ON THE UTILIZATION OF THE IEAv's HYPERSONIC TUNNEL T2 FOR TESTING THE SARA VEHICLE

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Abstract. *The purpose of this work, which has been done under the Space Brazilian Agency´s (AEB) UNIESPAÇO Program, is mainly to show, at least preliminarily, the conditions in which the Advanced Studies Institute' s hypersonic shock tunnel T2 can be used for reproducing some of important atmospheric re-entry conditions of the Brazilian space vehicle SARA (achronimous for* ***SA****télite de* ***R****eentrada* ***A****tmosférica), which is presently under development at the Space and Aeronautics Institute-IAE. For this purpose a series of experiments in the tunnel has been executed with a methodology described here. Based on operational performance maps derived from the processing of the experimental results and also on available data for SARA atmospheric re-entry corridor, it can be concluded that with the 200 mm diameter nozzle and using helium as the driver gas, the shock tunnel T2 is capable of simulating SARA free-stream conditions for altitudes in the vicinity of 30 km and below.*

Keywords*: Hypersonic shock tunnel, Ballistic re-entry vehicle, Experimental research, Re-entry parameter*

1. INTRODUCTION

The aerospace research, in particular the one aimed to the development of space vehicles, cannot leave aside the realization of a large variety of tests that will allow the reproduction, as best as possible, of several conditions encountered during the space flight. Just as example, during the return to Earth, these vehicles may be submitted to temperatures as high as 10.000 K (Anderson, 1989). At these temperatures, the environment involving the vehicle is not just the atmospheric air but it is constituted of a complex mixture of atoms, ions and electrons, which may affect both the flight conditions and the vehicle integrity.

This and other situations must be experimentally evaluated not only in the laboratory but also by means of flight tests, which are considerably more expensive. Only after an extensive testing, any decision regarding the vehicle´s geometry modification or the definition of its thermal protection system, for instance, may be safe and reliably taken.

For the execution of ground tests, the devices that are more commonly used are the pulsed hypersonic shock tunnels, such as the ones in operation at the Advanced Studies Institute-IEAv, in São José dos Campos, São Paulo and also in countries such as the United States, Australia, Japan, among others. The larger the quantity and the quality of the results for the experimental laboratory simulations, the better the data basis that will serve as a reference for the execution of the flight tests, which are an indispensable stage in the development of space vehicles.

As it is well known, the vehicle SARA is a small reusable ballistic re-entry vehicle, to be used for performing scientific experiments in the microgravity conditions and is being developed by the Space and Aeronautics Institute-IAE. In order to answer the question as to what extent the IEAv's hypersonic shock tunnel T2 can be useful for simulating the SARA atmospheric re-entry corridor, or at least a part of it, a series of experiments were firstly carried out and then their results processed to produce operational performance maps that graphically display a group of selected free-stream parameters (e.g. pressure, enthalpy, Mach number, temperature etc.) evaluated at the nozzle´s exit, as a function of the initial shock tunnel conditions. Using the existing theoretical data for the descending SARA trajectory for both its suborbital (Toro, 2006) and orbital (Moraes, Jr., 1997) versions, it is then possible to answer the question above by verifying what parts (in fact, their associated free-stream parameters) of the trajectory are inside the boundaries of those maps.

2. HYPERSONIC SHOCK TUNNELS – A BRIEF DESCRIPTION OF THE TUNNEL T2

Hypersonic shock tunnels are devices capable of producing, at relatively low costs, flow conditions that are very similar to the ones encountered by spaceships, including the most adverse, which occur for example when they re-enter the atmosphere in the direction of the soil. Although these tunnels can reproduce those conditions only for very short time intervals, typically of the order of a few milliseconds, they still are very important tools for supporting space vehicle designs, especially in their first stages.

