# NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF A HYPERSONIC FLOW OVER A RE-ENTRY VEHICLE

**Paulo G. de P. Toro** – toro@iae.cta.br
Instituto de Aeronaútica e Espaço - IAE - Centro Técnico Aeroespacial – CTA
São José dos Campos - SP 12228-904 – BRAZIL
**Marco A.S. Minucci** – sala@ieav.cta.br
Instituto de Aeronaútica e Espaço - IAE - Centro Técnico Aeroespacial – CTA
São José dos Campos - SP 12231-970 – BRAZIL
**Heidi Korzenowski** – heidi@univap.br
Universidade do Vale do Paraíba – UNIVAP
São José dos Campos - SP 12244-000 – BRAZIL
**Leik N. Myrabo** - myrabl@rpi.edu
**Henry T. Nagamatsu** - nagamh@rpi.edu
Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics
Rensselaer Polytechnic Institute, Troy, NY 12180-3590 – USA

***Abstract.*** *The feasibility of hypersonic flight is limited by phenomena such as aerodynamic drag and heating. 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 a hypersonic speeds, it is important to have a large nose radius and high aerodynamic drag. An efficient hypersonic vehicle design has to combine a low drag coefficient with low heat transfer. A small ballistic re-entry vehicle SARA configuration is numerically (low drag case) and experimentally (high drag case) investigated by using the Euler equations and the RPI 24-in. diameter Hypersonic Shock Tunnel (RPI-HST), respectively. The governing equations are discretized in a cell centered, finite volume procedure for unstructured triangular grids. Spatial discretization uses an upwind scheme. Time march uses, an explicit 2nd-order accurate, 5-stage Runge-Kutta time stepping scheme. A 6-in. diameter aluminum "double Apollo disc" model was fabricated and fitted with piezoelectric pressure transducers and thin-film platinum heat gauges over its forebody surface. Numerical (inviscid simulations) and experimental results are presented for the hypersonic flow. Freestream Mach 10 flow was selected to conduct numerical and experimental investigations.*

**Keywords:** Re-entry vehicle, numerical investigation, experimental investigation**,** hypersonic flow

## 1. INTRODUCTION

The feasibility of hypersonic flight is limited by phenomena such as aerodynamic drag and heating as well as related thermal management problems. 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. To resolve these difficulties, 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).

Toro (1998) has experimentally investigated the "Directed-Energy Air Spike" (DEAS) inlet concept. The DEAS inlet proposes the use of beamed electromagnetic power to induce a detached conical (parabolic-shaped) shock wave which substantially reduces the flow Mach number impacting the vehicle forebody, and consequently decreases the aerodynamic drag and most importantly, deflects the oncoming hypersonic air flow from the vehicle's path into an annular hypersonic inlet at the periphery of the vehicle.Recently, Toro et al. (1999) analyzed the "double Apollo disc" configuration, and the experimental results were found to be qualitatively similar to prior experimental and theoretical results.

The recent progress in Computational Fluid Dynamics (CFD) has made these techniques attractive tools for real life problems in aeronautical and aerospace applications. The numerical simulation carried out by Korzenowski (1998) is concerned with the implementation and validation of unstructured grid, mesh refinement techniques for two-dimensional inviscid flow problems of aerospace interest. The mesh refinement procedure uses a numerical sensor based on flow physical properties. The present development should be seen as an evolutionary step towards the desired three-dimensional capability. The goal is to develop all the criteria necessary to construct adaptive meshes suitable to the desired applications in the 2-D case, for computational cost reasons. Moreover, there is also interest in obtaining spatial discretization schemes, which were sufficiently robust in order to treat flows from the transonic regime up to hypersonic speeds.

