Experimental Investigation of the Re-entry Vehicle in Hypersonic Flow

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Abstract. The Brazilian Space Agency has proposed the development of experiments in a microgravity environment, using a recoverable orbital system. The system consists of a capsule shaped orbital platform. After the microgravity experiments were carried out, the reusable space vehicle will return to Earth and it will be recovered at ground. To understand the hypersonic flow characteristics (considering the aerodynamic aspects during the ballistic re-entry flight) of the returnable space vehicle, a 10-cm diameter Aluminum model has been fabricated and it has been instrumented with piezoelectric pressure transducers, to be tested in the IEAv 30-cm. diameter Hypersonic Shock Tunnel at freestream Mach from 6 to 8 with stagnation temperature from 5000K to 950K. Pressure distribution over the model and the photographs of the hypersonic flow are presented.

Key words: reusable space vehicle, hypersonic flow, blunt body, experimental pressure measurement, hypersonic shock tunnel.

1. INTRODUCTION

The primary objective of the present experimental investigation is to provide experimental data required for understanding the hypersonic flow characteristics over a reusable space vehicle. Such vehicle is intended for scientific and technological experiments in low-gravity environment, which it enables the production of homogeneous and perfect chemical crystals, the creation of new metallic alloys, new electronic components, unaccountable agronomic and biomaterial researches (Moraes, 1997)...The design of the micro-satellite ($\approx$150 kg) (recoverable at ground and reusable) performing scientific and technological experiment in low-gravity environment ($\approx 10^{-5}$ g), for short time (about 10 days), in equatorial orbit ($\approx$300 km), Figure 1, has been proposed by the Brazilian Space Agency. Among other applications of this reusable orbital platform, there are: *i)* experiments in low orbit (micro-gravity, vacuum, direct solar radiation, low temperature); *ii)* studies of re-entry flow and *iii)* as technological demonstrator. The main users are: Universities, research institutes, national industries, national and international space programs…

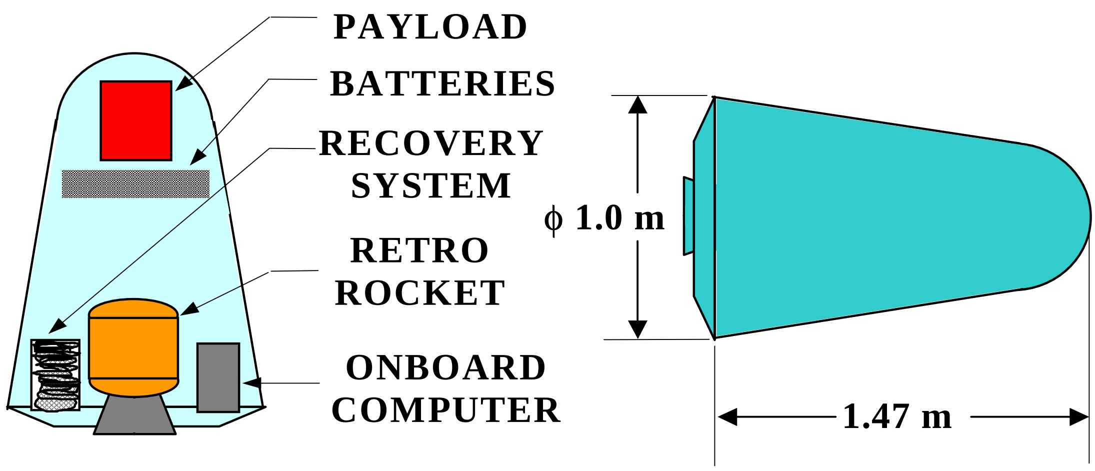

Figure 1: Preliminary concept of the Reusable Space Vehicle.

