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# BRAZILIAN 14-X SA HYPERSONIC AXISYMMETRICAL SCRAMJET AEROSPACE VEHICLE ANALYTICAL AND NUMERICAL ANALYSIS AT MACH NUMBER 7

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***Abstract.*** *The Brazilian 14-X SA Hypersonic scramjet Aerospace Vehicle, VHA 14-X SA, is an axisymmetrical hypersonic vehicle with airframe-integrated scramjet engine, where the scramjet engine is (in the present case) an axisymmetrical aeronautical engine that with no moving parts and uses the attached conical shock wave generated at the sharp cone inlet of the hypersonic vehicle during the hypersonic flight into Earth's atmosphere. The sharp cone inlet promotes compression and deceleration of atmospheric air into the combustion chamber (scramjet engine). This atmospheric air at supersonic speed is mixed and burned with an on-board fuel (hydrogen in this present case) suitable for the production of thrust. The combination of the high energies of the fuel and of the oncoming hypersonic airflow the combustion at supersonic speed starts. Pressure, temperature and density distributions as well as velocity (Mach number) at VHA 14-X SA scramjet power off surfaces will be obtain based on the analytical theoretical analysis using conical compressible flow. Also, countor plots of static pressure, static temperature and static density as well as countor plot os the Mach number will provide using the "Fluent" commercial software.*

***Keywords:*** *VHA 14-X B, hypersonic airbreathing propulsion, scramjet, hypersonic shock tunnel.*

## 1. INTRODUCTION

The aerospace technological products have grown that one cannot conceive of putting payloads (satellites) into Earth's orbit or beyond using technologies in operation (rockets carry out solid or liquid fuel). The knowledge required to keep the current launching vehicles is already so high that if the countries do not have a technological support for their own industry, they will depend on of the supplier countries and not have independent capacity sustained.

Aerospace vehicle limitations for launching payloads into orbit or beyond require a continuous reduction in size, weight and power consumption of launch vehicles. Some solutions to these challenges require paradigm shifts, new production methods, and new technologies of strategic nature. The requirements of platforms launched satellites, high performance and reliability, as well as the strict limitations of fuel (reduction of size, weight and power consumption) for launching payloads into orbit or beyond provide the development of hypersonic aircraft using hypersonic airbreathing propulsion based on supersonic combustion (scramjet).

The recent intensification of international efforts to develop hypersonic propulsion system based on supersonic combustion, signals that this is the way of effective access to space in a not too distant future. Therefore, the field of Hypersonic Airbreathing Propulsion based on supersonic combustion, will be essential in the near future for the aerospace industry, and allow the man to build hypersonic planes, to reach other continents in hours and achieve low orbits around Earth.

The scramjet is the only airbreathing propulsion system to be able to provide the thrust needed efficiently in hypersonic flight (Curran, 2001). In addition, it has the advantage over rocket engines not lead to oxidizing substance, reducing vehicle weight. To get an idea of structural weight savings this fact, one should bear in mind that the first stage of the Saturn-1, a rocket widely used by NASA, must carry 285ton of liquid oxygen to burn 125ton of RP-1 (a type of highly refined kerosene for rocket). Aerospace vehicles using scramjet have no moving parts, and the scramjet works as follows: slows the flow into the air intake through oblique or conical shock waves until the inlet air reaches the velocity and pressure necessary to ensure that there is combustion. Thus, the gases produced in combustor with its high enthalpy and pressure is expanded in the nozzle. This cycle is then responsible for the thrust generated by the engine. Normally, the fuel chosen for the scramjet is Hydrogen, due to the fast time of ignition and high specific impulse.

The recent success to demonstrate the supersonic combustion concept, through the (2004 about 10s burnt hydrogen scramjet-powered at Mach 7 and 10) X-43 Aerospace Vehicle flights (McClinton et al., 2001; Moses et al., 2004; Marshall et al., 2005 a; Marshall et al., 2005 b) and the (2010 about 140s burnt hydrocarbon scramjet-powered at Mach number 6+) X-51 Aerospace Vehicle flight (Hanks et al., 2008) provided by the new U.S. hypersonics strategy formulated (after NASP program) by NASA, U.S. Government agencies (Air Force, Army and Navy) and DARPA for the next generation of space transportation systems under NASA Marshall Space Flight Center's Advanced Space Transportation Program (ASTP) gave a fresh renaissance in hypersonic flight.

Basically, the scramjet is a fully integrated airbreathing aeronautical engine (that has no moving parts) that uses the oblique/conical shock waves generated during the hypersonic flight, to provide compression and deceleration of freestream atmospheric air at the inlet of the scramjet. This atmospheric air at supersonic speed is mixed and burned with an on-board fuel suitable for the production of thrust. Therefore, the combustion process occurs in supersonic regime. When the combustion process occurs in subsonic regime, it is called subsonic combustion or ramjet, the predecessor of the scramjet, which already finds many applications. The total pressure loss that occurs through normal shock wave (which slows the flow in ramjets) makes use of these engines impractical at hypersonic speeds.

An important feature of the scramjet is a highly integrated system, where engine and vehicle are indistinguishable. This tight integration is caused by the fact that the front section of the vehicle contributes to the compression of atmospheric air, while the rear contributes to the generation of thrust. The net thrust produced by the scramjet is the difference between the thrust (force that propels the vehicle) generated by the expansion of exhaust gases from the rear of the engine and the total drag (force that resists the movement of the vehicle). These forces may produce thrust to the flight of the vehicle or not depending on the balance of these forces in engine design in question.

Thus, aerospace vehicles propelled by scramjets carry only the fuel, usually Hydrogen, using atmospheric air as an oxidant itself by acquiring most of the kinetic energy required to reach Earth orbit during atmospheric flight. As a result of self-propulsive nature of the reactors, they are unable to produce thrust while standing still. The static thrust is zero. Accordingly, they must be accelerated to a speed such that the shock waves produced by the air intake are able to compress the atmospheric air. This velocity is approximately four times the speed of sound, Mach 4, considering scramjet.