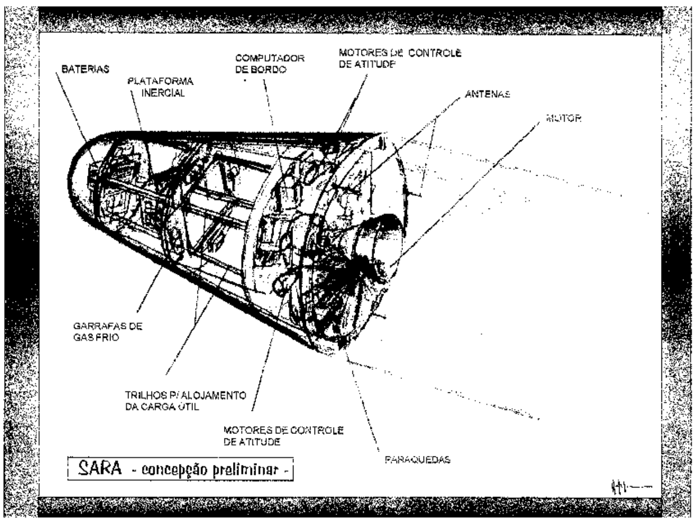

Figure 1 – Small ballistic re-entry vehicle SARA configuration.

## 2. MATHEMATICAL MODEL FOR A NUMERICAL SOLUTIONS

The two-dimensional time-dependent, compressible Euler equation (no body forces, no volumetric heating, no viscous terms and no mass diffusion) may be described, in conservative vector form, by

$$\frac{\partial U}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}=0 \tag{1}$$

Here U is the vector of conserved quantities; E and F are convective flux vectors, given by

$$U=\begin{Bmatrix}\rho\\ \rho u\\ \rho v\\ E_t\end{Bmatrix},\qquad E=\begin{Bmatrix}\rho u\\ \rho uu+p\\ \rho uv\\ (E_t+p)u\end{Bmatrix},\qquad F=\begin{Bmatrix}\rho v\\ \rho vu\\ \rho vv+p\\ (E_t+p)v\end{Bmatrix}. \tag{2}$$

The total energy is given by

$$E_t=\rho\left(e+\frac{|\vec{V}|^2}{2}\right) \tag{3}$$

The velocity vector and the absolute values of the velocity are given by

$$\vec{V}=u\vec{i}+v\vec{j},\qquad |\vec{V}|=\sqrt{u^2+v^2} \tag{4}$$

For a calorically perfect gas, the relation between the internal energy and specific heat at constant volume and pressure may be calculated by

$$p=\rho RT,\qquad e=c_vT,\qquad c_v=\frac{R}{\gamma-1},\qquad c_p=\gamma c_v \tag{5}$$

### Numerical technique

The numerical scheme discretized the Euler equations in conservative form in an upwind, finite volume context considering an unstructured grid made up of triangles. For the flux-vector splitting case, a Liou (1996) formulation has been tested. The 2nd-order flux-vector splitting scheme has used a MUSCL-type extrapolation (Hirsh, 1967) in order to determine left and right states at the interfaces. A minmod limiter was used in order to avoid oscillations. Time integration used an explicit, 2nd-order accurate, hybrid method, which evolved from a of Runge-Kutta time stepping scheme.

Adaptive mesh refinement, based on a sensor of flow property gradients, was performed to obtain a better resolution of strong discontinuities. The automated adaptive environment consisted of a mesh enrichment procedure that divides each identified triangle, which needs refinement into four new triangles by adding a new point on each face. In order to avoid hanging nodes, the triangles that had only one face marked should be divided in two. The properties of each new triangle were set equal to those of the original one in order to restart the time iteration process.

## 3. EXPERIMENTAL APPARATUS

The model geometry (Figure 2) consists of a "double Apollo disc", wherein the upper and lower contours are identical and are "scaled" directly from the Apollo Command Module's lower heat shield. A 6-in. diameter aluminum model of the vehicle was constructed to investigate the incident hypersonic flow in the RPI 24-in. diameter Hypersonic Shock Tunnel. The "double Apollo disc" model (Figure 3) was designed to enable the measurement of heat-transfer and pressure drag across a blunt "double Apollo disc" forebody at hypersonic speeds.