Returnable space vehicles undergo several velocity regimes and flight conditions that may difficult their aerodynamic design. Only gravitational and drag forces $\left({}^{lift}\!/_{drag} \approx zero \right)$ act during the ballistic re-entry flight of reusable space vehicle into the Earth atmosphere. At high altitude ($\approx$300 km) the gravitational field is nearly constant, Figure 2. At altitudes higher than > 90 km the drag force is very low. Consequently, the velocity of the Atmospheric Reusable SAtellite (*SARA*) does not vary significantly in altitudes higher than 100 km. The velocity increment, at the beginning of the *SARA* re-entry trajectory, is due to the earth gravity in the rarefied environment. When the *SARA* goes to lower altitudes, its velocity decreases (from 8 km/s to 80 m/s in about 3 minutes). Consequently, the reduction of velocity results in conversion of kinetic energy into thermal energy, due to the friction, between the microsatellite external surface and the Earth atmosphere (Pessoa Filho, 1997).

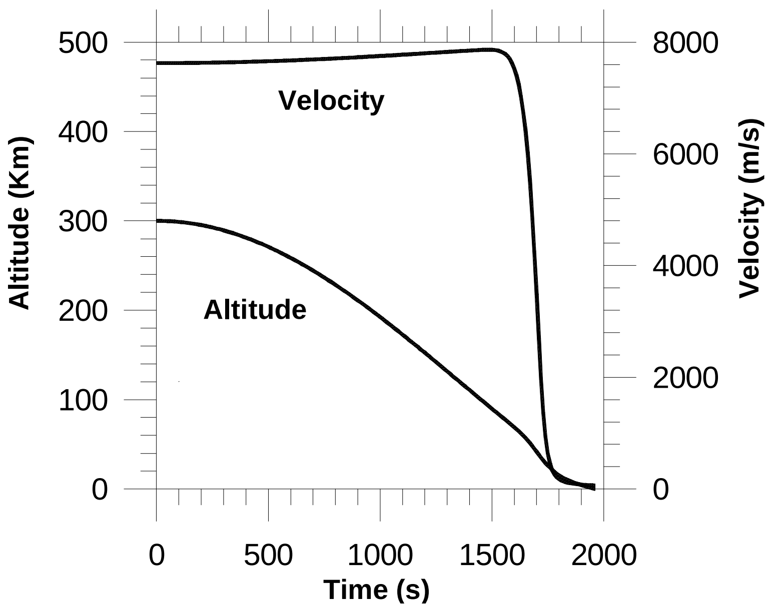

Figure 2: *SARA* re-entry typical trajectory.

The feasibility of transatmospheric flight is limited by phenomena such as aerodynamic drag and heating as well as related thermal management problems. Therefore, an efficient transatmospheric hypersonic vehicle design has to combine a low drag coefficient (to maximize the net propulsive thrust) with low heat transfer rates (to minimize thermal protection system mass).

Traditional blunt-nosed hypersonic vehicles generate a strong detached normal shock wave in the nose region, which produces high aerodynamic drag. The temperature behind this strong shock wave increases at hypersonic velocities, although the aerodynamic heating rates are reduced compared with that of an attached shock wave on a conical body. On the other hand, a traditional slender body with a sharp leading edge produces a conical weak attached shock wave with low drag coefficient, but extreme heating is created at the tip of the forebody.

For take off, escape from and flight through the earth's atmosphere the drag on the body should be reduced. For re-entry vehicle into the earth's atmosphere at hypersonic speeds, it is important to have a large nose radius, consequently, low aerodynamic heating, Figure 3.

For the lowest drag coefficient case, Figure 3, C_D = 0.4, the maximum heat flux (at the stagnation point of *SARA* nose) is about 2.5 MW/m^2 during about 3 minutes of re-entry trajectory (Pessoa Filho, 1997). In this condition, the temperature of the air, after the detached normal shock wave is about 6500K (the ambient air temperature is about –30°C). On the other hand, for the highest drag coefficient case, C_D = 1.2, the maximum heat flux (at the stagnation point) is about 0.8 MW/m^2 at the same re-entry trajectory.