## 2. SCRAMJET RESEARCH AT THE INSTITUTE FOR ADVANCED STUDIES

### 2.1 The Brazilian 14-X Projects

The Brazilian 14-X Hypersonic Aerospace Vehicle, VHA 14-X, project (Fig. 1) named after 14-Bis developed by aviation pioneer Alberto Santos Dumont, is being designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies (IEAv) since 2007 (Ricco et al., 2011; Toro et al., 2012).

Today, the VHA 14-X is a strategic project of the Department of Aerospace Science and Technology (DCTA), where the goal is to design, to develop, to manufacture and to demonstrate, in free flight at 30km altitude at Mach number 10, a technology demonstrator using ”scramjet” as an hypersonic airbreathing propulsion system based on supersonic combustion.

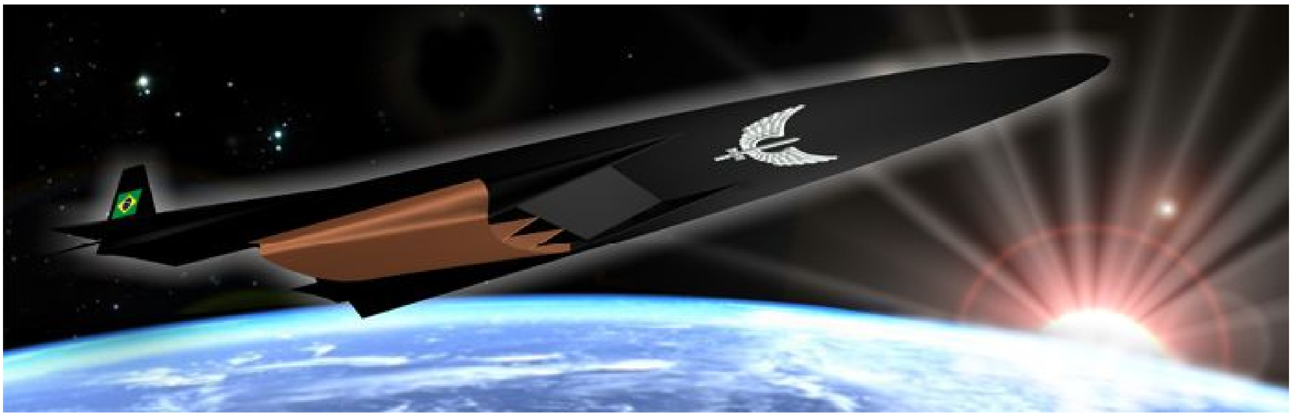

Figure 1: Brazilian 14-X Hypersonic Aerospace Vehicle, VHA 14-X.

In March 2012, the coordination of the VHA 14-X proposed new versions based on the VHA 14-X (Toro et al., 2013), where the VHA 14-X SA (Fig. 2) has been designed to demonstrate the fully axisymmetrical scramjet technology at 30km altitude with Mach number 7.

Since, the scramjet is a fully integrated airbreathing aeronautical engine (that has no moving parts) the VHA 14-X SA will be operational only on hypersonic speeds, and a hypersonic accelerator vehicle will be needed to take the VHA

14-X SA at 30km altitude at Mach number 7. As a low-cost solution to launch scramjet integrated vehicle to flight test conditions (30km altitude at Mach number 7) is to use rocket engines based on solid propulsion, in ballistic trajectory. Such approach may provide an affordable path for maturing Brazilian hypersonic airbreathing components and systems in flight.

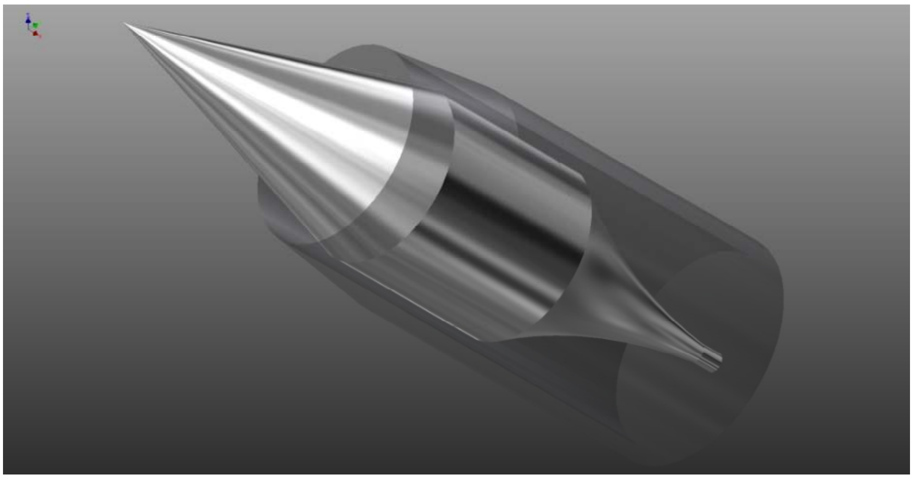

Figure 2: 14-X SA Hypersonic Aerospace Vehicle, VHA 14-X SA.

In general, analytical theoretical analysis (closed form equations), computational fluid dynamics simulation and experimental investigation are the methodological tools used to design a technological demonstrator, before flight throughout Earth's atmosphere.

Analytical theoretical analysis provides simplified mathematical models; which are able to obtain a fast and reliable set of optimal parameters to be used on the nose-to-tail hypersonic vehicle with airframe-integrated scramjet engine preliminary design.

A nomenclature needed not only in the analytical theoretical analysis but also may be used in the numerical simulation and experimental investigations are presented by Heiser and Pratt (1994) and it is adapted for the VHA 14-X SA. which it is divided in three main components (Fig. 3): external and internal compression section (inlet), combustion chamber (combustor) and internal and external expansion section (outlet).