The RPI 24-in. diameter Hypersonic Shock Tunnel was used for the Mach number 10 flow for the "double Apollo disc" experimental investigation. Minucci (1991) describes in detail the five components of this facility: the driver tube section, the DDS (Double Diaphragm Section), the driven tube section, the nozzle, and the dump tank. The facility is capable of generating reservoir enthalpies up to 6.5 MJ/kg at a stagnation temperature of 4100 K when operating in the equilibrium interface mode with helium in the driver section.

Figure 2 - "Double Apollo Disc" Vehicle in Hypersonic Flight.

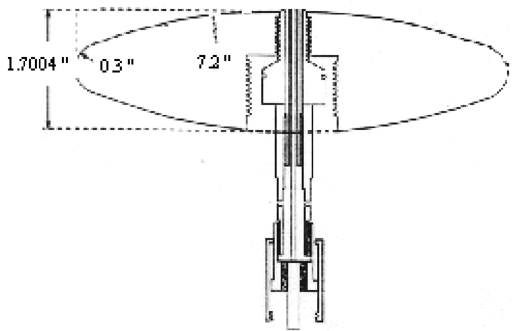


Figure 3 - "Double Apollo Disc" Model.

The present re-entry vehicle SARA Y (high drag) and the "double Apollo disc" configurations are very similar; then the experimental pressure and heat flux data of the "double Apollo disc" may be used to help the re-entry vehicle SARA Y configuration design.

## 4. EXPERIMENTAL RESULTS FOR HIGH DRAG SARA CONFIGURATION

When the "double Apollo disc" model was tested, nine thin-film platinum heat gauges and eight piezoelectric pressure transducers were used to measure the heat flux and the static pressure along the frontal surface.

The Schlieren photograph of Mach number 10 flow over a “double Apollo disc”, shows that the shock is symmetrical, and the shock detachment distance may be estimated by Billing’s correlation (1967) based on experimental data. The stand-off distance of 0.8 in (20.32 mm) agrees with theoretical calculations (Figure 4).

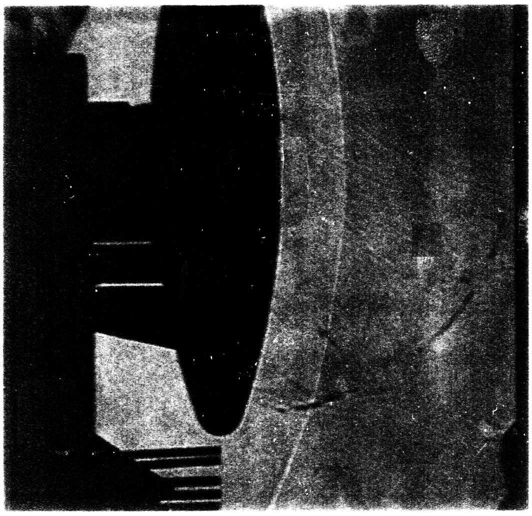

Figure 4 - Schlieren photograph of “double Apollo disc” model.

When the "double Apollo disc" 6-in. diameter was tested in the 24-in. diameter Hypersonic Shock Tunnel, the experimental pressure results were found to agree quite well with the analytical results of Modified Newtonian theory (Figure 5). The experimental pressure ratio over the “double Apollo disc” model agrees qualitatively with the experimental and the locally self-similar solutions pressure ratio over a flat-nosed body presented by Kemp et al. (1959).