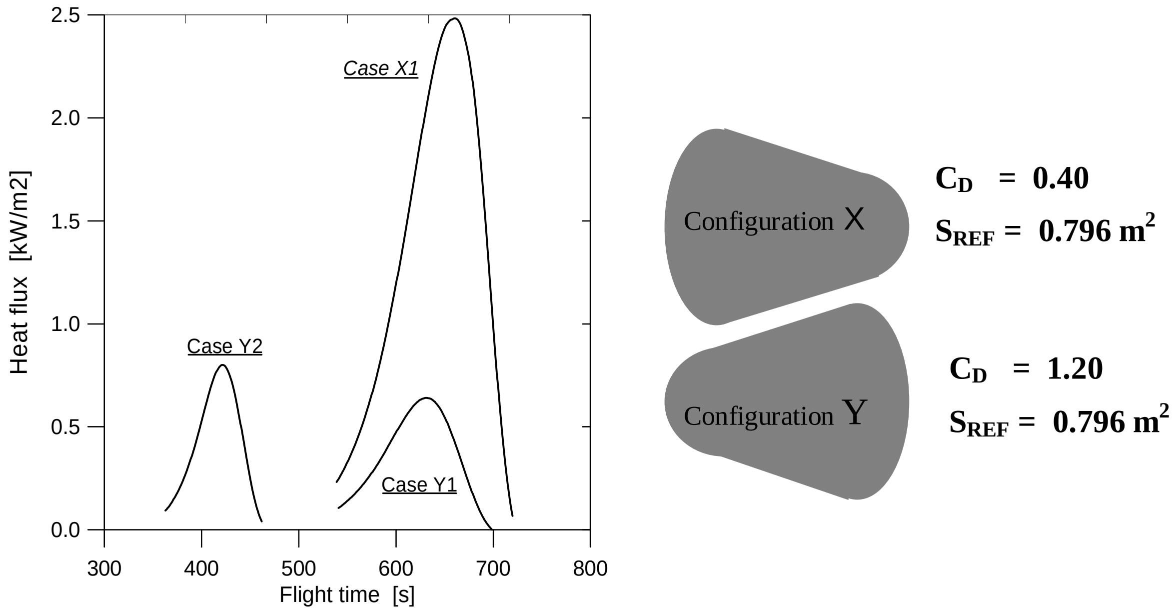

Figure 3: Heat flux and analytical drag coefficient.

The fundamental knowledge necessary for complex flow phenomena at hypersonic flows is important. Therefore, a combination of Computational Fluid Dynamic (CFD) and experimental investigations that simulate the Mach numbers and the enthalpies for the hypersonic flight conditions is necessary. The experimental data (by ground test facilities and by flight tests) should define the physics of the hypersonic flow phenomena to validate or to modify the available CFD codes.

Shock tubes and shock tunnels are the most versatile experimental short duration facilities (Nagamatsu, 1961). They have been widely used for high velocity and high temperature research since the early 1950s. Both shock tubes and shock tunnels are ground test facilities which provide high enthalpy flows close to those encountered during the reentry of a space vehicle into the earth’s atmosphere at hypersonic flight speeds. These short running time facilities require special measurement techniques to measure pressure and temperature (heat flux) for the models in the test section.

Since the ability to conduct ground tests at high flight Mach numbers and high enthalpies are limited; expensive flight experiments are also used to design the hypersonic vehicles. An increase in the capability of existing ground test facilities is necessary to reduce the number of required flight tests.

The goal is to simulate the hypersonic flow (Mach number and stagnation temperature) over the *SARA* configuration (capsule shaped orbital platform), with the lowest drag coefficient, using the IEAv 30-cm. diameter Hypersonic Shock Tunnel at freestream Mach from 6 to 8 with stagnation temperature from 5000K to 950K.

