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EXPERIMENTAL INVESTIGATION OF THE BRAZILIAN 14-X B HYPERSONIC SCRAMJET AEROSPACE VEHICLE

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Resumo: *The Brazilian hypersonic scramjet aerospace vehicle 14-X B is a technological demonstrator of a hypersonic airbreathing propulsion system based on the supersonic combustion (scramjet) intended to fly into the Earth's atmosphere at 30 km altitude and Mach number 7. The 14-X B was designed of the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, of the Institute for Advanced Studies (IEAv). Hypersonic wind tunnels are one of the most important ground-based experimental facilities intended to simulate the flight conditions providing experimental data to design hypersonic aerospace vehicles and engines. The IEAv 0.61-m nozzle exit diameter Reflected Hypersonic Shock Tunnel named T3 and funded by São Paulo Research Foundation (FAPESP), was designed as a research & development facility for basic investigations in supersonic combustion. The T3 Hypersonic Shock Tunnel is a shock tube equipped 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 aerospace vehicle into the Earth's atmosphere at hypersonic flight speeds. A 1-m long stainless steel 14-X B model was instrumented with twenty-nine piezoelectric pressure transducers along its compression surface, combustion chamber and expansion nozzle. It was experimentally investigated on the equilibrium interface operational mode of the T3 Hypersonic Shock Tunnel, yielding a freestream Mach number from 7 to 8. Static pressure measurements at the lower surface of the 14-X B as well as high speed schlieren photographs taken from the 5.5° leading edge and the 14.5° deflection compression ramp provide experimental data that was compared to the analytical theoretical analysis and computational fluid dynamics simulation, both applied to the design of the 14-X B. Some physical phenomena were observed such as chocked flow due to growth of boundary layer and interaction boundary layer and oblique shock between ramps of compression. Therefore, it became necessary some adjustments at the model so it would be possible to accommodate the mass flux at the combustion chamber by increasing the height and repositioning the leading edge of the cowl to preserve de shock on lip condition. The results obtained experimentally (pressure and schlieren photographs) and computationally were qualitatively similar which demonstrates the importance of these methods in a project of a hypersonic aerospace vehicle.*

Palavras-chave: *14-X B, Scramjet, Hypersonic*

1. HYPERSONIC FLIGHT

Hypersonic flight has been developed since 22 September 1963, when Robert M. White flew the North American X-15 at 2020.6 m/s at an altitude of 108 km at a Mach number of 6.7. This remarkable achievement was accomplished over six decades due to intensive research and development by a large number of scientists and engineers. In spite of that momentous achievement, designers have found the hypersonic environment to be harsh and non-forgiving. New programs since the 1960s have often uncovered the unknown unknowns, usually the hard way, early flights of new systems have often revealed problems of which the designers were unaware. Such problems include: the ineffectiveness of the body flap for the Space Shuttle Orbiter, the viscous/inviscid interactions produced by the umbilical fairings that damaged the conical section tile protection system of the Gemini Capsule, and the shock/shock interaction that damaged the X-15A-2 when it carried the hypersonic ramjet experiment. In order to continue to make advances in hypersonic flight a sustained and visionary effort is essential to generate required knowledge and technology. In order to better prepare for future developments in hypersonic flight, this article reviews the advances made within the past 50 years and then looks into the future, not just for new technological developments, but for new ways of thinking about the unknown challenges that lie ahead (Bertin and Cummings, 2003).

Allen (1958) pointed out that rocket and airbreathing engines are the most suitable propulsion system capable of provide hypersonic speeds to aerospace vehicle to bring payloads (and astronauts) into Earth's orbit. Additionally, Weber and Mackay (1958), also, indicated that the supersonic combustion (scramjet) may provide superior performance at higher hypersonic flight speeds than any other air-breather engines at speeds about Mach number 7. Besides that, only chemical propulsion system (rockets), at that time, was developed to carry, initially, payloads into the Earth's orbit, and lately, to bring astronauts to Earth's moon, which culminates as U.S. Space Apollo Program. Today the access to space is done, only, by multi-stage rocket-powered vehicles, which have flown hypersonically, carrying their own propellant (solid and/or liquid, oxidizer along with fuel) to propel payloads and astronauts to Earth's orbit. Several other propulsion systems are used and in developing to outer Earth's space.

