EVALUATION AND IMPROVEMENT OF THE SCIROCCO FACILITY FOR SIMULATION OF CO_2 PLASMA IN CASE OF MARS AND VENUS ENTRY

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ABSTRACT

The objective of this study is to analyse the performances of the SCIROCCO Plasma Wind Tunnel using CO2 as process fluid, instead of air. This research deals with the possibility of simulating the vehicles atmospheric entering in planets such as Mars and Venus, whose atmosphere is almost totally composed by carbon dioxide. The performance map of the facility in this operative condition will be expressed in terms of stagnation heat flux and stagnation pressure on a reference model, that is a fully catalytic 600-mm diameter copper water-cooled probe

A bibliographic research about the most important Mars landing missions has been started and in particular Pathfinder entry has been analysed. Pathfinder trajectory has been compared with the performance map of the facility. In this way, the capability of SCIROCCO to perform ground tests for interplanetary entry is shown to the aerospace community.

1. INTRODUCTION

SCIROCCO, the name of the hot wind which blows in the Mediterranean area, is the name given to the project of the biggest European plasma facility (PWT). This high power hypersonic arc-jet wind tunnel has been erected at CIRA (Centro Italiano Ricerche Aerospaziali) in Capua, near Naples, South of Italy. The project was financed by the Italian Ministry for University and Scientific Research (MURST) and the European Space Agency (ESA) [1].

The facility is driven by an arc jet of 70 MW power and produces hypersonic plasma-jet with a diameter up to 2 meters, the maximum run time is about 30 minutes. The importance of SCIROCCO lies in the possibility to perform Earth re-entering tests on large dimension samples (until 800 mm diameter) , even using models in scale 1:1. Besides, this facility is almost disposed to carbon dioxide gas employment to simulate other planets' entry conditions.

In an international scenario more and more devoted to the Solar System planets exploration, SCIROCCO represents an outstanding potential facility for entry experimental simulations.

Until today, the Mars re-entry projects have been concerned of small size probes. Missions such as Pathfinder and Mars Express, performed by NASA and ESA respectively, needed of aero-thermodynamic tests implemented in low-power and small dimension facilities because of the smallness of their Thermal Protection System. In prospect of a human landing on Mars, performing more and more reliable and frequent tests on large scale samples will be necessary, to highly guarantee the crew safety. So, in this new testing field, the Plasma Wind Tunnel SCIROCCO would cover a central rule, requiring only some upgrades to simulate manned space vehicles Mars entry. The devices and the experimental resources made available with the realization of SCIROCCO constitute an important chance for the development of future space transportation systems needing entry different types of atmospheres [2].

2. THE SCIROCCO FACILITY

The SCIROCCO Plasma Wind Tunnel is a major hypersonic arc heated facility, capable of producing a low- pressure high-enthalpy plasma flow of large dimension on samples in scale 1:1 with a test duration up to 30 minutes. Until now the facility's most important employ is testing and validating Thermal Protection System materials. In

addition to these features, the facility may also be upgraded to operate with process gas different than air to simulate re-entry conditions of other planet atmospheres and for experiments in the field of propulsion systems such as scram-jet and ramjet engines [1].

The design and engineering of the SCIROCCO-PWT represents the state of art for the arc jet technology.

The primary units of the facility are:

- arc heater, conical nozzle, test chamber, model support system, diffuser, plasma heat exchanger, and control/DAS&safety.

The auxiliary units of the facility are:

- power supply, vacuum and stream supply, cooling fluids, compressed air, argon supply, electrical system, $DeNO_x$/Osmosis, test instrumentation, hoist equipment, and civil works.

The arc heater of the SCIROCCO-PWT is one of the biggest in the world in the family of constricted, low-pressure arc heaters. It is segmented into 580 discs with a bore diameter of 0.11m and a length of 5.5 m. At the extremities of this tube there are 9 and 9 discs (cathode and anode), so in the axial direction a confined electrical discharge is generated.

Process air at a mass flow rate in the range of 0.3-3.5 kg/s at high pressure (87 bar), coming from a compressed air plant, is supplied to the arc heater, with an argon gas flow of about 0.07 kg/s . It is important to facilitate the ignition of the electrical arc and to reduce electrodes oxidation. Process fluid is injected in the column tangentially to follow a semi-circumference in order to avoid electric discharges from the axis towards the inner surface of discs. This injection method phenomenon is named “swirl” and it has the effect to assure axial the flow.