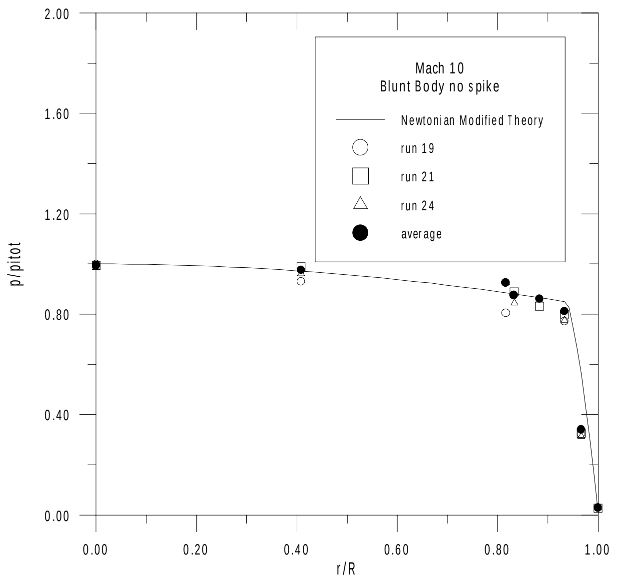


Figure 5 - Pressure ratio at "double Apollo disc" model.

The short test time of the RPI Hypersonic Shock Tunnel, of the order of a few milliseconds, requires the development of fast response heat flux sensors. Thin-film platinum heat gauges are specially suited for use in shock tubes and shock tunnels. Small diameter (2.4 to 3.4 mm) thin-film platinum heat transfer gauges were designed, developed, and constructed to measure the voltage changes when installed on the "double Apollo disc" model. Pyrex and Macor materials were used as a substrate for the thin-film.

Experimental heat transfer measurements across the "double Apollo disc" model surface presents a behavior in general agreement with available experimental data and theoretical heat transfer predictions (using the locally self-similar solutions, Kemp et al., 1959). Due to rapid flow expansion around the perimeter of a "double Apollo disc" body, the maximum heat transfer is predicted not at the stagnation point, but just at the beginning of the "corner" of the flat-faced nose. In a very large radius region (i.e., nearly flat surface), the heat transfer tends to the Modified Newtonian theory heat transfer calculation (Figure 6).

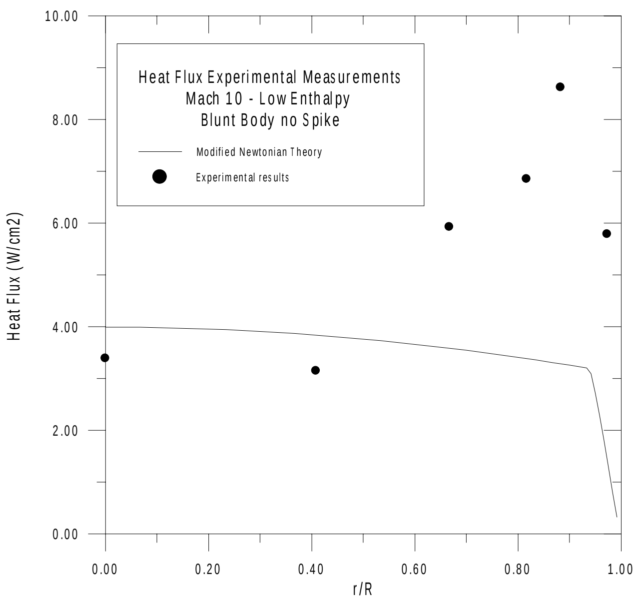


Figure 6 - Heat flux at "double Apollo disc" model.

The rapid expansion of the inviscid flow around the corner imposes an extremely large favorable pressure gradient on the boundary layer, which results in an actual reduction of the boundary layer thickness. Since the temperature gradient is inversely proportional to the boundary layer thickness, a smaller boundary layer thickness results in a higher temperature gradient, and consequently, higher heat flux at the wall, $q_w = k\left(\frac{\partial T}{\partial y}\right)_w$, therefore, the local heat transfer is expected to increase at the corner (Anderson Jr., 1989).