Very concisely, shock tunnels are constituted of a cylindrical or a rectangular tube, divided by a main diaphragm in two regions, one called *driver* and the other called *driven*, this one coupled to a convergent-divergent nozzle that ends inside a test section, which is followed by an exhaustion tank. The driver is the high pressure region and is usually filled with helium gas, although other gases may be used; the low pressure region, or the driven, contains the test gas, normally air, when simulating the Earth's atmosphere and is separated from the nozzle by a thin secondary diaphragm to avoid the inflow of the test gas into the dump tank before the test starts. To initiate the test, the main diaphragm is burst by any means, and a shock wave propagates into the test gas, compressing it to a higher pressure and temperature. When the shock wave reaches the end of the driven, it is reflected and the secondary diaphragm also bursts. The highly compressed and high temperature test gas then expands through the nozzle, converting its stagnation enthalpy to a high free-stream velocity in the test section, where the model to be studied is located.

The hypersonic tunnel T2 (Fig. 1) is one of the three tunnels in operation at the "Prof. Henry T. Nagamatsu" Aerothermodynamics and Hypersonics Laboratory, in IEAv. It consists of a high pressure 180 cm long driver cylindrical tube connected to a 640 cm low pressure driven, separated by a Double-Diaphragm Section (DDS), which is in general filled with argon and is used to have a more precise control of the main copper diaphragms rupture. At the end of the driven section, there is a secondary aluminum diaphragm that prevents the test gas to flow into the test section before the experiment actually begins. The test section has a cylindrical shape with 60 cm length and 40 cm internal diameter and is connected to a 2 m^3 exhaustion tank. The total length of the T2 hypersonic tunnel is about 12 meters. Although the tunnel has been designed to operate up to a maximum pressure of 23.0 MPa, for safety reasons the pressure in the driver has been set to 3000 psi (about 20 MPa) for all runs.

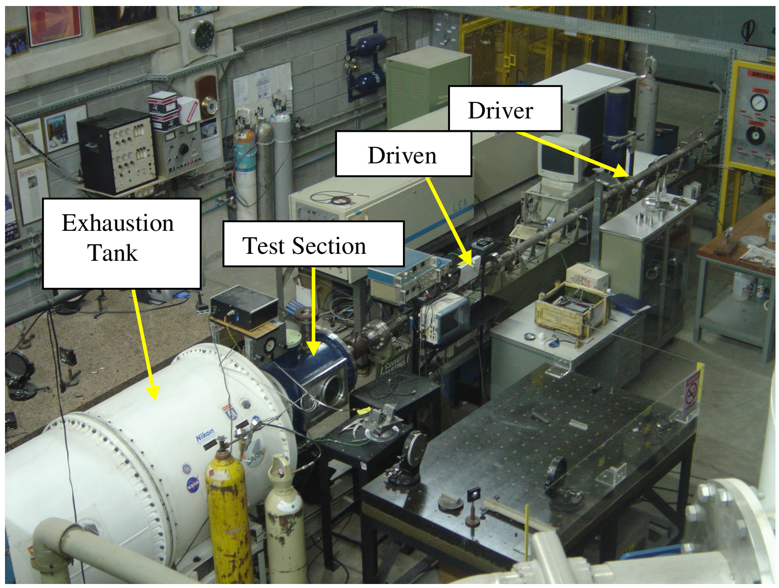

Figure 1. Panoramic view of the T2 hypersonic tunnel

3. METHODOLOGY FOR GENERATION OF T2 PERFORMANCE MAPS

For the generation of the tunnel T2 performance maps, a large number of runs has been executed, for different combinations of driver gases, driven pressures, nozzle throat diameters and nozzle exit diameters, in order to cover, as best as possible, the many situations in which the tunnel has been routinely operated. For every run, the gas pressure in the driver was maintained at about 20 MPa (3000 psi), for safety reasons. The utilization of two already existing conical nozzles, a 10 degree half-angle (200 mm exit diameter) and a 15 degree half-angle (300 mm exit diameter), each one with its corresponding interchangeable throats, would in principle enable us to cover a range from about Mach 6 to about Mach 15.