However, from 60's, several programs were created to develop a hypersonic research vehicle that include a scramjet engine to demonstrate the supersonic combustion concept (Hallion, 1997). Even in the mid-1980s, the last hypersonic era began with the National Aero-Space Plane (NASP) program, developed in the United State of America, which was undertaken first by the Defense Advance Research Projects Administration (DARPA) in 1983. NASP was the first ambitious hypersonic aircraft project Single-Stage-To-Orbit (SSTO) reusable multi-cycle propulsion system vehicle envisioned to take off horizontally from a conventional runway, using airbreathing propulsion to accelerate to hypersonic speeds, fly into space to achieve low Earth orbit, and return for a runway landing. NASP fuselage lower front portion should operate as a shock wave compression ramp for air entering the supersonic combustion ramjet (scramjet) engines. NASP fuselage aft portion is a single expansion ramp nozzle used to expand the exhaust flow for maximum engine thrust (Barthelemy, 1989).

The fully integrated X-30 NASP research aircraft mission should consist of three separate cycles:

- a low-speed propulsion unit to take off from a normal runway, to climb and to descent to Mach number (2 or) 3 and to land to a normal runway;
- a mid-speed ramjet engine to kick the aircraft in at Mach number (2 or) 3 to Mach number 5 to climb and to accelerate to sufficient altitude and velocity, and;
- a hypervelocity supersonic combustion ramjet (scramjet) engine to complete the mission and to reach speeds of 8.3 km/s or Mach number 25, and boosting the aircraft into the orbit without a rocket assist.

To reduce costs and technical risks the NASP program was re-examined in 1993, and terminated in January 1995. However, the enormous amount of ramjet/scramjet engine research generated at that time created conditions for a modern treatment of hypersonic aerothermodynamic and airbreathing propulsion analysis and design principles for the academic, industrial and government communities.

The aerospace technological products have grown that one cannot conceive of putting payloads (satellites) into Earth 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.

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 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 5) X-51 Aerospace Vehicle flight (Hank 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.

Also, in 2000's The University of Queensland, Australia, demonstrate the feasibility of scramjet engine concept using the Hyshot (Paull et al., 2005) flights. After the lessons learned The University of Queensland and his partners are looking for the same goal as X-43 and X-51 aerospace vehicles, through the HIFiRE (Dolvin, 2008) and SCRAMSPACE (Tirtey et al., 2011) projects, means to flight a hypersonic Mach 8 scramjet-powered aircraft.

In 2007 research in hypersonic airbreathing vehicle with airframe-integrated scramjet engine began at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies (IEAv), Brazil (Ricco et al., 2011). Initially, Brazilian researchers proposed to design, to develop, to manufacture and to demonstrate, in free flight, a technology demonstrator using: i) waverider technology to provide lift to the aerospace vehicle, and ii) scramjet technology to provide hypersonic airbreathing propulsion system based on supersonic combustion.

1.1. THE BRAZILIAN 14-X B HYPERSONIC AEROSPACE VEHICLE

The Brazilian hypersonic aerospace vehicle 14-X B “Fig. 1” is being designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics since March 2012, as an option to demonstrate the hypersonic airbreathing propulsion system based on supersonic combustion at free flight at 30 km altitude at Mach number 7. Today, the 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 7 to 10, a technology demonstrator using scramjet as a hypersonic airbreathing propulsion system based on supersonic combustion.

In March 2012, the coordination of the 14-X proposed new versions based on the 14-X (Toro et al., 2012), where the 14-X B “Fig. 1” has been designed to demonstrate the scramjet technology at 30km altitude with Mach number 7, using the Brazilian solid rocket engines (S31 and S30). Analytical theoretical analysis (Galvão and Toro, 2013, Silva and Toro, 2013), computational fluid dynamics simulation (Carvalhal, 2015 e Teixeira and Toro, 2013) and experimental investigation, before flight throughout Earth’s atmosphere.

