Experimental measurement of plasma jet flow under high enthalpy supersonic flow conditions achieved on 1MW Segmented Plasma Arc Tunnel

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Abstract: This paper describes an experimental investigation of plasma jet properties of a 1MW Tekna Segmented Plasma torch operated in Plasma Arc Tunnel (SPAT) designed for thermal material protection research and experimental studies of aerodynamics heating effect under high enthalpy flow testing. The 1MW (SPAT) can be operated from 3-20bar and develops an enthalpy flow conditions up to 20MJ/Kg. Various experimental measurements such us heat flux, enthalpy, and sample surface temperature are presented and discussed.

Keywords: Tekna Segmented DC torch, SPAT, Supersonic flow, High Enthalpy flow.

1. Introduction

The plasma wind tunnel consists of a stationary test facility in which a high enthalpy flow is generated using plasma generator and a pumping station to reproduce the re-entry conditions of space vehicles.

The main purpose of this installation is to reproduce the re-entry conditions where a material samples are tested under high enthalpy flow such an aerodynamic heating effect under supersonic flow that the capsules may be faced during re-entry to the atmosphere. For this purpose, a complete study and simulation of the physical phenomena, have to be studied and completely understood at the ground facility. On this paper we are presenting an experimental measurements of plasma physical parameters on graphite material sample compared to the numerical model calculations.

2. 1MW SPAT installed at ASL-Facility

The proposed 1 MW segmented DC plasma system will have the ability to perform thermal tests between 30-1000 mbar chamber pressure with 100 % air. Exhaustive instrumentations are also provided with the system allowing characterization of the plasma flow and heat flux on the sample.

The performance testing of insulation thermal system such as the improvement of flow characteristics on this plasma arc tunnel passes by a design of high quality equipment and high control and regulation such as 1) Segmented DC torch 2) Test chamber 3) Supersonic diffuser 4) Vacuum system 5) Heat exchanger 6) Power supply 7) Advanced control system.

2.1 Segmented Arc Heater

Tekna segmented-disk type arc heater consists from the inlet argon section to the plasma discharge chamber of a dual rear anode part, the convergent ring pack, 3 constrictor ring pack (1MW), the divergent ring pack, and a dual front cathode part. This arrangement is shown in figure 1.

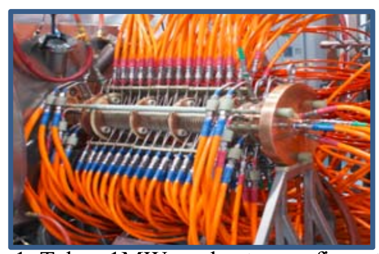


Fig. 1. Tekna 1MW arc heater configuration

The arc discharge is adjusted to achieve the desired test conditions and stabilized between the two electrodes located at the end of convergent/divergent section respectively. In order to minimize the electrode erosion due to the current concentration, an axial magnetic field is applied to the arc-root by a magnet coil built inside each electrode segment. The arc-root rotates in radial plane under the influence of the Lorenz force.

Table 1. The specification of the arc-heater

Type	Dual electrode segmented-disk Type
Current	500 amperes max per electrodes
Voltage	3600 VDC
Maximum Input Power	1.5 MW
Mass Flow Rate	15-60g/s at 50mbar
Max pressure	20 bar
Constrictor Inner Diameter	22 mm
Throat Diameter	7.8-15 mm
Nozzle Exit Diameter	9-47.5 mm

2.2 Facility sub-systems

Inside the vacuum chamber, an automatized 3 axis rotary arms, for holding samples, is disposed on the left side of the catch cone. It has a 4 cooled arms rotating in 360° to allow in the same test having various physical parameters measured. (Figure 2)

Fig. 2. Catch cone and rotary arm with probes for plasma plume and material characterization

3. Experimental set-up of 1MW Segmented Plasma Arc tunnel

The experimental measurements of plasma jet parameters such as: the specific enthalpy, plasma temperature, velocity, and heat flux have been achieved. This method of plasma characteristics is based on the suitable design of mechanical probes.

The results of the measurements achieved are presented and discussed on this paragraph.

3.1 Enthalpy using supersonic Tekna probe

The Tekna supersonic enthalpy probe is used for local plasma enthalpy, plasma temperature, plasma velocity and Mach number measurements. [1]

The main advantage of Tekna supersonic enthalpy probe is designed to have the measurement of the static pressure of the flow and the total pressure on the same probe as shown on the figure 3.