The work consisted essentially in measuring, for each run, the pressure values at conveniently chosen locations in the shock tunnel T2 and to use them along with known correlations (Srinivasan et al., 1987) implemented in the computer program STCALC (Rosa et al., 2009), for the determination of the free-stream parameters that at present cannot be directly measured in T2. Basically, STCALC calculates those parameters by using the stagnation conditions at the entrance of the convergent-divergent nozzle and the pressure measured at geometric center of the nozzle exit, and also assuming that the air (the test gas) expands isentropically in its interior. This results in a set of non-linear algebraic equations, which are iteratively solved. The air in the driven section of the shock tunnel is treated as a real gas, assuming chemical and thermodynamics equilibrium, whose thermodynamics properties are related by means of correlations that exist in the literature, such as the ones developed by Srinivasan and implemented in STCALC.

The operational performance maps are just the graphic displays of free-stream temperature, enthalpy, Mach number etc., as a function of any chosen initial parameter; in the present work, all results are expressed in terms of the initial T2 driven pressure.

4. THE EXPERIMENTAL SETUP

The pressure measurements were made by means of pressure transducers disposed as follows: two transducers (Kistler, model 701 A) located in the driven section and positioned 50 cm from one another, for the determination of the velocity of the incident shock wave; one transducer (Kistler. Model 701 A), located at the very end of the driven section, for the measurement of the stagnation pressure and; thirteen transducers (PCB Piezotronics, model 112A22) adequately fixed in a cruciform support ("rake") positioned at the nozzle exit, with the objective of producing information on the radial pressure profiles at that location. After amplification, the signals from the transducers were collected by a Yokogawa Model DL 750 acquisition system.

4.1. Evaluation of the "quality" of the flow at the exit of the nozzles

One of the concerns before initiating the series of experiments in the tunnel was how to evaluate the "quality" of the flow at the exit of the convergent-divergent nozzles, or in other words, its degree of homogeneity, which could give an indication of possible geometric imperfections in the nozzles. For this purpose, the cruciform rake was positioned in the interior of the test section, at the exit of the nozzle, in order to give an indication of the degree of axial symmetry of the pressures at that location, and then a few exploratory runs were made.

Figures 2 to 5 display, for four different runs, the measured pressures from the transducers located in the North, South, East and West branches of the cruciform rake, normalized to the pressure measured by the transducer located at the very center of the rake, as a function of their radial positions.

Figures 2 and 3, which show results at the exit of the 200 mm nozzle, indicate not only a high degree of axial symmetry, but also a radial pressure distribution that is practically flat for all four branches. For this nozzle, the rake outermost transducer position is external to the flow region, and as a result the pressure at that location is zero. Figures 4 and 5, both for the 300 mm nozzle, also indicate a good degree of axial symmetry, despite of the failure of a few transducers. For this larger diameter nozzle, there is a more pronounced radial dependence, but still well-behaved.

By the observation of these graphs, it is reasonable to conclude that both the 200 mm and the 300 mm diameter nozzles may be used for the planned experiments without the fear of the production of spurious or unwanted reflected waves caused by any imperfections, which certainly would mask the readings of the pressure transducers fixed in the rake.