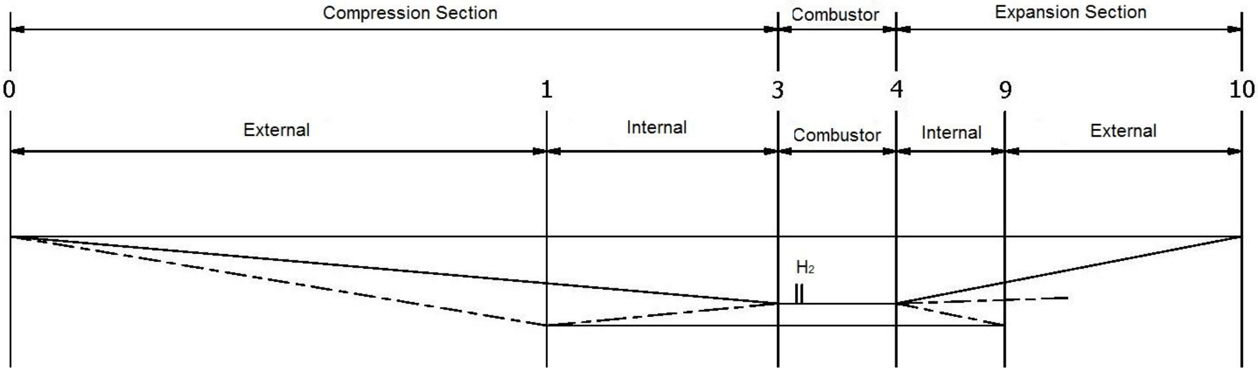

Figure 3: Hypersonic vehicle with airframe-integrated scramjet engine stations and reference terminology.

### 2.2 Experimental Investigation of the axisymmetrical Scramjet at the T2 Hypersonic Shock Tunnel

An experimental investigation of supersonic combustion was developed, during 2007-2009, at the T2 IEAv Hypersonic Shock Tunnel (Alcaide, 2009) and the main results were presented by Romanelli Pinto et al. (2011).

The conceptual design of the 15° axisymmetrical conical supersonic combustion model (Fig. 4) consists by a conical inlet following by axisymmetrical cylindrical combustion chamber, where, internally, there is the fuel tank. The cylindrical part is tightly integrated with the front and rear in order to reduce drag and weight at hypersonic speeds. At the rear has a cone shape, where the products of combustion are exhausted (Alcaide, 2009).

Figure 4: Supersonic combustion model installed at the T2 Hypersonic Shock Tunnel test section.

Schlieren visualization system using high speed camera (Cordin 550-32C) was used to observe the injection of fuel (on-board Hydrogen gas) during the test time of the T2 Hypersonic Shock Tunnel (Fig. 5). One may observe that the conical attached shock wave at the leading edge of the scramjet model reach the cowl of the inlet. The onboard Hydrogen gas fuel is injected into the atmospheric supersonic airflow. Due to the geometry of the scramjet (axisymmetrical) is not possible to visualize the combustion.

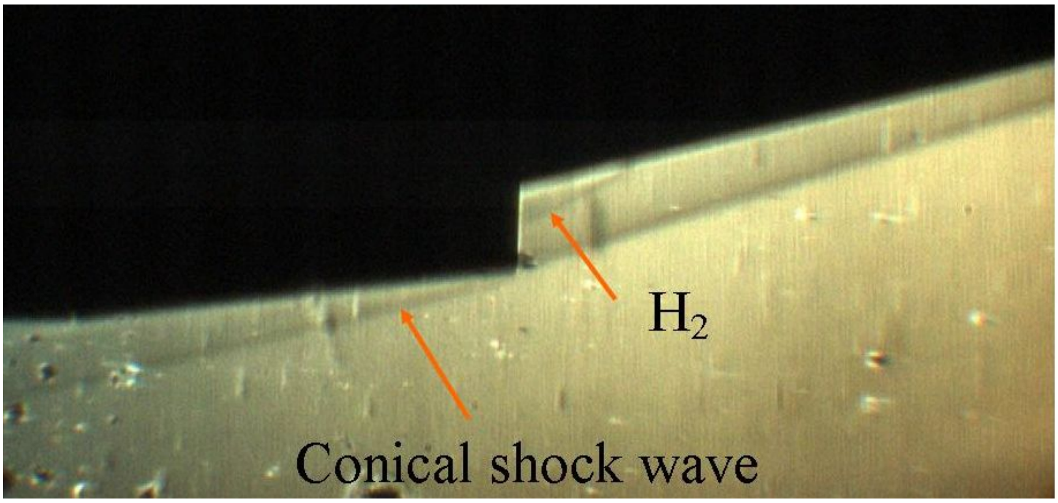

Figure 5: On-board Hydrogen gas injection in supersonic airflow.

A time-lapse photography obtained through the integrated camera Nikkon D-1 (Fig. 6) shows the exhaustion of combustion products during the test of supersonic combustion. An obstacle was added at the combustion chamber to generate a high temperature stagnant spot to increase the probability to start the combustion.

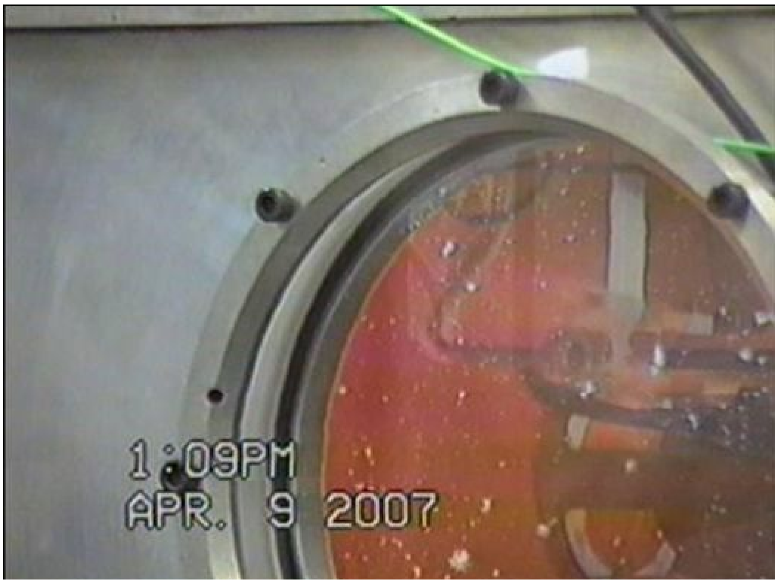

Figure 6: Time-lapse photography of the combustion products.