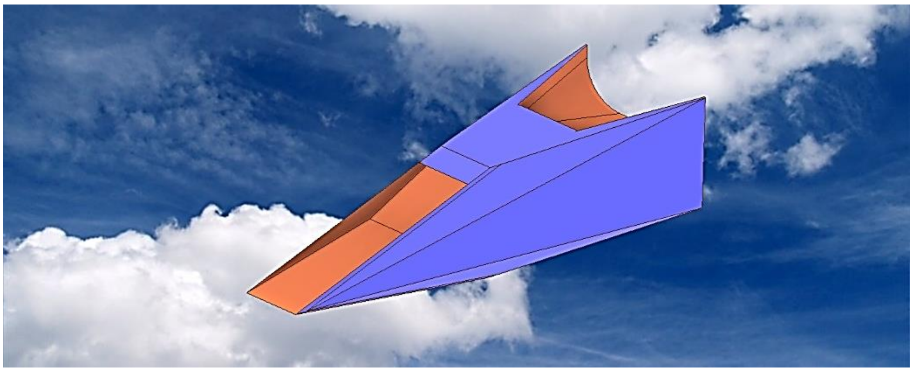

Figure 1. Conceptual design of the 14-X B Hypersonic Aerospace Vehicle.

Basically, the scramjet is a fully integrated airbreathing aeronautical engine 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. Therefore, the 14-X B is operational only on hypersonic speeds, and a hypersonic accelerator vehicle will be needed to reach the 14-X B at 30 km altitude at Mach number 7. As a low-cost solution to launch scramjet integrated vehicle to flight test conditions (30 km 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.

The Brazilian hypersonic accelerator vehicle which is composed by two-stage (S31 and S30 rocket engines), unguided, rail launched, solid rocket engines is able to accelerate the 14-X to the predetermined conditions of the scramjet operation, 30 km altitude at Mach number 7 from a Brazilian Launch Center.

1.2. HYPERSONIC EXPERIMENTAL INVESTIGATION RELATED TO SUPERSONIC COMBUSTION

The T3 0.60-m. nozzle exit diameter Reflected Hypersonic Shock Tunnel, is a new Hypersonic High Enthalpy Real Gas Pulsed Reflected Shock Tunnel (Fig. 2) funded by São Paulo Research Foundation (FAPESP, process nº 2004/00525-7), which was designed by Toro et al. (2005) 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.

The simplest Reflected Hypersonic Shock Tunnel “Fig. 2” 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 basic shock tunnel consists of a high-pressure (driver) section and a low-pressure (driven) section separated by a main diaphragm (DDS), a convergent-divergent nozzle and its diaphragm (attached at the end of the driven section), and a dump tank with the test section.

Figure 2. T3 0.61-m. nozzle exit diameter Hypersonic Shock Tunnel.

The T3 Hypersonic Shock Tunnel “Fig. 2” was designed (Toro et al, 2005) to be operated in the 6-25 flow Mach number range, generating reservoir enthalpies in excess of 10 MJ/Kg and reservoir pressures up to 25 MPa when operated in the equilibrium interface mode, with estimated useful test time of 2 ms to 10 ms. These conditions are estimated based on the driver-to-driven area ratio, $(\phi_{driver}/\phi_{driven})^2 = 2.25$, on the driven length equal 100 times the driven internal diameter, $\phi_{driven} = 127\ mm$, and on the operating driver pressure 5000 psi. The T3 Hypersonic Shock Tunnel “Fig. 2”, which has been used to conduct the Experimental Investigation of Hypersonic Flow Characterization, is capable of generating both high to low enthalpy hypersonic flow conditions. In the present investigation, of high enthalpy runs, helium is used as the driver gas and the tunnel operates in the equilibrium interface condition to produce a useful test time of roughly 2 ms. The test section airflow Mach number is 7 to 8 and pressure and temperature similar to those encountered in 28 km in the high enthalpy operation mode (Romanelli et al, 2011).