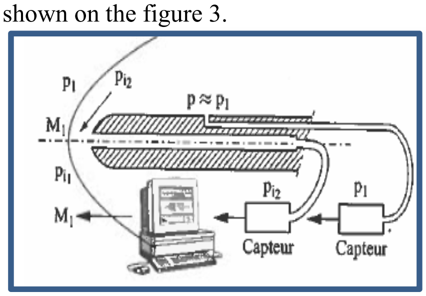


Fig. 3. Tekna supersonic enthalpy probe design

This design allows reducing the uncertainty of measurement which may occur because of using various probes, such as aerodynamic wedge probe used to measure Mach number or pitot tube used to measure dynamic pressure [2], which leads to perturb the plasma differently. The error is also made by considering a static pressure to be equal to the pressure inside the vacuum chamber.

The post-shock static pressure described by [3] measures the static pressure after a shock generated on the nose tip of enthalpy probe but using a separate probe. Even if this probe tends to reproduce the shock it has the disadvantage to use 2 different probes which inevitably leads to increase error in measurements. The Tekna enthalpy probe measure static and stagnation pressure using the same probe.

3.1.1 Enthalpy measurement principle

The local enthalpy of the plasma can be derived from an energy balance applied to the cooling water flowing through the probe and the gas sample extracted from the plasma and described in details by [1].

The second hole of the probe, dedicated for static pressure flow measurement, is disposed on rear back of the probe, downstream of the shock wave.

The equation used to determine the Mach number, in supersonic plasma jet, is called Rayleigh formula (2) and expressed as [4]:

$$\frac{P_{i2}}{P_1} = \left[1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1)\right]^{\frac{-1}{\gamma-1}} \left[1 - \frac{2}{\gamma+1}(1 - \frac{1}{M_1^2}\right]^{\frac{-\gamma}{\gamma-1}} \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma}{\gamma-1}} \quad (2)$$

The pressure ratio $\frac{P_{i2}}{P_1}$ is measured experimentally via dedicated gauges connected to the both holes of the probes as shown by the figure 6. [4]

The Mach number is computed by solving a Rayleigh equation (2).

3.1.2 Enthalpy measured with 1MW DC Tekna Segmented torch

The table 2 shows the plasma conditions of the enthalpy measurement in a supersonic flow. The gas plasma is considered as total mixture of Air with a small amount of Argon gas.

Table 2. The Plasma conditions

Plasma condition	Mass flow rate (g/s)	Power (MW)	Chamber pressure (mbar)
A) Nozzle R=5	21	.84	120
B) Nozzle R=15	44	1.05	75-95

The pressure inside the torch vary from 3 bar to 20 bar respectively following conditions A and B described on the table above.

The probe distance, from the exit plan of nozzle, is x = 80mm for condition (A), and x = 100mm for condition

(B). The local enthalpy has been measured in the center line of the plasma only. The probe has been aligned with the center line of the nozzle (Figure 4).

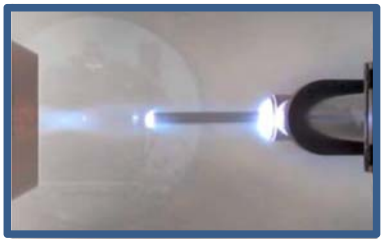


Fig. 4. Tekna enthalpy probe inside the plasma plume using a nozzle with ratio 5

The stagnation enthalpy measured using Tekna supersonic probe, has been compared with the enthalpy calculated using a numerical model and the total enthalpy deduced from the heat balance.

The total enthalpy measured experimentally by Tekna probe, in the case of torch pressure of 3 bar is 17.8MJ/kg, when the CFD model calculated 21.2 MJ/kg (figure 5 a-b). The experimental measurements show a deviation of 15% regarding the CFD model. The static pressure measured experimentally shows a deviation 15.5% compared to the static enthalpy estimated numerically. The experimental measurement presents a good match with a CFD model and lead to conclude that the probe can be used to estimate both stagnation/total and static enthalpy with an error of 15%.