## 3. VHA 14-X SA ANALYTICAL THEORETICAL ANALYSIS

An in-house Fortran code was developed to determine the thermodynamic (pressure, temperature and density) air properties ratio, the Mach number behind the conical shock wave and the shock wave angle based on the conical supersonic/hypersonic steady, no viscous, no heat conducting calorically perfect airflow (Anderson, 2003).

The VHA 14-X SA (Fig. 4) with $15^o$ leading-edge flying at 30km altitude (where the static pressure, static temperature, static density and sound velocity are given by $p = 1197(Pa)$, $T = 226.5(K)$, $\rho = 0.01841\left(kg/m^3\right)$, $a = 301{,}7(m/s)$, respectively (U.S. standard Atmosphere, 1976)) at Mach number 7 is not capable to genetarate a static temperature higher than 845K (ignition temperature of Hydrogen) at the combustor (Table 1). Consequently, an increase of the leading-edge to a $15^o$ is proposed to obtain reasonable conditions (Table 2) at the combustor chamber.

Note, the flow across the conical shock wave promote an increase of pressure, density, temperature and a decrease of Mach number, however it is assumed the flow remains supersonic/hypersonic and parallel to the conical streamline starting at $15^o$ (or 23°) leading-edge, therefore the average of the properties at the streamline at the conical (body) surface and the properties at the streamline right after the conical shock wave is used as input to evaluate the reflected shock wave (and properties). Also, it is assumed the reflected shock wave is determined by oblique shock relationships.

Along the present analytical theoretical analysis (closed form equations) the subscripts $in$ and $out$ will be used to identify the upstream (inlet) and the downstream (outlet) conditions, respectively, of the each station (Fig. 3) of the hypersonic vehicle with airframe-integrated scramjet engine lower surface.

Table 1: Thermodynamic properties at the VHA 14-X SA 15º leading-edge at 30km at Mach number 7, $\gamma = 1.4$ .

| | | station 0 | station 1 (deflection cone 15º) | station 1 (deflection oblique 15º) |
|---|---|---|---|---|
| $M_{in}$ | | 7 | 7 | 3.7013 |
| $\theta_{in}$ | | | 15 | 15 |
| $\beta_{out}$ | | | 18.3643 | 24.6249 |
| $M_{out}$ | | | 4.8588 | 3.4284 |
| $T_{out}$ | K | 226.5 | 427.5867 | 730.1043 |
| $p_{out}$ | Pa | 1197 | 6929.9118 | 31982.9289 |
| $\rho_{out}$ | kg/m$^3$ | 0.01841 | 0.05642 | 0.15249 |
| $a_{out}$ | m/s | 301.7 | 415.3585 | 542.7453 |
| $u_{out}$ | m/s | 2111.9 | 2018.1439 | 1860.7479 |

The present analytical theoretical analysis has been carried out in the VHA 14-X SA (Fig. 2) framework. The conceptual design axisymmetrical configuration of the VHA 14-X SA (Fig. 7) consists by an inlet (frontal) sharp conical segment with 23° leading-edge of, following by the combustion chamber with axisymmetrical cylindrical geometry, where, internally, there is the fuel tank. With the same purpose of the axisymmetrical scramjet model (Fig. 4) the cylindrical part is tightly integrated with the front and rear regions in order to reduce drag and weight at hypersonic speeds. The external diameter of the combustion chamber was defined to be $370-mm.$ (Fig. 7).

Table 2: Thermodynamic properties at the VHA 14-X SA 23º leading-edge at 30km at Mach number 7, $\gamma = 1.4$ .

| | | station 0 | station 1 (deflection cone 15º) | station 1 (deflection oblique 15º) |
|---|---|---|---|---|
| $M_{in}$ | | 7 | 7 | 3.7013 |
| $\theta_{in}$ | | | 23 | 23 |
| $\beta_{out}$ | | | 26.7302 | 37.1855 |
| $M_{out}$ | | | 3.7013 | 2.2125 |
| $T_{out}$ | K | 226.5 | 654.1093 | 1236.1357 |
| $p_{out}$ | Pa | 1197 | 14158.3554 | 80303.3601 |
| $\rho_{out}$ | kg/m$^3$ | 0.01841 | 0.07538 | 0.22624 |
| $a_{out}$ | m/s | 301.7 | 513.7227 | 706.2146 |
| $u_{out}$ | m/s | 2111.9 | 1901.4418 | 1562.4998 |

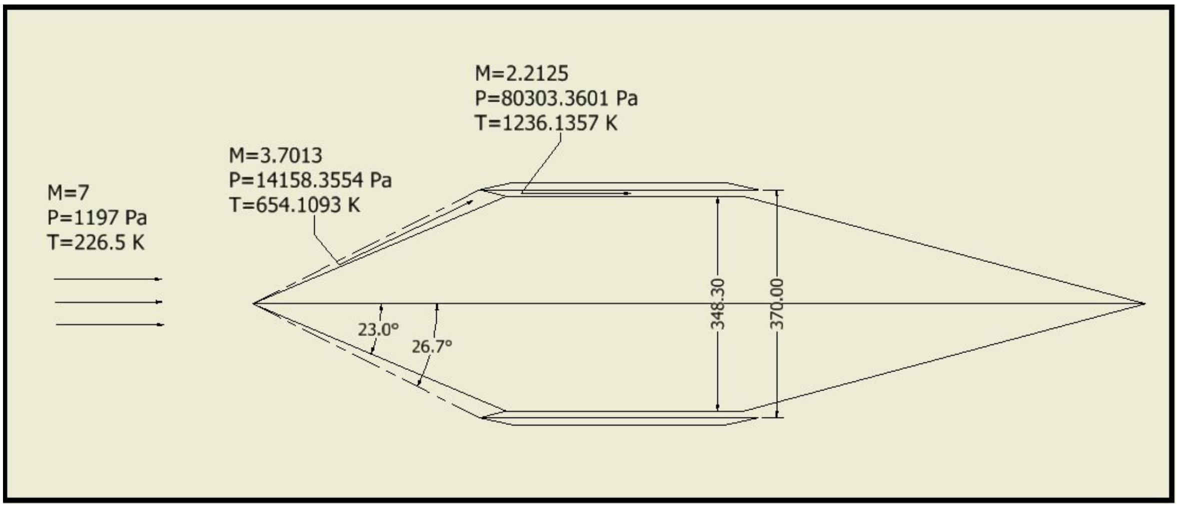

Figure 7: Cross-section of the V14-X SA and analytical theoretical results.