A high-speed camera Phanton V411, coupled with mirror-based schlieren ‘Z’ configuration with the schlieren light beam path and placement of the camera “Fig. 3” has been used for dynamic flow visualization. The schlieren system is composed of a LED as light source, an optical slit and focusing lens, two parabolic and three flat mirrors and the knife edge which provides the necessary light cut-off to the schlieren system. The Phanton camera was set to acquire 43,329 fps with a resolution of 368 x 200 pixels, which is enough to record the entire experiment.

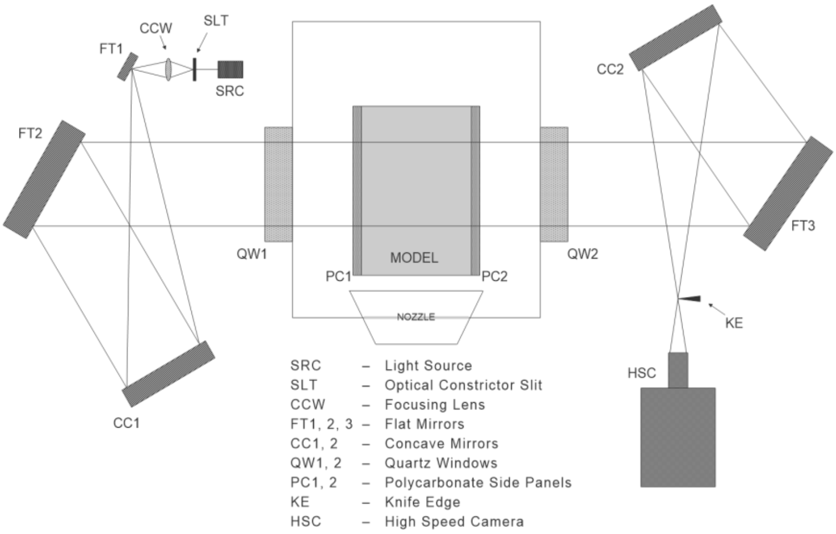

Figure 3. Schlieren visualization and high speed camera system setup.

A multichannel oscillography is used to synchronize all the equipment used to 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.

2. 14-X B MODEL DESIGN

For experimental investigation on the T3 Hypersonic Shock Tunnel, the 14-X B model, was scaled based on the 14-X B hypersonic scramjet aerospace vehicle design to demonstrate the scramjet engine at 30km altitude at Mach number 7. The 14-X B "Fig. 4" consist of a two-dimensional configuration, with a constant cross-section, where the upper flat surface, with zero angle of attack, is aligned with the freestream Mach number 7 hypersonic airflow. The lower surface consists of a frontal surface with a leading edge angle (5.5º) compression ramp angle of 14.5º (related to the angle of the leading edge), the expansion combustion chamber angle of (4.27º) and expansion angle of (10,73º) (related to the angle of expansion). The cross-section height is 165 mm a suitable size to accommodate the vehicle as a payload for the Brazilian rockets S30 and S31. The combustor chamber 258.63 mm long with constant area, following by 134 mm long with 4.27º (to accommodate the boundary layer and expansion due H_2 and O_2 combustion). The constant area combustion chamber is 15.2 mm high (to accommodate the airflow captured by the 14-X B frontal area).

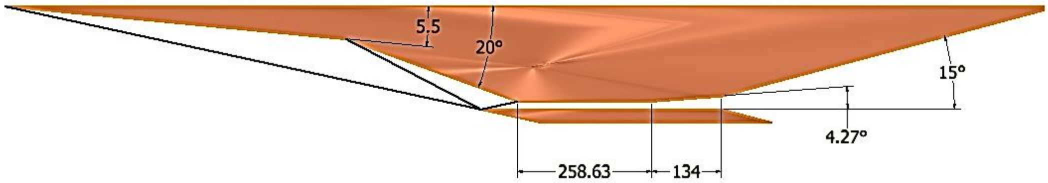

Figure 4. Cross-section of the 14-X B hypersonic scramjet aerospace vehicle.

The 14-X B model lower surface was designed based on the two-dimensional compressible flow (oblique shock wave relationships) and expansion wave (Prandtl-Meyer theory) considering the simplest case, i. e., no viscous flow, calorically perfect air ($\gamma = 1.4$) and scramjet engine with power off "Tab. 1". It was applied the following restriction: the incident shock waves generated at the 5.5° attached leading-edge deflection angle and at the 14.5° deflection hit the cowl leading-edge (shock-on-lip condition). The reflected shock wave generated at the cowl leading-edge hits the entrance of the combustor station (shock-on-corner condition) "Fig. 4".