The electrical arc, stabilized inside the arc heater, transforms the electrical energy into thermal energy and increases the temperature of the process gas. So the presence of new free electric charges induced by high temperatures determines the passage of fluid to the state of *plasma.*
The process air into the arc heater is at an average pressure of 2-17 bar and is heated to 2,000-10,000 K [2].

The minimum enthalpy of the segmented arc-jet is of about 10 MJ/kg linked to the minimum allowable current necessary to sustain the electrical discharge. Into the SCIROCCO facility a device to reduce the minimum jet enthalpy down to 2,5 MJ/kg is implemented. It is the ‘plenum chamber’ located at the end of the arc heater to carry out the injection of ambient cold air.

The heated compressed air is accelerated through a convergent-divergent conical nozzle. The geometry of the nozzle may be varied in four different configuration in order to permit the achievement of the desired flow condition and to match any model size. Then the plasma flow impacts the model that is injected into the stream by an automated arm (Model Support System) fixed on the lower part of the test chamber.

The test Chamber has a cylindrical vertical shape with an overall height of 9.217m and an inner diameter of 5.17m.

Successively, the hypersonic jet is collected by a very long diffuser (50m). The diffuser has a variable diameter, with an average of 3 m. During the passage through the diffuser the flow reduces the velocity from hypersonic regime to subsonic regime through the generation of a shock wave train confined into the diffuser and don’t affecting the test condition in Test Chamber, thanks the exceptional length of the diffuser [3].

The diffuser is directly connected to heat exchanger whose purpose is to cool the stream to a range of temperature acceptable for a comfortable working and sizing of the vacuum system. This generates and maintains the appropriate vacuum conditions in the test chamber required by each test. It is a very powerful system (80 MW of energy) and it’s constituted by 12 ejectors and has an arrangement with 3 different stream-jet parallel lines and with four section stages.

A $DeNO_x$ system follows the vacuum system to neutralize nitrogen oxide created during the test [2]. An automation and data acquisition system provides an high level performances in the control of the whole facility.

The full characterisation of the plasma flow characteristics impacting the test model can be performed by using the calibration probes. They are two arms water cooled and their function is to support and locate all instruments for plasma flow diagnostics such as heat flux, pressure and temperature sensors [1].

A cooling fluid system interfaces with every unit and is devoted to remove the heat through cooling circuits in which H_2O in different conditions of pressure.

3. SCIROCCO PERFORMANCES

SCIROCCO has been designed to duplicate aero-thermodynamic conditions encountered by space vehicles while re-enter the Earth's atmosphere. Requirements for SCIROCCO have been specified by ESA/CNES for the HERMES spaceplane in terms of pressure and temperature at the stagnation point of the nose and wing leading edges of test models [2].
The main facility performance map used to design the facility components and obtained by extrapolations of semi-empirical correlations is reported in figure 1. The curve has been obtained taking into account either the operative conditions or technological limits. It shows the values of stagnation heat flux and stagnation pressure that is foreseen to be reached on a test article in test chamber. The curve are represented: the first one obtained by the designer by using conservative formulas and the second one obtained by using CFD codes. The three boxes represent the initial facility user requirements.
Two test models are considered: hemi-spheres with radius of 0.3 and 0.24 mt., respectively. The material of the sample is considered fully catalytic. The facility envelope is considered referring to all four available nozzles with the exit diameter of 0.9, 1.15, 1.35 and 1.95 mt., respectively [3].

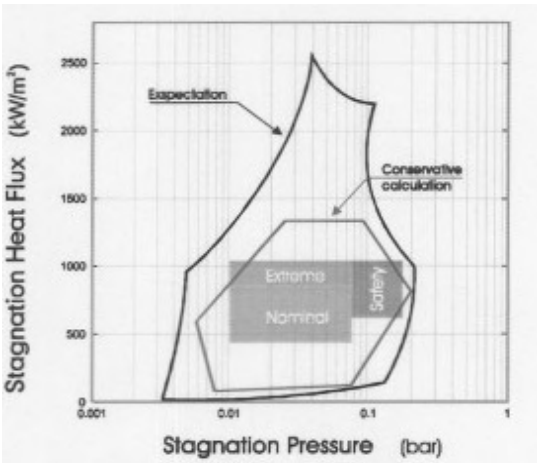

Fig. 2 – Facility Performance Map

SCIROCCO is operative since October 2001 and about 200 tests have been carried out until today. The most part of these tests have been devoted to calibrate the facility and the previous predicted performances have been almost completely confirmed.