## 5. NUMERICAL RESULTS FOR LOW DRAG SARA COFIGURATION

The results obtained for an inviscid flow over a low drag configuration (Figure 1) at Mach number 10 is presented. The fluid is treated as perfect gas, and no chemical reactions are taken into account. The numerical results presented here show the capability of the present formulation developed by Azevedo et al. (1998) and Korzenowski (1998).

The mesh (Figure 7) with 5526 nodes and 10842 volumes was used to compute the hypersonic flowfield characteristics: Mach number, pressure, density and temperature (Figure 8-11) over the low drag SARA configuration (Figure 1). The adaptive mesh was obtained with one pass of refinement. The sensor used on the adaptive refinement procedure was based on all primitive variable gradients. The initial mesh had 3036 nodes and 5890 volumes. In the present case, 2000 iterations were performed before the first refinement pass.

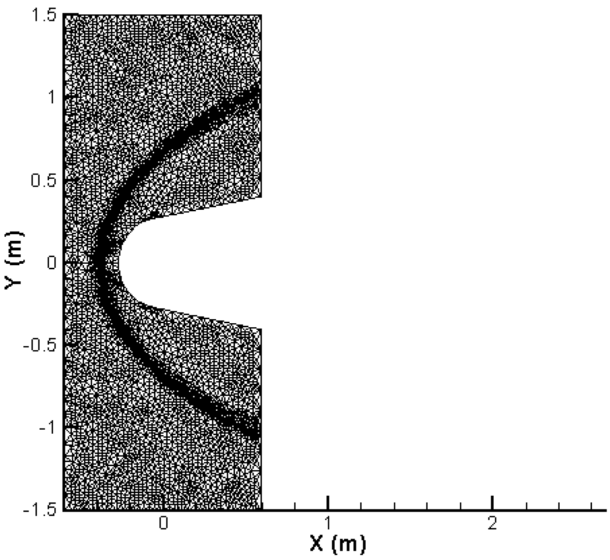


Figure 7 – Adaptive mesh obtained with one pass of refinement

The Mach number contours obtained with the second-order van Leer scheme are presented (Figure 8). The contours indicate that the flow features are well captured by this scheme, the bow shock and the flow expansion over the body are well represented. One can see that at the nose of the body the shock is normal, and away from this the shock wave gradually becomes curved and weaker. The hypersonic flow ahead the shock becomes subsonic downstream of the shock, that is, there is a strong compression of the flow in this region.

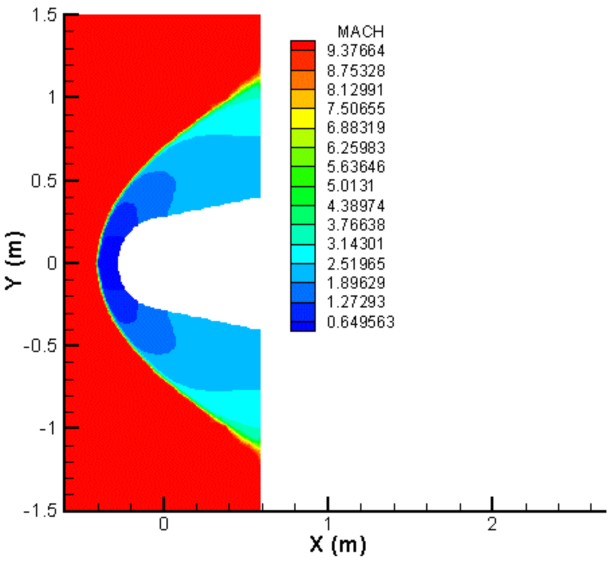


Figure 8 - Mach number contours obtained using 2nd-order van Leer scheme ( $M_\infty = 10$ )

The pressure, density and temperature contours are presented (Figure 9-11). These properties, downstream of the wave, obtained by use of the basic normal shock equations, are $p_2 = 83{,}21$, $\rho_2 = 5{,}714$, $T_2 = 20{,}39$, respectively. The properties obtained by the numerical solution simulations are $p_2 = 85{,}63$, $\rho_2 = 5{,}59$, $T_2 = 21{,}42$. One can observe a maximum error of 5% between the analytical and numerical results, indicating that the scheme was adequate to assess the properties of the flow.