Table 1. Thermodynamic properties at the 14-X B model lower surfaces, power off, inviscid, $\gamma = 1.4$.

		station 0	station 1 (deflection 5.5º)	station 2 (deflection 14.5º)	station 3 (deflection 20º)	station 4 power off (deflection 4.27º)	station 4 (deflection 10.73º)
M_{in}		7	7	6.0188	4.0645	2.6012	2.7981
θ_{in}	º		5.5	14.5	20	4.27	10.73
β_{out}	º		12.2428	22.1143	32.2381		
M_{out}			6.0188	4.0645	2.6012	2.793	3.3715
T_{out}	K	226.5	296.7470	568.4645	1039.720	953.4543	747.1747
p_{out}	Pa	1197	2877.565	16755.80	89105.97	65803.41	28052.13
ρ_{out}	kg/m^3	0.01841	0.033788	0.102703	0.298616	0.240476	0.13079
a_{out}	m/s	301.7	345.9846	478.8732	647.6307	620.1719	549.0535
u_{out}	m/s	2111.9	2082.412	1946.38	1684.617	1735.303	1851.134
μ_{head}	º					22.6107	20.9375
μ_{tail}	º					16.6775	6.52109

2.1. 14-X B MODEL HYPERSONIC EXPERIMENTAL INVESTIGATION

A 1-m. long stainless steel 14-X B model "Fig. 5" instrumented with twenty-nine piezoelectric pressure transducers on its lower surface was experimentally investigated on the equilibrium interface mode operation at the T3 Hypersonic Shock Tunnel at freestream Mach number from 7 to 8. The 14-X B model was installed on the heavy steel stands, specially designed to hold firmly the model, in the test section of the T3 Hypersonic Shock Tunnel "Fig. 5". Since the two symmetrical windows used in the schlieren technique has its limitations as non-variable position and useful area of visualization, the 14-X B model was positioned to optimize the visualization area for the leading edge (position 1) “Fig. 5 a)” and combustion chamber inlet (position 2) “Fig. 5 b)”.

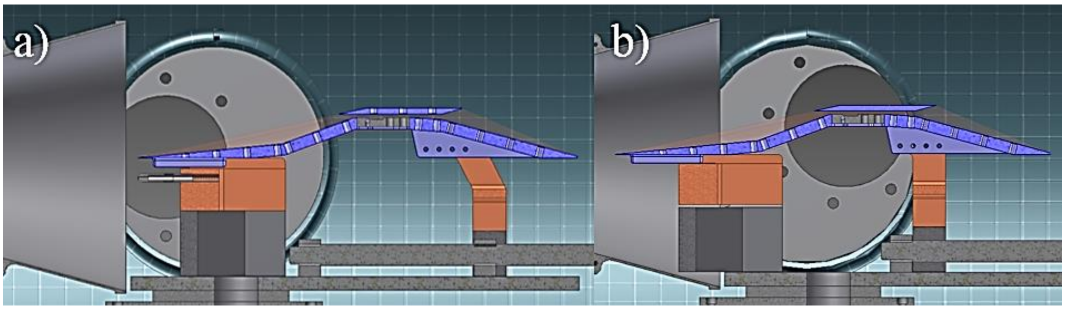

Figure 5. 14-X B model installed at T3 test section: a) leading edge, b) combustion chamber inlet visualizations.

For this paper thirty three runs were made some of these using air (perfect gas simulation) on the driver and some using helium (real gas simulation). The first 17 runs were made to correct some design errors and ensure that the acquisition system was fully operational. Some problems were founded as: a 0.5º angle of attack and did not have pitch control; blending at the leading edge due to its thickness; a chamfer at the Lexan side panels that blacked out the schlieren photographs; the height of combustion chamber was not enough to accommodate the viscous effects resulting in chocked flow “Fig. 6”.