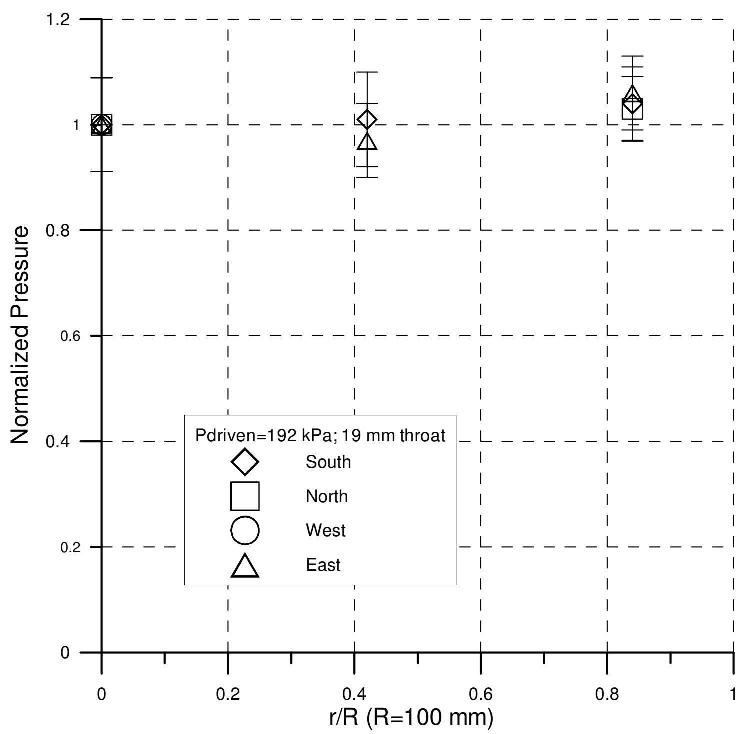

Figure 2. Normalized pressure distribution as a function of transducer position (Pdriven=192 kPa; helium in driver)

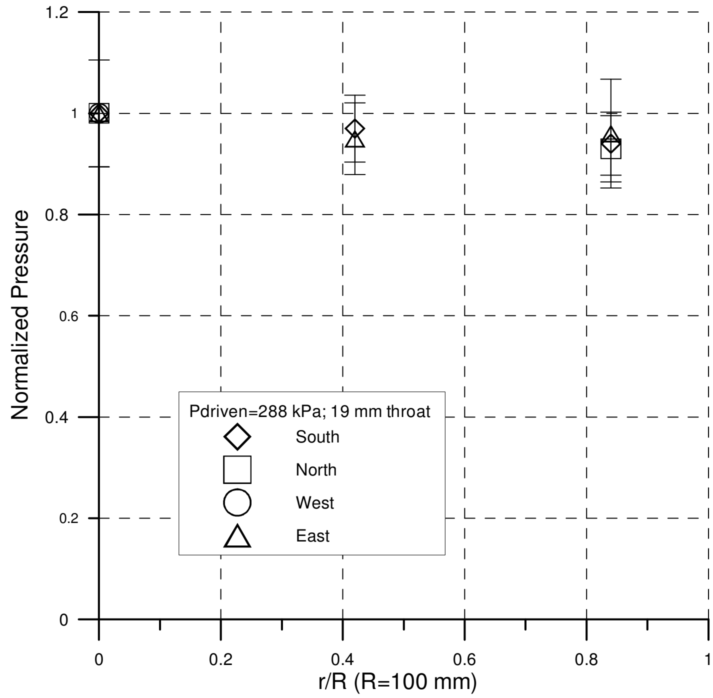

Figure 3. Normalized pressure distribution as a function of transducer position (Pdriven=288 kPa; helium in driver)