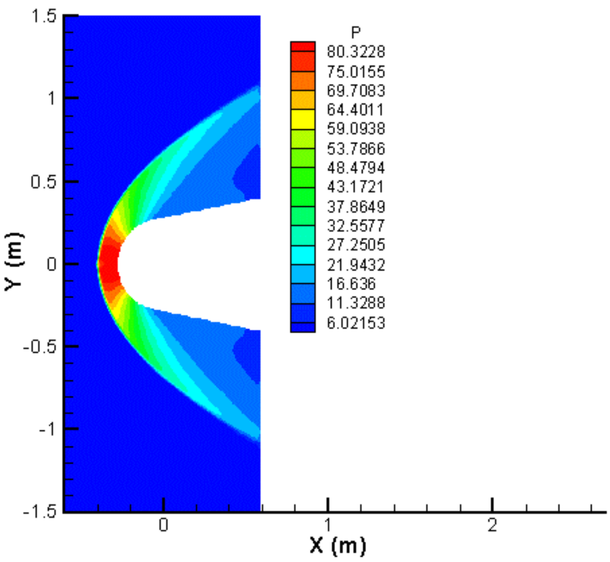


Figure 9 – Pressure contours obtained using 2nd-order van Leer scheme ( $M_\infty = 10$ )

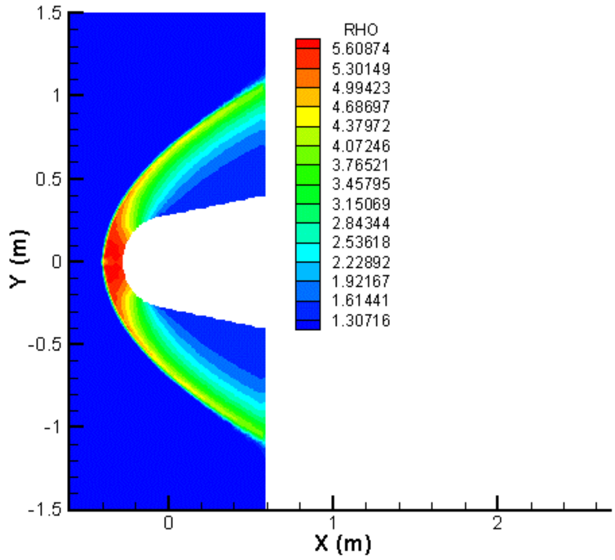


Figure 10 – Density contours obtained using 2nd-order van Leer scheme ($M_\infty = 10$)

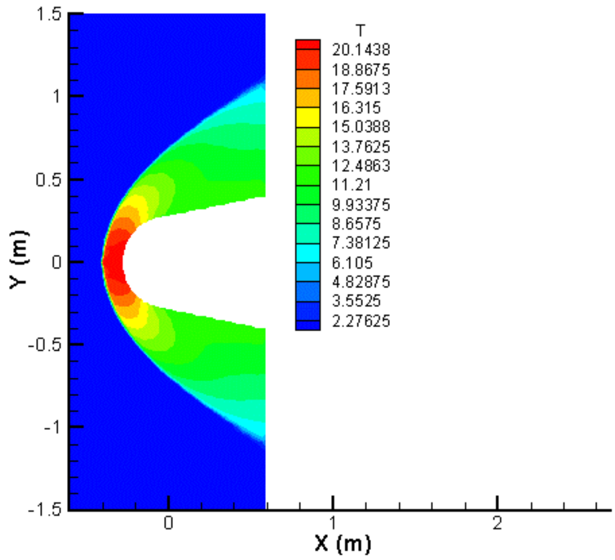


Figure 11 – Temperature contours obtained using 2nd-order van Leer scheme ($M_\infty = 10$)

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