In the case of torch operating at 20 bar, the total enthalpy measured experimentally is 11.39 MJ/kg (figure 6b) and is validated with numerical calculation which has calculated 12.4 MJ/kg as the deviation is less than 9%. For the static enthalpy both are very close each to other, and the deviation between the experimental measurement vs numerical calculation is less than 13%.

The plasma temperature is deuced from the gas table mixture created at chamber pressure directly via a software. Knowing the enthalpy measured experimentally, via the probe, the plasma properties is deduced from the gas mixture table.

The deviation between both temperatures calculated experimentally and numerically, shows a deviation of 3%, in case of P torch= 3bar, and is about 6% in case if P torch= 20bar.

For the velocity measurement (figure 6), both values are in the same range but present a deviation of 25% in case of P torch= 20bar. This deviation drops to 9% in case of P torch= 20bar.

We can conclude from the results presented in figure 5 & 6, the Tekna enthalpy probe can be used for enthalpy, temperature and velocity measurements under high enthalpy and high velocity conditions.

3.2 Heat flux measurement in: steady state and transient mode

Both stationary and non-stationary heat flux probes have been used to measure heat flux at 1MW segmented plasma Arc tunnel. The stationary probe is water cooled, and mounted with a heat transducer which is cooled separately and called Gardon gage and described well in the literature [2].

3.2.1 Heat flux measurement using Gardon gage:

The calibrated Gardon gage probe, which measures a proportional net absorbed heat transfer rate to the sensing tip at the stagnation point, has been inserted inside the plasma plume when the chamber pressure was at 55 mbar. The Heat flux measured experimentally is in agreement with the result obtained by CFD model and present a deviation of 6.5% (figure 7).

The heat flux obtained numerically is 8.32 MW/m2 and the Gardon gage has measured 7.8 MW/m2. This result reinforces our CFD model to evaluate a heat flux under high enthalpy supersonic flow and confirm the Gardon gage technology at high enthalpy conditions.

3.3 Surface temperature measurement using: IR camera, Pyrometer and Fast Response Thermocouple

The main objective from those techniques [5] is to study the ablative materials at high heat flux levels and provide a database on precise information about the materials to be characterised and developed for thermal barrier protection used for re-entry of space shuttle. Both IR camera and pyrometer used on this experimental measurement of surface temperature behaviour are operating in the close spectral range near infrared to avoid measuring the light coming from the plasma. The IR camera is operating in spectral range of 0.9 to 1.7 µm. It is provided with 2 calibrated intensity filter allowing measurement from 500-1200°C and from 1200-3000°C respectively.

The pyrometer used is operating bi-chromatic which measures the intensity of infrared radiation at two different wavelengths ($\lambda 1$ = 950 nm and $\lambda 2$ = 1050nm) at the same time. The ratio of these two intensities is proportional to the temperature. Thus a two-colour pyrometer measurement is not influenced by emissivity changes or obstructions within the sight path such as dust or water vapour.

The both optical techniques are mounted at the external windows of the vacuum chamber and disposed at the same distance from the target. The fast thermocouple is installed inside the material and connected to high data acquisition device.

As shown from the figure 8 a) and b), the surface temperature measured by the pyrometer is 2175 °C and the temperature measured by the IR camera delimited by the blue circle (1) shows a maximum temperature of 2109.09°C. The software also allows to determine in the delimited circle the minimum and average temperature estimated to be 2092.58°C and 2102.66°C respectively.

Considering the minimum, maximum and average temperature measured by the IR camera, in all cases, the deviation comparing to the surface temperature measured by the pyrometer is not exceeding 4%.

The thermocouple is choosing to be as thin as possible, in arrange of less than 1 millimetre diameter, to be as less intrusive as possible to the material to be characterized. It is mounted inside the material in the way that is aligned with the front nose tip of the sample but touching the upper surface.

As the sample probe is facing a high heat flux at its front, this results in the fast rising temperature of the thermocouple sometimes beyond its limit. This leads inevitably of damaging the thermocouple after certain or unique use. For this reason, the response of the thermocouple is read via a high data acquisition device which has been set in 1 microsecond for a maximum duration of 10 seconds.

The figure 9, show the inner temperature surface increase in function of time, and seems to be stabilized 2 second before the end of the test at 1285 °C. This result is obtained in plasma condition of 20bar- 11MJ/kg.