The primary objective of the present analytical theoretical analysis is applying the to the inlet and the combustion chamber only, in order to obtain the preliminary conditions to design an axisymmetrical model to experimental investigate at the T3 Hypersonic Shock Tunnel existing at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics.

In order to confirm the hypothesis of oblique shock angle define at the reflected flow from the 23° leading-edge of a numerical simulation was performed, using the axisymmetrical geometry (Fig. 8).

## 4. NUMERICAL THEORETICAL ANALYSIS

The commercial "Fluent" software, which solves the mass, momentum and energy conservation equations, considering reacting flow and includes routines (solvers) that accurately simulate the behavior of flow, single phase and multiphase, Newtonian and non-Newtonian flow from subsonic to hypersonic speed, is able to perform a numerical theoretical simulation applied to the Brazilian technological demonstrators.

Steady state, non-viscous, no heat conduction axisymmetrical geometry of the compressible flow using implicit second order upwind spatial discretization are used to nose-to-tail numerical modeling of VHA 14-X SA (Fig. 8) geometry.

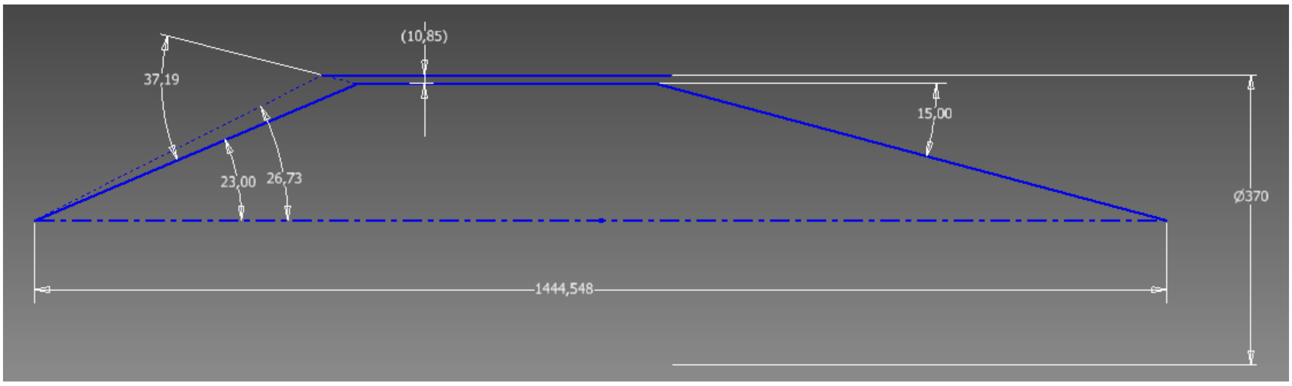

Figure 8: External configuration of the VHA 14-X SA, based in the analytical theoretical analysis.

The numerical test case is related to the hypersonic vehicle with airframe-integrated scramjet engine flying at Mach number 7 at 30km altitude (U.S. standard Atmosphere, 1976) where the static pressure, static temperature, static density and sound velocity are given by $p = 1197\left(Pa\right)$, $T = 226.5\left(K\right)$, $\rho = 0.01841\left(kg/m^3\right)$, $a = 301{,}7\left(m/s\right)$, respectively.

For the present numerical test case, with power-off scramjet engine, the flow from the external and internal compression section are deflected to the combustor entrance (Fig. 3) at supersonic speed (at constant pressure, constant density, constant temperature and constant Mach number) and remains constant at the exit of the combustor.

Note that the incident attached conical shock waves (at the 23° leading-edge deflection angle) hits (very closely) the cowl leading-edge (Figs. 9 and 10) conforms the inlet design criteria of the VHA 14-X SA. Also, the reflected shock wave due to the incident conical shock waves impinges (very closely) the entrance of the combustor (Fig. 10). Figure 10 shows a very weak shock train at the combustor inlet entrance.

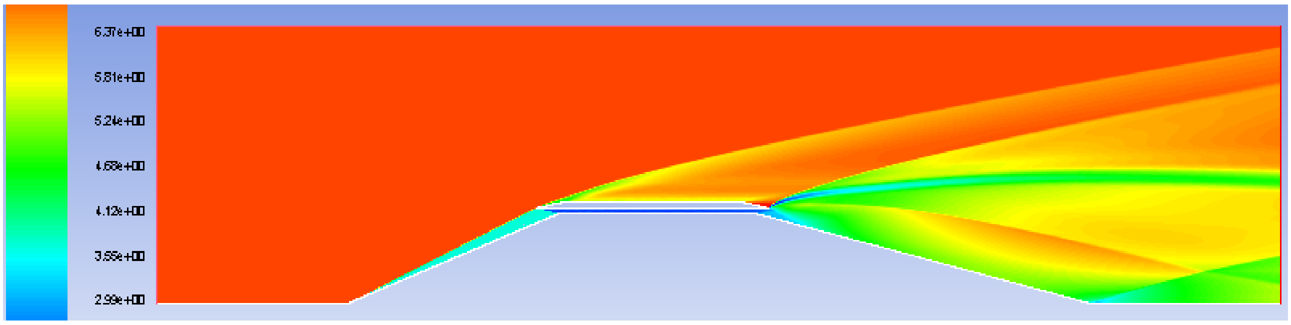

Figure 9: Countor plot of the Mach number.