The development of SCIROCCO has been done keeping in mind its possible use for other domains like planetary entries for the Scientific Exploration Program of ESA. As a matter of fact the design allows a great flexibility of the facility such as capabilities to work using gas different from the air (i.e. CO_2) [1].

About this subject, a significant study has been performed and published by F. De Filippis and S. Caristia, researchers at CIRA in Capua, in cooperation with ESA in 2001[4].

The present paper investigates the capabilities of the facility to simulate flight conditions during entries into planet atmospheres containing CO_2.

Performances of SCIROCCO facility have been calculated considering two atmosphere models:

- A 100% CO_2 atmosphere, modelling Venus environment;
- A 95% CO_2 and 5% N_2 atmosphere (in mole fraction), modelling Mars environment.

This performances evaluation has been developed in three phases: the gas composition analysis, the quasi one-dimensional prediction of the nozzle flow and the axisymmetric non-equilibrium simulations on a model.
The gas composition analysis has allowed the investigation at equilibrium of chemical and thermal states of the mixture for a large range of temperature and pressure. A database has been developed from the literature on the termo-chemical model.

The equilibrium chemical analysis has been used to develop a quasi one-dimensional approach of the flow in the nozzle. Successively, the flow has been considered chemically frozen for high velocities and low pressures and the parameters have been calculated with isentropic relations for a perfect gas.

A three dimensional non equilibrium solver named TINA [4] has been employed to perform axial-symmetric simulations on the model. However, a complete investigation of the arc-heater envelope of SCIROCCO with a Navier-Stokes solver is not realistic due to the cost of such calculations. The few results obtained using TINA have been compared with those given by the quasi–one-dimensional approach of the flow. This comparison is given in figure 2 which shows the heat flux and

stagnation pressure conditions that SCIROCCO facility is able to produce with a plasma in the arc chamber [4].

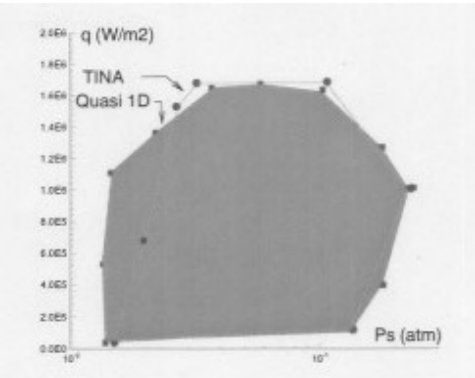

Fig. 2 – Stagnation Pressure and Heat Flux on the model using CO_2.

The figure 3 is obtained using air in the arc heater, where every couple (I; m) of current (up to 9000 A) and flow-rate (from 0,1 to 3,5 kg/s) corresponds to a particular couple (H_0,P_0) of stagnation enthalpy and pressure.

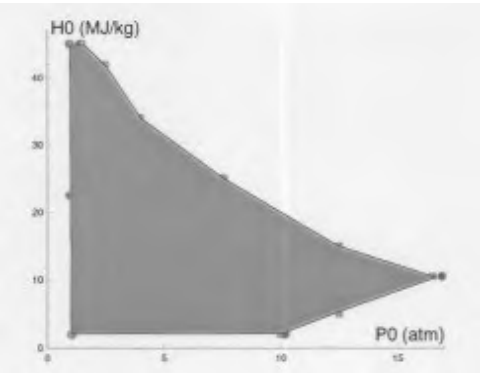

Fig.3 – Arc Heater Performance

Since this couple of values (H_0,P_0) varies also in relation to the process gas, the figure 3 should be modified for CO_2 applications. However, in this study the approximation of such a behaviour for CO_2 and air in the arc heater has been considered. Therefore, while q and p_s are obtained by computational (and not experimental) methods using carbon dioxide, H_0 and P_0 for CO_2 are assumed coincident with values for air.

4. MARS MISSIONS

In this paragraph an overview of past Mars missions and of future entry programs is presented to analyse the curves of entry trajectories relevant to each program.

The first program for a close Mars observation was designed by the NASA Jet Propulsion Laboratory between 1962 and 1973 and consist on 10 spacecraft named *Mariner*. They were small robotic explorers whose mission was to collect photos of the planet to have the-map of the whole Mars surface[5].