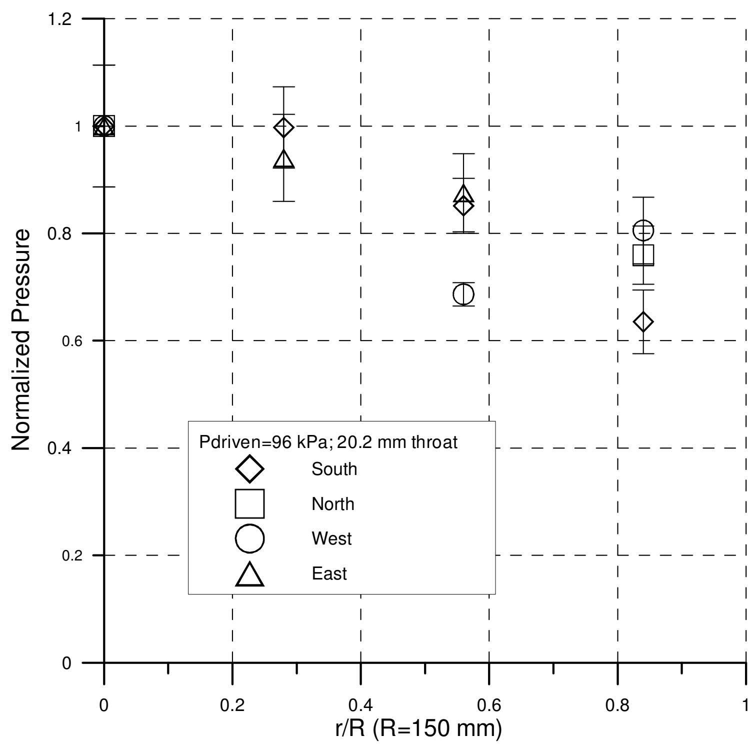

Figure 4. Normalized pressure distribution as a function of transducer position (Pdriven=96 kPa; air in driver)

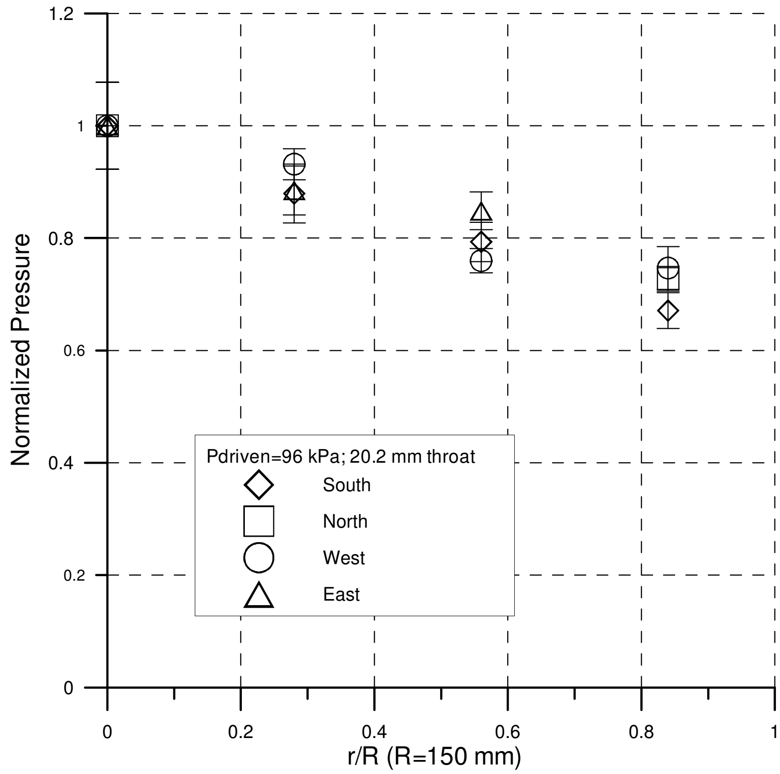

Figure 5. Normalized pressure distribution as a function of transducer position (Pdriven=96 kPa; helium in driver)

5. THE TUNNEL T2 PERFORMANCE MAPS-PRELIMINARY RESULTS

As mentioned before, a large number of T2 runs has been made, for both the 200 mm and the 300 mm nozzles and either helium or dry air as the driver gas. Since the results for air and the 300 mm nozzle are still under analysis, only the operational maps for the runs with the 200 mm nozzle are shown. Although the program STCALC calculates sufficient free-stream parameters to allow a good characterization of the conditions at the nozzle's exit, only the maps relating temperature, pressure and velocity to the initial T2 driven pressure are shown here, for illustrative purposes.

All results presented in this work were generated using helium gas in the driver at a fixed pressure equal to 20.7 MPa (3000 psi), and dry air in the driven under four different pressures: 288.0, 96.0, 26.7 and 6.7 kPa, which correspond respectively to 3.0, 1.0, 0.3 and about 0.07 atm, as measured in the "Prof. Henry T. Nagamatsu" Aerothermodynamics and Hypersonics Laboratory. Three different nozzle throat diameters were used with the 200 mm nozzle: 10, 15 and 19 mm. Based on simple calculations and assuming perfect gas conditions, these combinations would produce Mach numbers ranging from about Mach 7 to around Mach 10.