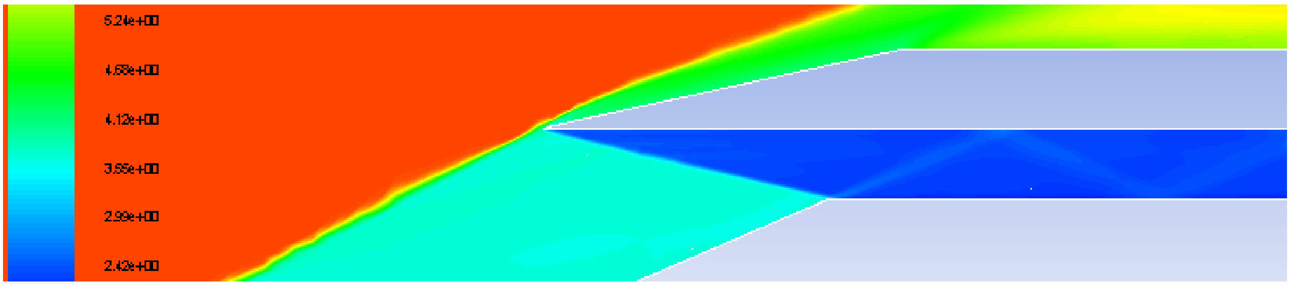

Figure 10: Detailed of the countors plot of the Mach number at the combustor chamber entrance.

The same behavior (incident attached conical shock waves hits the cowl leading-edge) is showing at the countor plots of the pressure (Fig. 11), temperature (Fig. 12) and density (Fig. 13). Additionally, the maximun static pressure (Fig. 8) occurs at the combustor (Fig. 11) and may be used as a guide to specify the conditions to the static and dynamic structural analysis to be perfomed for VHA 14-X SA flying at 30km altitude at Mach number 7.

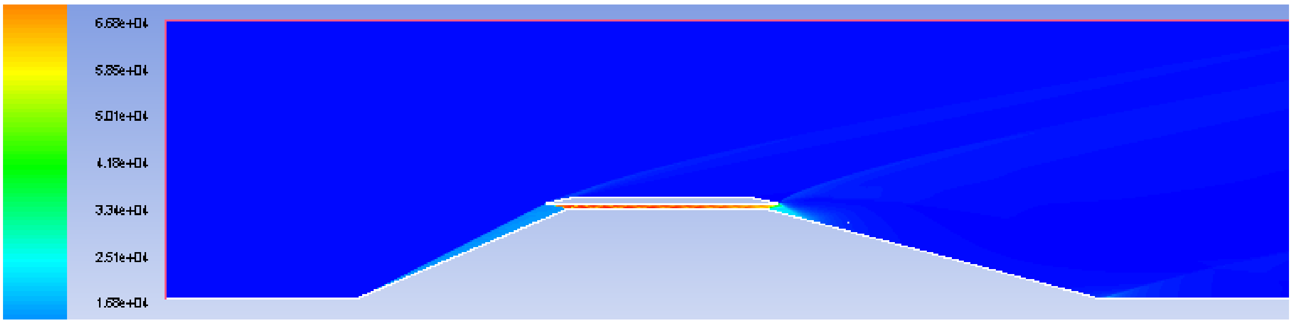

Figure 11: Countor plot of the pressure.

The 23° leading-edge conical deflection angle (Fig. 12) is capable to genetarate a static temperature about 1236K at the combustor (Fig. 8) higher than the ignition temperature of 845K for Hydrogen (Kuchta, 1985), with supersonic Mach number higher than 2 at the combustor (Figs. 8 and 10).

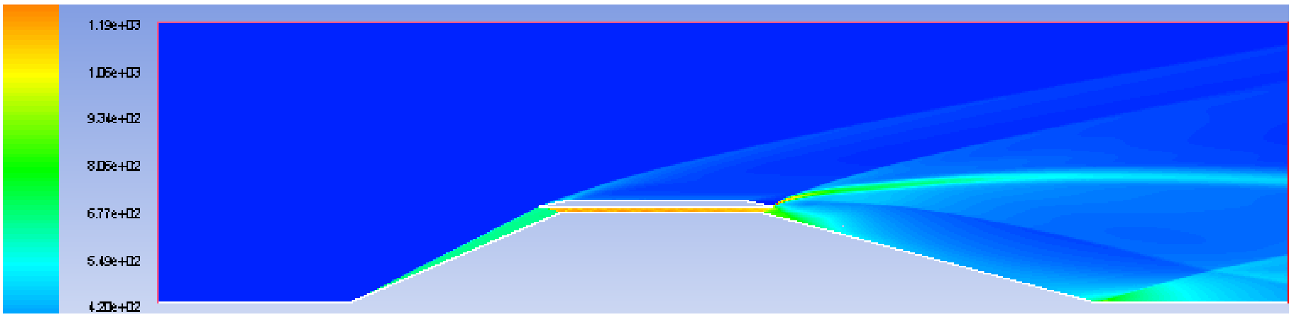

Figure 12: Countor plot of the temperature.

The contour of the static density gradients across the VHA 14-X SA scramjet engine (Figs. 13 and 14) shows there is a very weak shock train at the combustor chamber, which means the optimum combustor chamber design is not achivied, therefore with the flow mass rate at the entrance of the combustor chamber is not the same at the entrance of the VHA 14-X SA vehicle.

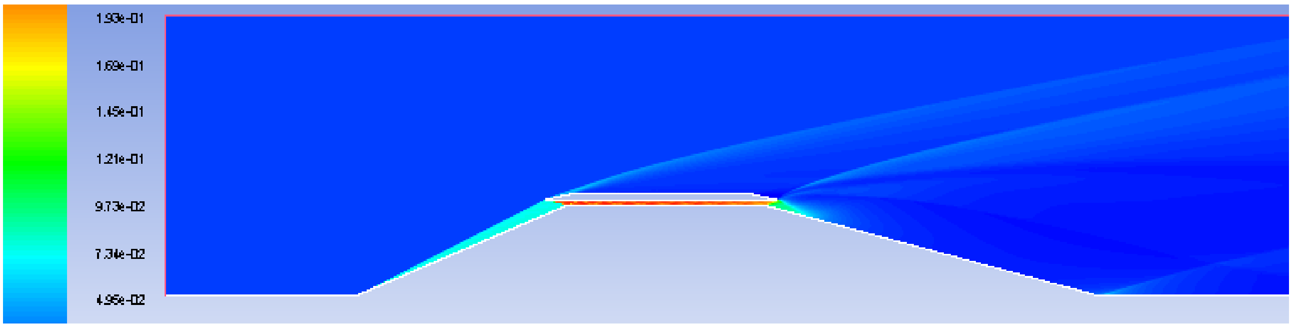

Figure 13: Countor plot of the density.