The mission that performed the first landing on the red planet was the NASA *Mars Pathfinder*. This program used an innovative method for directly enter the Mars atmosphere: a parachute was used to slow its descent through the thin Martian atmosphere and a giant system of airbags to cushion the impact. The landing site was an ancient flood plain in the Mars northern hemisphere, known as Ares Vallis, located in the rockiest parts of Mars. It was chosen because scientists believed to be a relatively safe surface for landing and containing a wide variety of rocks deposited during a catastrophic flood.
From landing until the final data transmission on September 27, 1997, *Mars Pathfinder* returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors [6].

In 2003 NASA started a new project named *Mars Exploration Rover Mission,* consisting of two rovers equipped of instruments for water traces diagnostic.
The mission *Mars Express* set off on 2 June 2003 becoming the first European landing project on the Red Planet realized by ESA in co-operation with NASA and ASI (Agenzia Spaziale Italiana).
On 25 December 2003, Mars Express ejected the rovers. During this time, the point of the orbit closest to Mars (pericentre) will move around to give the scientific instruments coverage of the entire Martian surface at all kinds of viewing angles [8].
For the next future, NASA is preparing a project which will start in August 2005 named *Mars Reconnaissance Orbiter*.
It is a research to give evidence that water persisted on the surface of Mars for a long period of time. While other Mars missions have shown that water flowed across the surface in Mars history, it remains a mystery whether water was ever around long enough to provide a habitat for life. Science instruments onboard will zoom in for extreme close-up photography of the martian surface, analyze minerals, look for subsurface water, trace how much dust and water are distributed in the

atmosphere, and monitor daily global weather. Besides the orbiter is provided with telecommunications systems to establish a crucial service for future spacecraft, becoming the first link in a communications bridge back to Earth, an "interplanetary Internet" that can be used by numerous international spacecraft in coming years [9].
"Mars Reconnaissance Orbiter is a quantum leap in our spacecraft and instrument capabilities at Mars," said James Graf, the mission's project manager at NASA's Jet Propulsion Laboratory, Pasadena, Calif. "The data rate from the orbiter at Mars back to Earth will be three times faster than a high-speed residential telephone line. This rate will enable us to return a tremendous amount of data and dramatically increase our understanding of this mysterious planet"[10].

5. SCIROCCO CAPABILITIES

In this paragraph the SCIROCCO capability for the Pathfinder entry trajectory simulation is analysed. The aim is to match the numerical data of the SCIROCCO facility using CO_2 to the particular geometry of the probe. The forebody is a sphere-cone shape with a nose radius of 0.66 m and half angle cone of 70 deg, the base radius is 1.32 m; the afterbody is a truncated cone with a half angle of 46 deg. The heat flux is maximum on the forebody in the region next to the probe axis, so the study is restricted to this zone. From a Physical analysis of the phenomenon, the heating flux on a flat sample can be estimated as the half of the one acting on a same dimension sphere. Being Pathfinder a non totally flat body in the region near the axis, the thermal flux on the central part of probe has been considered as the 75% of the flux on a sphere with a radius of 0.3 m.
Figure 5 and 6 show the values of stagnation pressure and heat flux on the probe as function of the Altitude during Mars entry [11,12].

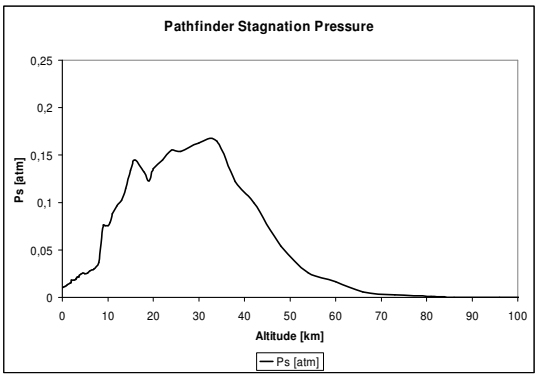

Fig. 5 – Stagnation Pressure on Pathfinder.

The two graphics are obtained using a Martian atmosphere model derived from numerical and experimental data [11].
The analysis of SCIROCCO capabilities for Pathfinder trajectory simulation is performed by overlapping the diagram of the facility performances using CO_2 (figure 4) to the plot of stagnation heat flux vs stagnation pressure for Pathfinder. The synthesis of the study is shown in figure 7.

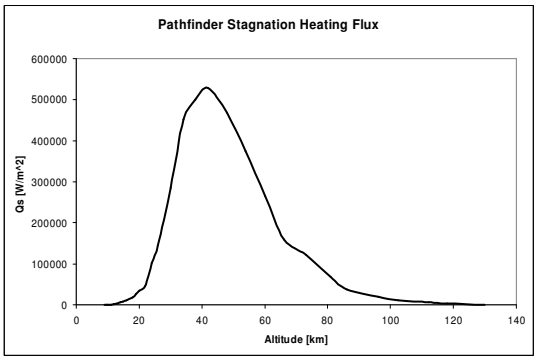

Fig. 6 – Heating Flux on Pathfinder.