Figures 6, 7 and 8 display the free-stream pressure, temperature and velocity, respectively, evaluated at the nozzle's exit, as a function of the initial driven pressure, for the 10 mm, 15 mm and 19 mm diameter throats. It can be observed (Fig. 6 and 7) that for lower driven pressures, there is a rise in both the free-stream pressure and temperature values, which is due to the successive reflections of the shock wave at the end of the driven, yielding higher values of the stagnation pressure and temperature. Figure 8 indicates that the free-stream velocity practically does not depend on the throat diameter, at least for the cases shown in this work, which only considers helium gas in driver and the 200 mm nozzle.

6. ON THE USE OF TUNNEL T2 FOR TESTING THE SARA VEHICLE

The vehicle SARA is being developed to be a recovery platform to perform orbital flights for the realization of scientific experiments in the micro-gravity conditions. Its first version is being designed for a suborbital flight and the definite version is planned to stay in a 300 km terrestrial orbit for about ten days. A small segment of the descending trajectory for each of the versions is shown in Figure 9, and based on a simple calculation using the data available we find that the two intersect each other at an altitude of the order of 34 km, which corresponds to a free-stream velocity of approximately 2465 m/s. With the help of the 1976 Standard Atmosphere Calculator (NASA, 1976), ones finds that for that altitude, the free-stream pressure and temperature are about 660 Pa and 230 K, respectively.

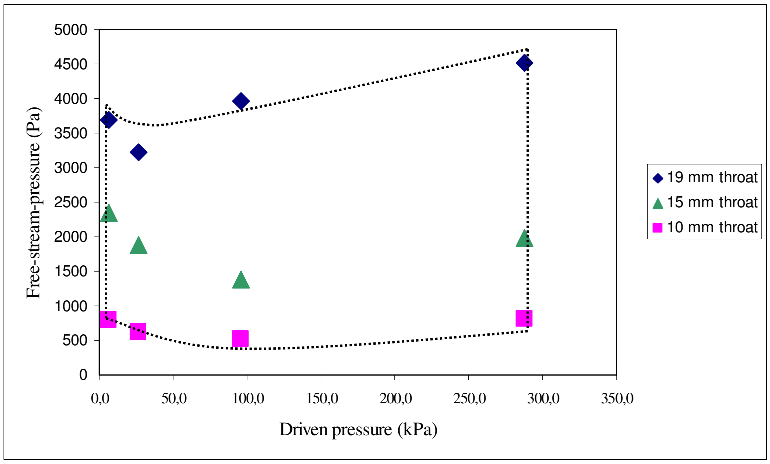

Figure 6. Free-stream pressures as a function of the shock tunnel T2 driven pressures

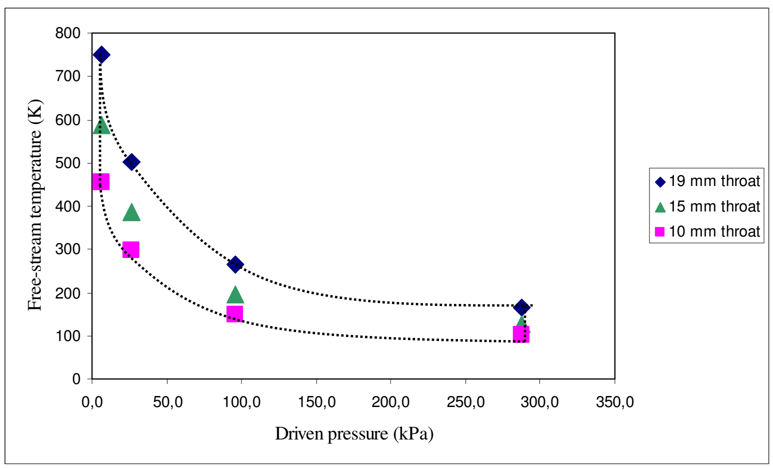

Figure 7. Free-stream temperatures as a function of the shock tunnel T2 driven pressures