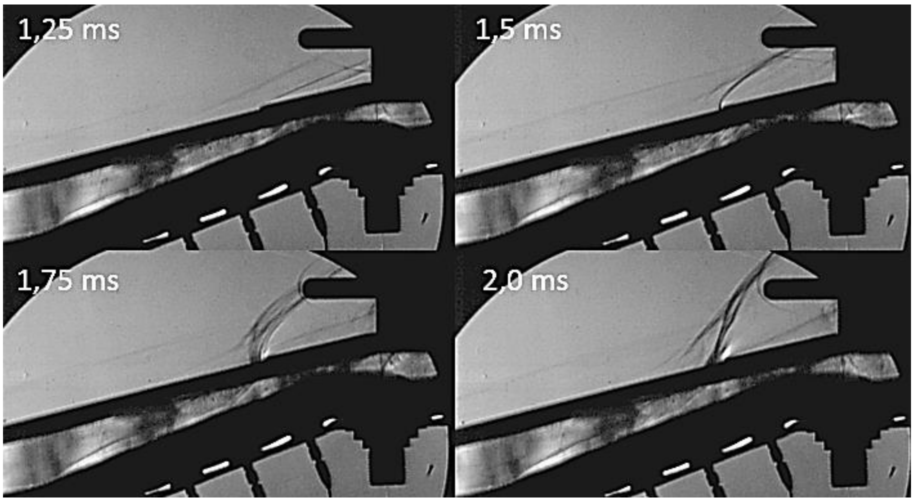

Figure 6. Temporal evolution of the chocked flow, run #17 Mach 7.63.

After run #17 the problems founded were solved, the biggest modification was change the cowl position and its height to prevent the chocked flow and ensure the shock-on-lip condition in instead of the shock-on-corner condition. “Figure 7” shows the pressure distribution for the experiments of the 14-X B model in the position 2 and its new configuration (combustion chamber height 14.5 mm) simulating perfect gas condition (air in the driver) with a Mach number $7.725 \pm 1\,\%$. The static pressure measurements “Fig. 7” at the lower surface of the 14-X B model are compared with the static pressure evaluated by no viscous flow, calorically perfect air ($\gamma = 1.4$) oblique shock wave relationships “Tab. 1” and computational fluid dynamics analysis made in the ANSYS FLUENT software (Carvalhal, 2015).