2. IEAv 30-cm DIAMETER HYPERSONIC SHOCK TUNNEL

The IEAv 0.3-m. Hypersonic Shock Tunnel, Figure 4, is the first hypersonic ground test facility in Brazil (Minucci et all, 2001), was used to produce high to low enthalpy hypersonic flow conditions. In the high enthalpy runs, helium was used as the driver gas and the tunnel was operated in the equilibrium interface condition to produce a useful test time of roughly 500μs and reservoir conditions of 5,000 K, temperature, and 120 bar, pressure. In the low enthalpy case, air was used as the driver gas to produce a useful test time of 1.5 ms and reservoir conditions of 950 K, temperature, and 25 bar, pressure, Table 1. The test section airflow Mach number was 6.2 in the high enthalpy tests and 7.8 in the low enthalpy ones. The same conical, 15^o half angle, 300mm exit diameter, nozzle with a throat diameter of 22.5mm was used in all cases. The different Mach numbers achieved are the result of the different reservoir conditions and real gas effects present in the tests.

Figure 4: IEAv 30-cm. Diameter Hypersonic Shock Tunnel.

Table 1. Hypersonic Shock Tunnel Test Conditions

		High Enthalpy	**Medium Enthalpy**	**Low Enthalpy**
Stagnation Conditions	**Pressure**	120 bar	140 bar	20 bar
	Temperature	5000 K	2000 K	950 K
	Enthalpy	9 MJ/kg	2 MJ/kg	1 MJ/kg
Freestream Flow Conditions	**Pressure**	12 mbar	4 mbar	4 mbar
	Temperature	1000 K	192 K	77 K
	Density	4.0 g/m^3	33 g/m^3	17 g/m^3
	Mach	6.2	7.3	7.8

3. EXPERIMENTAL APPARATUS

The model geometry, Figure 5, consists of a capsule shaped orbital platform, wherein the front nose is a hemispherical shape followed by a conical segment. A 10-cm. diameter Aluminum model has been fabricated and it has been instrumented with piezoelectric pressure transducers, to be tested in the IEAv 30-cm. diameter Hypersonic Shock Tunnel at freestream Mach from 6 to 8 with stagnation temperature from 5000K to 950K.

Figure 5: Ballistic re-entry vehicle *SARA* model (with the locations of pressure transducers).

4. EXPERIMENTAL RESULTS AND DISCUSSION

The nominal shock tunnel test conditions, to run the low drag *SARA* configuration, Figure 5, are presented in Table I. These conditions did not vary more than 5% from run to run.

Time-lapse type photographs of the luminous air flow around the model were taken by using a Nikon camera model N6006 with AF35-70mm f/3.3-f/4.5 Nikkor lenses and ISO 100 color film.

All the data, with the exception of the flow visualization, were recorded using a Tektronix VX4244 16-channel 200kHz data acquisition system.

Figures 6 and 7 show a time-lapse photograph of the luminous airflow around the model at Mach 6.2 (high enthalpy) and 7.3 (medium enthalpy) flow conditions. At low enthalpy there is no dissociation of the air. Therefore, there is no air luminosity. Consequently no photograph was taken. It is possible to observe in figures 6 and 7 the bow shock wave structures in front of the model.

The experimental pressure ratio at the *SARA* static surface for free stream Mach numbers of 6.2 (high enthalpy), 7.3 (medium enthalpy) and 7.8 (low enthalpy) agrees quite well with the theoretical pressure ratio using the Modified Newtonian theory calculations, Figure 8.