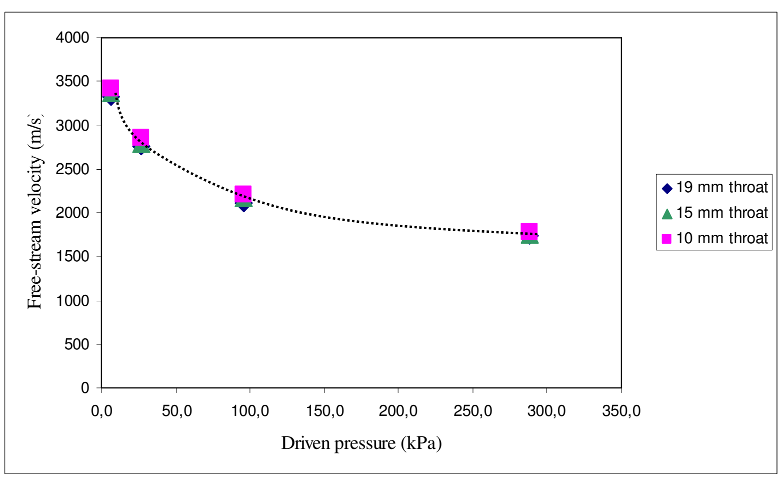

Figure 8. Free-stream velocities as a function of the shock tunnel T2 driven pressures

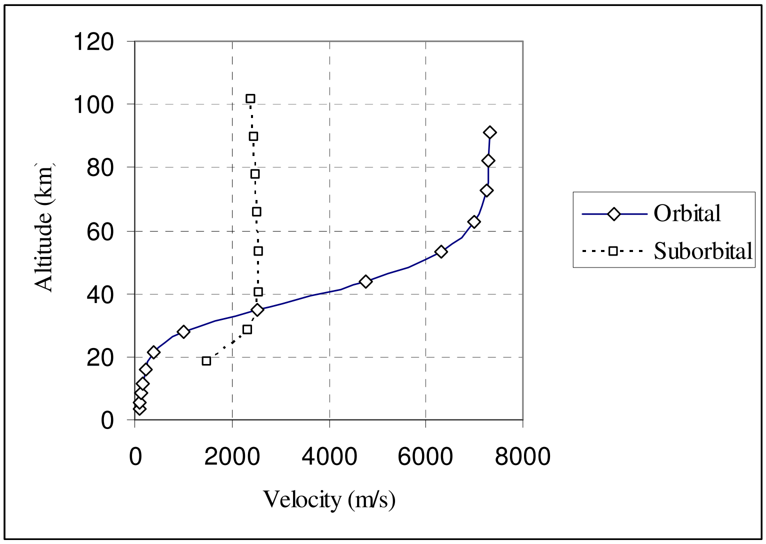

Figure 9. Segments of the orbital and suborbital descending trajectories of SARA vehicle

The observation of Figures 10 and 11 indicates that with the 200 mm diameter nozzle and using helium as the driver gas, the hypersonic tunnel T2 is capable of simulating atmospheric conditions for altitudes a little higher than 30 km and below. It also can be seen that the intersection of the orbital and suborbital SARA trajectories lie just above the lower boundaries of both the pressure and temperature operational maps., which is a clear indication that the tunnel T2 can be used for this condition.

The analysis of the results for air as the driver gas and the 300 mm nozzle is in progress, but it already can be anticipated that lower free-stream pressures and temperatures at the exit of the nozzle can be reached, which means that higher altitude conditions may certainly be simulated.