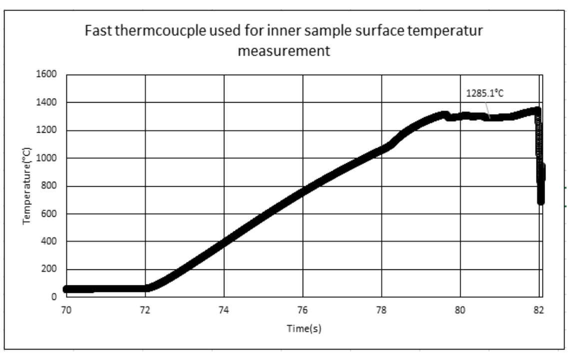


Fig. 9. Surface temperature measurement using a thermocouple mounted inside the sample material at P torch= 20bar.

The information resulting from this experiment is that the material tested present a difference of 824 °C between the inner and outer surface sample temperature. As we do not have enough information about the material tested, we cannot estimate if this result is valid or not. However, the duration of the test for this kind of material and the technique of surface measurement using a thermocouple is validated as a method of inner sample surface temperature measurement.

4. Conclusion:

The measurements of plasma physicals parameters have been conducted using a various intrusive instruments and compared to the CFD model calculation. The measurements have been limited at the center line of the plasma. Indeed, in the center line of the plasma, the thermal equilibrium is approached and/or reached. Therefore, the effect of non-equilibrium because of low pressure and supersonic flow are less significant. This allow us to be confident with our experimental measurements. The CFD calculation has reinforced our measures and are in accordance with our results. The deviation between both methods is contained within a reasonable percentage (less than 16%) for a measurement under high enthalpy flow conditions. These results can serve as an interesting database for experimental measurements in this type of installation and in our knowledge there is no much experimental data reported in such facility.

Using non-intrusive instruments such as IR camera and pyrometer to measure the sample surface temperature has shown a very good interesting results. The measurements resulting from both techniques have been confronted and present a similarity on the target point. Finally, it has been demonstrated that using some experimental set-up and rules before starting plasma, the data collected under high enthalpy and velocity flow, can be used, with confident, to characterize and qualify the material to be used as a thermal barrier material on aerospace shuttle vehicles.

5. Reference:

[1] M. RAHMANE, G. SOUCY and M. BOULOS, ‘’Analysis of the enthalpy probe technique for thermal plasma diagnostics’’, Rev.Scl.Instrumen.Vol.66, No.6, June 1995.

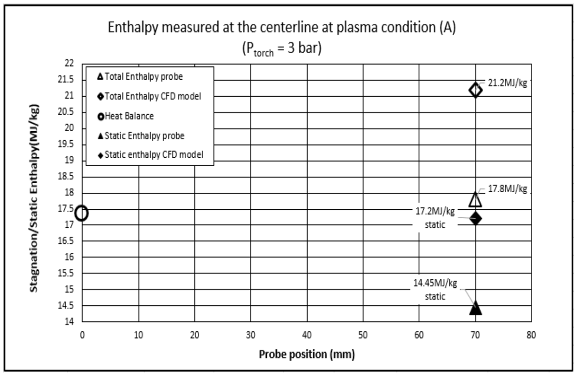
[2] M. AUWETER-KURTZ, M. FEIGL, M. WINTER ‘’Diagnostic Tools for Plasma Wind Tunnels and Re-entry Vehicles at the IRS", Rhode-Saint-Genkse, Belgium, 25-29 October 1999, and published in RTO EN-8.

[3] J.-L. DORIER, B. JODOIN, M. GINDRAT ‘’A novel approach to interpret enthalpy probe measurements in low pressure supersonic plasma jets ‘’, Proc. of 16th International Symposium on Plasma Chemistry, Taormina, Italy, 22 – 27 June 2003.

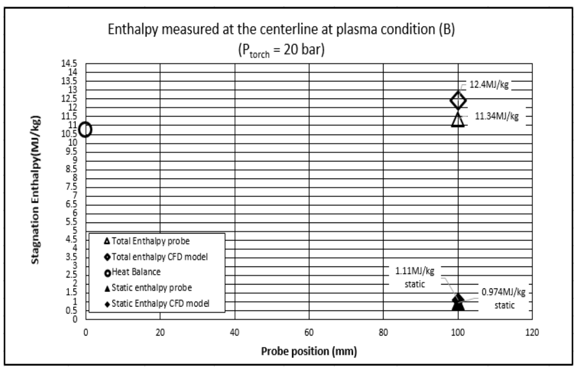
[4] J. D. ANDERSON, ‘’ Fundamentals of aerodynamics’’, 4th Edition.