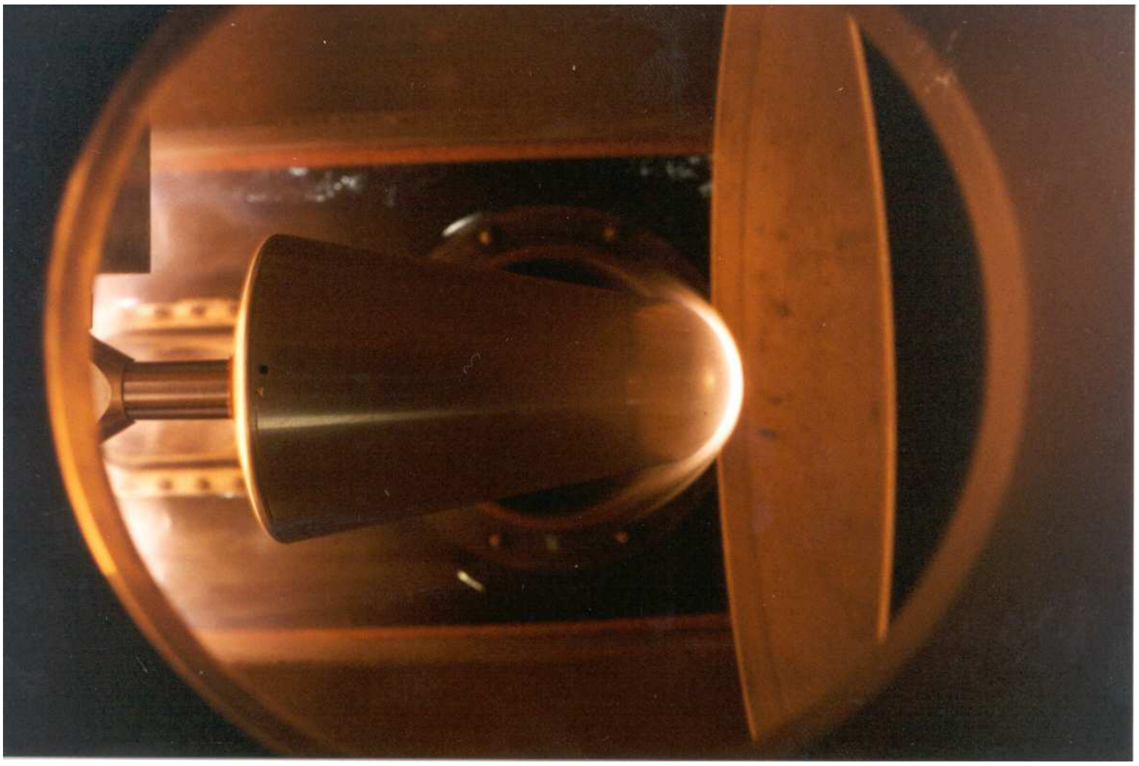

Figure 6. Open shutter photograph of the airflow luminosity upstream of a SARA model in Mach 6.2 flow.