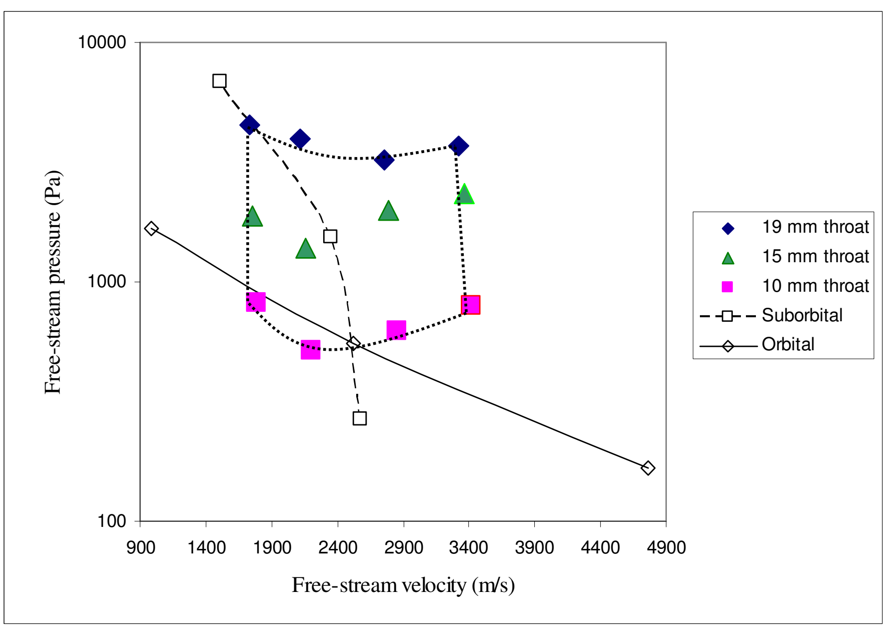

Figure 10. The SARA trajectories and the tunnel T2 operational map (Pressure x Velocity)

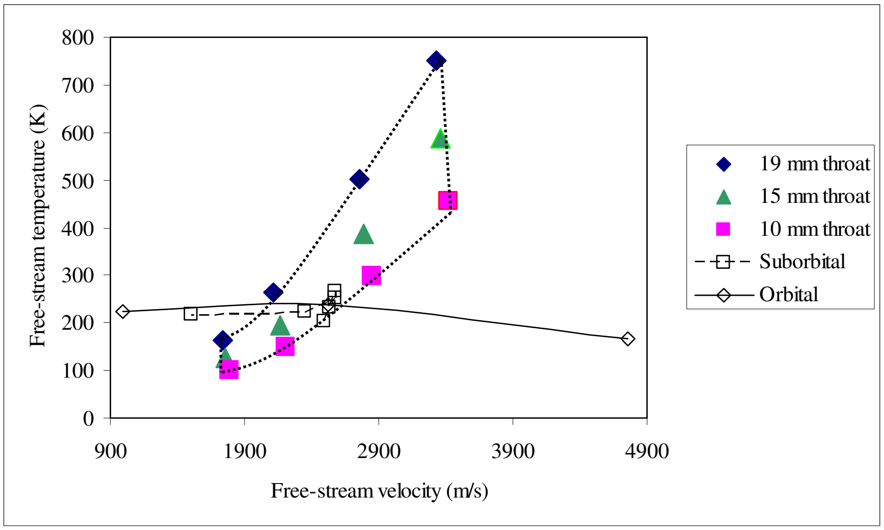

Figure 11. The SARA trajectories and the tunnel T2 operational map (Temperature x Velocity)

7. FINAL REMARKS

Although the entire set of results for the large series of experiments done in the tunnel T2 have not been completely analyzed as yet, the ones shown is this paper, for the 200 mm nozzle and using helium in the driver section, indicate that the tunnel can be useful to the SARA project. The remaining results (for air in the driver and the 300 mm diameter nozzle) will certainly allow the simulation of altitudes higher than about 30 km.

Due to physical dimensions and also to mechanical constrains, the utilization of the hypersonic tunnel T2 for contributing to the SARA development is certainly limited. For example, the test section dimensions prevents the use of nozzles with exit diameters much larger than 300 mm, such as the one utilized here, which ends up imposing a limitation in the free-stream Mach numbers, for instance. An alternative would be for example to use the tunnel T3, also in operation in the "Prof. Henry T. Nagamatsu" Aerothermodynamics and Hypersonics Laboratory: with its about 24 meters total length and a test section volume equal to 2220 liters (vs. about 76 liters for T2), T3 is capable of simulating up to Mach 25 flows.

8. ACKNOWLEDGEMENTS

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