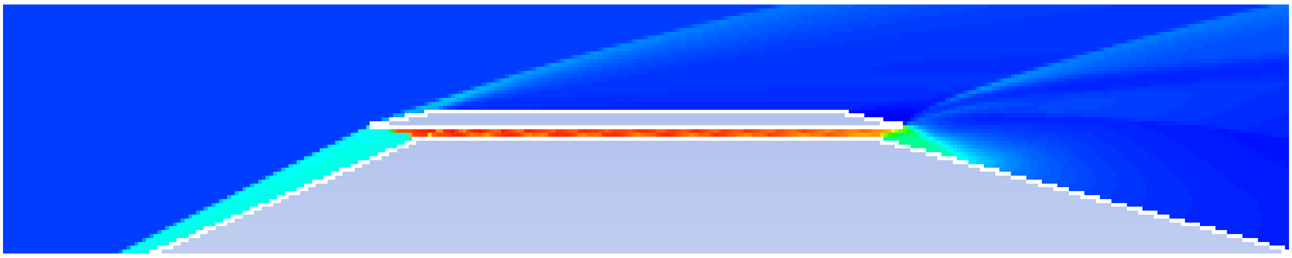

Figure 14: Detailed of the countors plot of the Mach number at the combustor chamber entrance.

Figures 15 and 16 show the temperature and pressure numerical simulation results are comparable to the temperature and pressure analytical theoretical analysis (Fig. 8), respectively. Also, both numerical results show the shock train at the combustor section of the VHA 14-X SA.

Finally, the temperature (Fig. 15) and pressure (Fig. 16) numerical simulation results show the expansion section must be re-design to obtain at least a (probably) constant thermodynamic properties (pressure, temperature, density, Mach number) lower than the thermodynamic properties at the 23° leading-edge conical deflection angle , to be expand to close conditions on no disturbed Earth’s atmosphere at desired (in this case 30km) altitude.

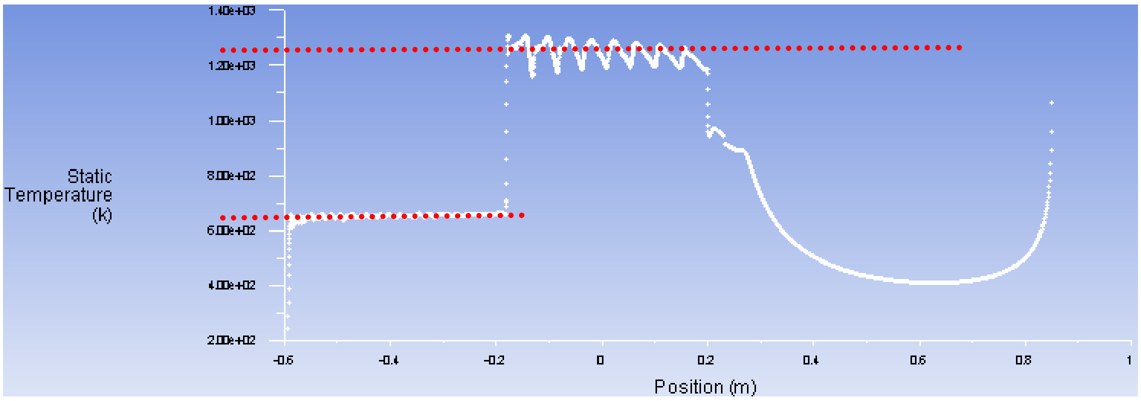

Figure 15: Numerical and analytical temperature distribution at the VHA 14-X SA.

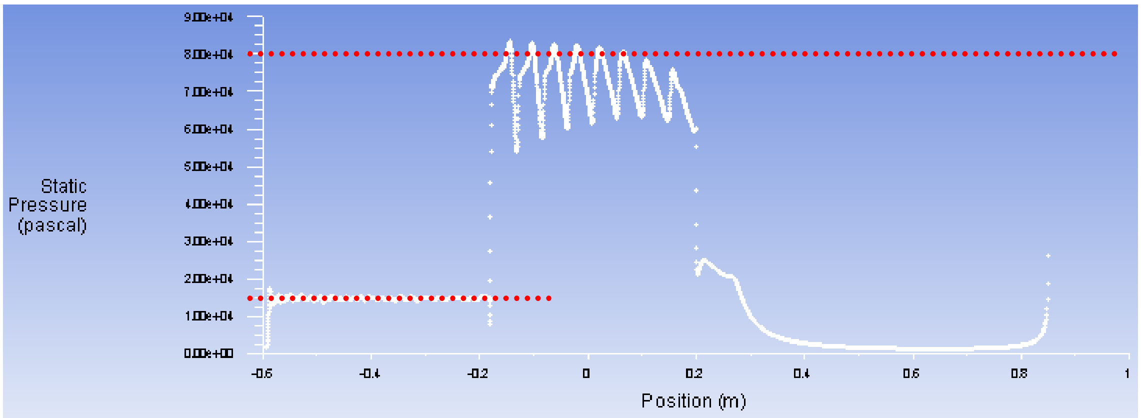

Figure 16: Numerical and analytical pressure distribution at the VHA 14-X SA.

## 5. DESIGN OF THE INWARD-TURNING INLET MODEL FOR EXPERIMENTAL INVESTIGATION

Hypersonic Shock Tunnel is a shock tube fitted with a convergent-divergent nozzle to produce high Mach number and high enthalpy flows in the test section close to those encountered during the flight of a space vehicle into the Earth's atmosphere at hypersonic flight speeds.

The T3 0.60-m. nozzle exit diameter Reflected Hypersonic Shock Tunnel, which is a new Hypersonic High Enthalpy Real Gas Pulsed Reflected Shock Tunnel (Fig. 17) funded by São Paulo Research Foundation (FAPESP, process nº 2004/00525-7), was designed by Toro et al (2005;2007) at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, primarily as Research and Development (R& D) facility for basic investigations in supersonic combustion applied to high-speed advanced airbreathing propulsion.