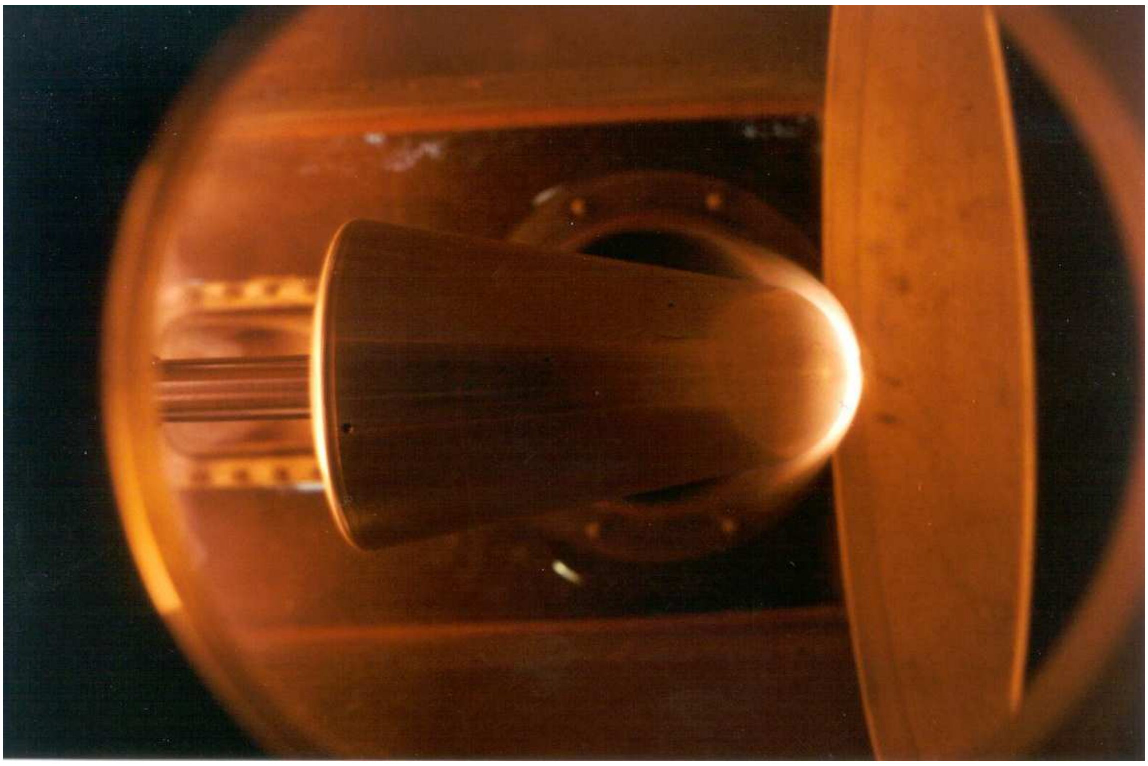

Figure 7. Open shutter photograph of the airflow luminosity upstream of a SARA model in Mach 7.3 flow.

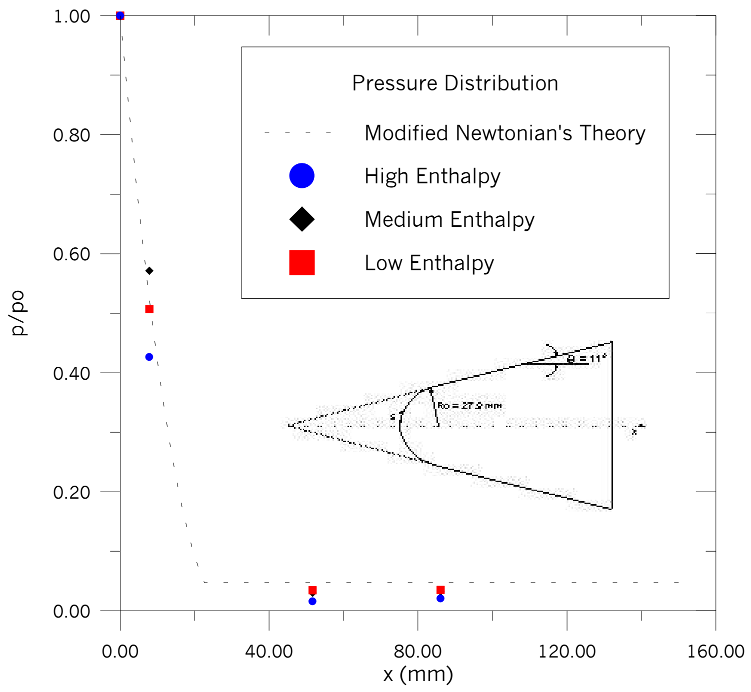

Figure 8. Pressure distribution over *SARA* low drag configuration.

5. CONCLUSIONS

The development of experiments in a microgravity environment, using a recoverable orbital system has been proposed by Brazilian Space Agency. The system consists of a capsule shaped orbital platform. To understand the hypersonic flow characteristics of the returnable space vehicle, a 10-cm diameter Aluminum model has been fabricated and instrumented with piezoelectric pressure transducers, to be investigated in the IEAv 30-cm. diameter Hypersonic Shock Tunnel at freestream Mach from 6 to 8 with stagnation temperature from 5000K to 950 K. The time-lapse photograph of the luminous airflow around the model at Mach 6.2 (high enthalpy) and 7.3 (media enthalpy) flow conditions were taken. There is a good agreement between the experimental data and theory for the conditions tested.

6. ACKNOWLEDGMENTS

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