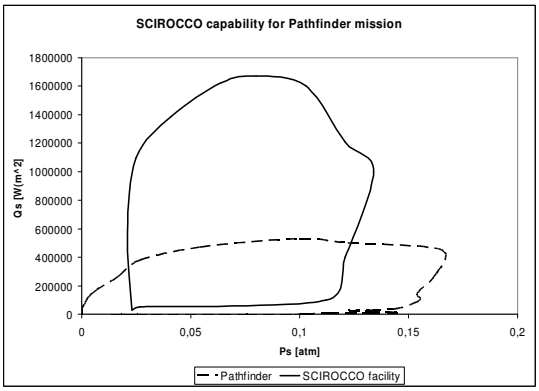

Fig. 7 – Heat Flux and Stagnation pressure for Pathfinder and SCIROCCO.

As the graphic suggests, SCIROCCO is able to reproduce globally the pressure and thermal conditions of a probe (like Pathfinder) during Martian Entry. The facility can simulate the stagnation pressure in a range from 0.025 to 0.13 atm and the heat flux up to 167 kW/m^2, a value largely higher than the maximum flux on Martian Probes such as Pathfinder.

6. SCIROCCO UPGRADES

Planetary missions require simulation of typical planetary atmospheres. Since SCIROCCO operates air flow, the addition of other gas delivery systems (gas storage, valves, flow controls, flow

measurements and plumbing, etc.) should provide SCIROCCO the capability of performing planetary atmosphere simulations.

The implementation for alternative gases in the facility was originated from the indications of the ESA Advisory Group. In fact, when the HERMES Project was erased in 1993, the committee decided to promote the realization of SCIROCCO but with the constraint of an easily upgradeable facility for simulations with fluids different from air but simple, not aggressive, not corrosive or poisoning gases. The main criteria followed in defining the implementation of the facility are easy configuration, low lay-out design, minimum overall cost of implementation.

A general review of possible implementations was presented by AEROTHERM with a dedicated report, preliminary discussed during the meeting of December 6, 1995. In that occasion was agreed by ESA/CISA/CIRA to concentrate the industrial feasibility analysis to those implementations that allow the highest flexibility of the facility with a reasonable impact on the present configuration. Some aspects of this analysis were discussed during the IX PROME on December 20-21, 1995.

The first foreseen upgrade regards the control valves for feeding the arc-heater, that must be as close as possible to the arc itself. The use of dedicated valve for each gas requires the replacing of the previous ones. No more than the actually foreseen valves can be installed in the future.

As a consequence, it is required to use stainless steel piping only inside the test building for the handling of different gases with the same piping. The upgrade of the safety equipments is suggested in view of an extensive use of H_2, as well as the installation of gas sensors in the test hall.

The bottles storage area will be prepared by levelling and provided by a concrete basement. This area will be fenced and protected with a roofing. The bottles storage area will be suppied of electrical lines to feed heating equipments necessary to warm the bottles to avoid their freezing during discharge. Feeding lines to connect the storage area to the experimental hall will be provided for each gas, they are installed in a dedicated trench.

In order to allow the installation of the new piping, the distance between experimental hall and power supply building will be increased of two meters. The implementation of this option will require higher voltage than the actual power supply; therefore, the gallery for the inlet of the bus bars in the arc pit must be slightly modified in order to increase spacing of the bars with higher voltage.

8. CONCLUSIONS

A study about the capability of the SCIROCCO PWT for simulation of Mars and Venus Entry has been developed. First, an analysis of the facility performances in presence of CO_2 using a three dimensional non equilibrium solver named TINA. Results show that SCIROCCO is able to simulate stagnation pressure in a range from 0.025 to 0.13 atm and the heat flux up to 167 kW/m^2. After, an historical excursus about past, present and future Mars missions. The study has been focused on Pathfinder mission. The plot of heat flux and stagnation pressure for this Martian probe has been overlapped to the diagram of the PWT performances using CO_2 as operating fluid. The overlapping shows that SCIROCCO is able to simulate almost all the aerothermal conditions for Mars Pathfinder entry. Finally, the upgrades necessary for the facility employment as a simulator for Mars and Venus entry are shown.

9. REFERENCES

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