York, 1989.

[3] Purpura, C. et al; The GHIBLI plasma wind tunnel: Description of the new CIRA-PWT facility; Italian Aerospace Research Centre, Capua, Italy, 2007.

[4] Bittencourt, J. A.; Fundamentals of Plasma Physics; Pergamon Press, 3th Edition; Oxford, U.K., 1987.

[5] Boulos, M. I; Fauchais, P.; Pfender, E.; Thermal Plasmas: Fundamentals and Applications, Vol I; Plenum Press; New York; 1994.

[7] Barros, E. A.; Dissertação de Mestrado; Câmara de Plasma Reativo para Ensaios de Materiais de Sistema de Proteção Térmica em Ambiente de Reentrada, ITA, São José dos Campos, Brasil, 2002.

[8] Purpura, C. et al; Experimental Characterization of the CIRA Plasma Wind Tunnel SCIROCCO Test Section; Italian Aerospace Research Centre, Capua, Italy, 2008.

[9] Abramovich, G. N.; Applied Gas Dynamics. Nauka, Moscow, Russia, 3 rd, 1969.

[10] Predvoditelev A.S., et al; The Tables of Thermodynamic Properties of Air; USSR Comp. Center, Moscow, USSR, 1962.

[11] Ogasawara, T.; Thermal Response and Ablation Characteristics of Carbon Fiber Reinforced Composite with Novel Silicon Containing Polymer MSP; Journal of Composite Materials,on line version: http://jcm.sagepub.com/cgi/content/abstract/36/2/143, 2002.

[12] Florain, M. et al; Themal Diffusivity and Thermal Conductivity of SiC$_f$/SiC Composite; 17^o CBECIMat – Congresso Brasileiro de Engenharia e Ciências dos Materiais; Brasil; 2006.