[5] C. O. ASMA, B. HELBER, ‘’ Infrared thermography measurements on ablative thermal protection systems for interplanetary space vehicles’’, 10th International Conference on Quantitative InfraRed Thermography, Québec, Canada, July-30, 2010.

ANNEXE

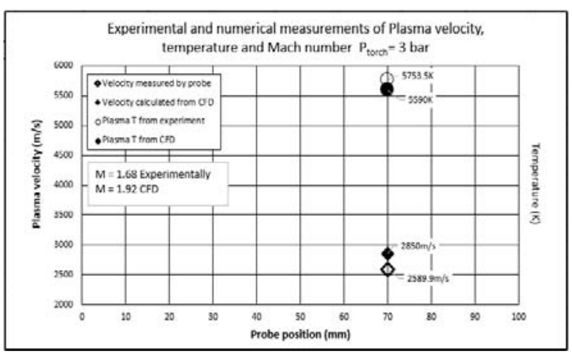


a)



b)

Fig. 5. Enthalpy results using enthalpy probe, numerical model and calorimetric balance, a) 3 bar and b) 20bar.



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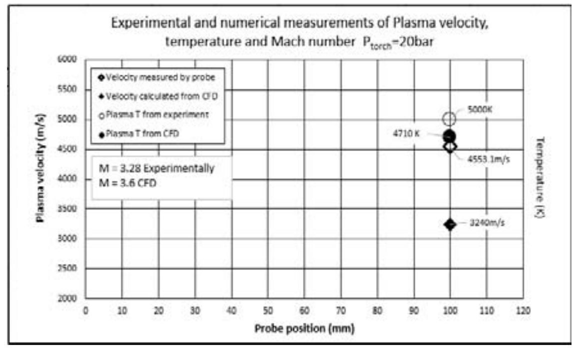


b)

Fig. 6. Temperature, velocity and Mach number calculated from Tekna enthalpy probe and CFD model a) 3 bar, b) 20 bar.

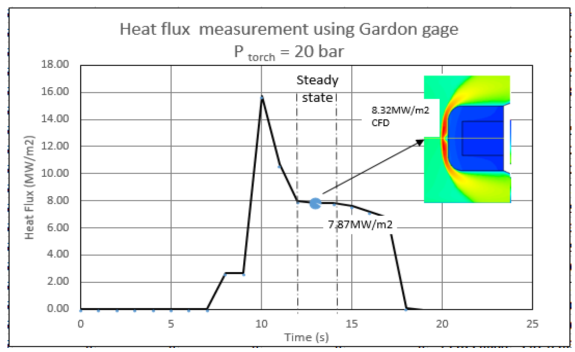
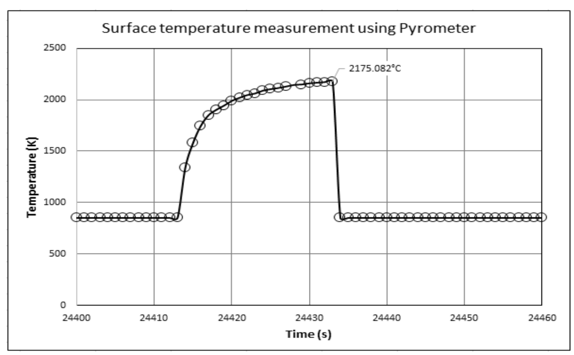


Fig. 7. Heat flux measurement in MW/2 obtained experimentally and compared to the CFD result.



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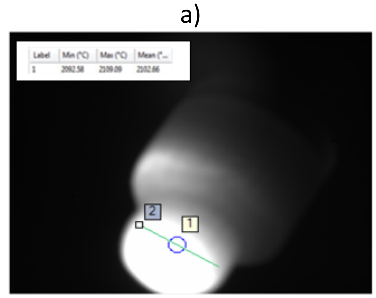

b)

Fig. 8. Surface temperature measurement of sample using a) Pyrometer b) IR camera at P torch= 20bar.