Figure 17: T3 0.60-m. nozzle exit diameter Hypersonic Shock Tunnel.

An (hypersonic vehicle with airframe-integrated) axisymmetrical inlet scramjet engine model (Fig. 18) (made by stainless steel) instrumented with piezoelectric pressure transducers on the compression surface and at the combustion chamber is being designed (based on analytical and numerical theoretical analysis) to be experimentally investigated on the equilibrium interface mode operation at the T3 Hypersonic Shock Tunnel at freestream Mach number from 7 to 8.

The axisymmetrical inlet scramjet engine model will be installed on the heavy steel stand (Fig. 18), specially designed to hold firmly the model, in the test section of the T3 Hypersonic Shock Tunnel. Two symmetrically windows were designed on the sides of the horizontal derivation of the tank dump, and they will be used as flow visualization windows.

An ultra high-speed camera, manufactured by CORDIN, model 550, coupled with mirror-based schlieren ‘Z’ configuration with the schlieren light beam path and placement of the Cordin camera has been used for dynamic flow visualization. The schlieren system is composed of a pulsed xenon flash lamp, an optical slit and focusing lens, two parabolic and three flat mirrors, the knife edge which provides the necessary light cut-off to the Cordin 550 ultra-high speed camera.

The Cordin 550 camera acquires 32 frames with a maximum resolution of 1000 x 1000 pixels at up to 2 million frames per second (fps) in full color. Such frame rates are achieved by a multi-faceted mirror spinning at high speeds, surrounded by 32 CCD elements which acquire images as the mirror rotates. Mirror rotation is driven by a turbine wheel supplied with high pressure $N_2$ for frame rates up to 500,000 fps, and pressurized He for the highest speeds. Even though extremely high speeds can be achieved, the present work demanded more modest 50,000 to 100,000 fps.

A multichannel time-delay generator is used to synchronize all the equipment used in the experiment (data acquisition system, and schlieren system) within the useful shock-tunnel time. The unit was triggered by a Kistler piezoelectric pressure transducer (model 701 A) located immediately upstream of the nozzle entrance. Also, this transducer supplies the reservoir pressure of the nozzle. Two other Kistler 701A transducers, located 0.314-m. apart at the end of the tunnel-driven section, mounted flush with the shock tube (heavy section) inner wall, were used to time the incident shock wave.

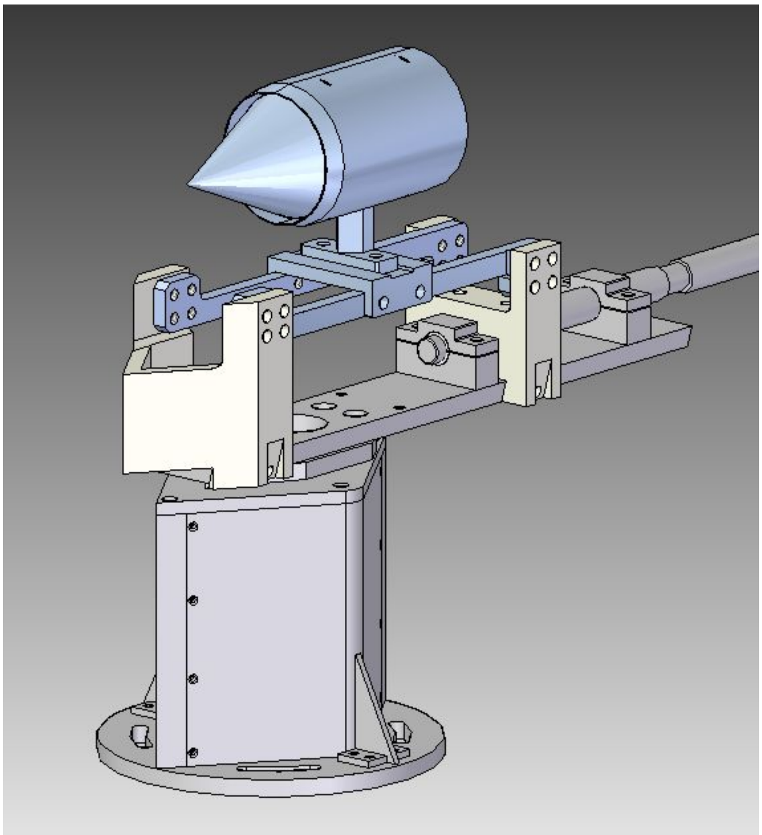

Figure 18: Axisymmetrical inlet scramjet engine model installed on the heavy steel stand.

## 6. CONCLUSION

The Brazilian VHA 14-X SA, designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, is part of the continuing effort of the Department of Aerospace Science and Technology (DCTA), to develop a technologic demonstrator using “scramjet” technology to provide hypersonic airbreathing propulsion system based on supersonic combustion.

An in-house Fortran code, considering supersonic/hypersonic calorically perfect airflow, was developed to estimate the aerothermodynamic properties along of the streamlines at the 23° leading-edge conical deflection angle of the VHA 14-X SA flying at 30km altitude at Mach number 7.

Fluent commercial code has been applied for the numerical simulation considering non viscous calorically airflow for the unpowered scramjet of the VHA 14-X SA at 30km altitude at Mach number 7. Implicit second order upwind spatial discretization is used to obtain the distributions of the static pressure, temperature and density and Mach number.

Numerical simulation results are comparable to the pressure analytical theoretical analysis applied to the VHA 14-X SA. The very weak shock train established at the combustor section shows the uniformity of the static pressure, static temperature, static density and Mach number. Also, the level of the temperature about 1250K at the combustor inlet is enough to burn the Hydrogen fuel.

Consequently, the in-house Fortran code drastically reduces the time and costs associated with the expensive time consuming of the Computational Fluid Dynamics commercial code.

A VHA 14-X SA model with 23° leading-edge conical deflection angle instrumented with piezoelectric pressure transducers on the compression surface and the combustion chamber is being designed and will be experimentally investigated on the equilibrium interface mode operation at the T3 Hypersonic Shock Tunnel at freestream Mach number simulating the flying conditions at 30km altitude.

## 7. ACKNOWLEDGEMENTS

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