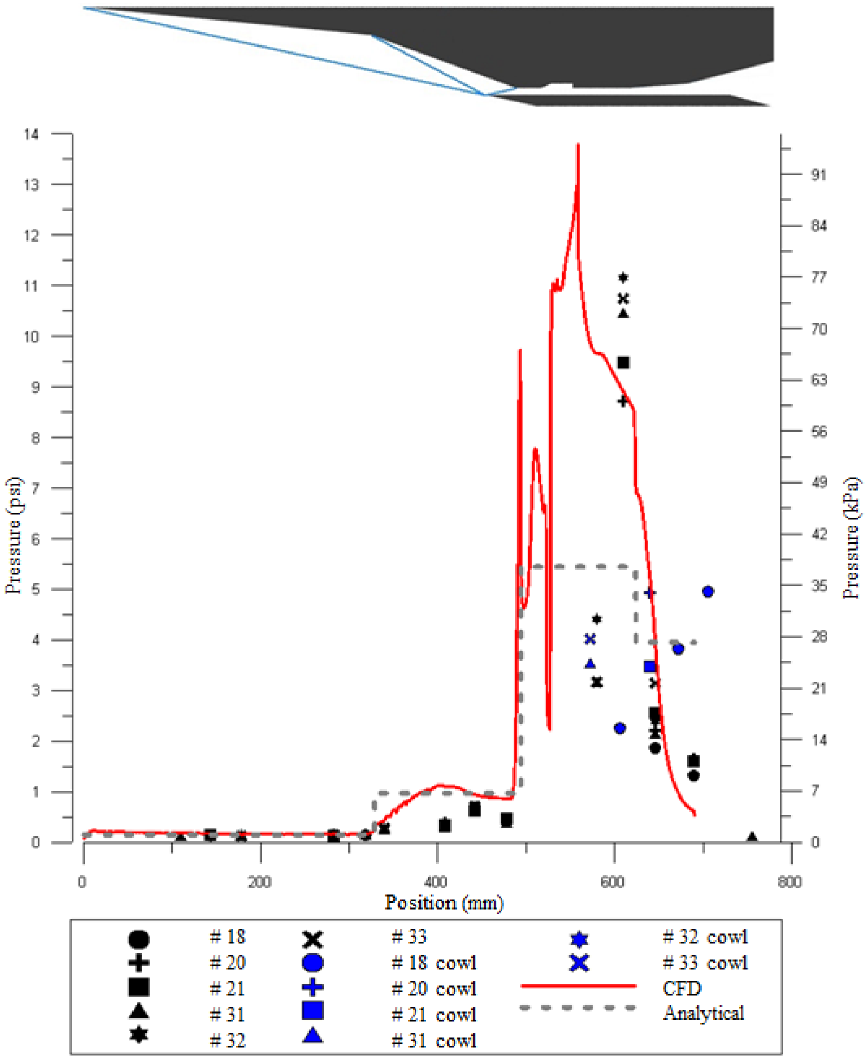

Figure 7. Static pressure measurements of the 14-X B model at Mach number 7.725 perfect gas.

Schlieren pictures of incident and reflected shock wave angles of the Mach number 7.725 perfect gas (air in the driver) “Fig. 8”, of the 14.5º deflection ramp and reflection at the cowl of 14-X B model in position 2 compared with the correspondents incident shock waves estimate using the oblique shock wave relationships. As expected the shock waves angles are similar with the theory.

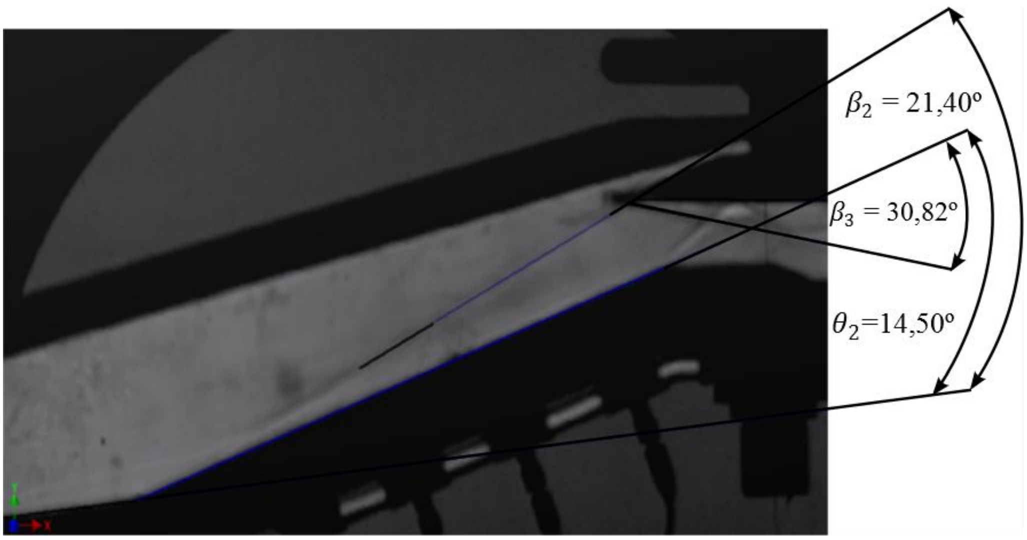

Figure 8. Schlieren picture of run # 31 Mach 7.725 perfect gas and expected shock wave angles.

"Figure 9" shows the pressure distribution for the experiments of the 14-X B model in the position 2 and its new configuration (combustion chamber height 14.5 mm) simulating real gas condition (helium in the driver) with a Mach number $7.09 \pm 1.5\ \%$. The static pressure measurements "Fig. 7" at the lower surface of the 14-X B model are compared with the static pressure evaluated by no viscous flow, calorically perfect air ($\gamma = 1.4$) oblique shock wave relationships "Tab. 1" and computational fluid dynamics analysis made in the ANSYS FLUENT software (Carvalhal, 2015).

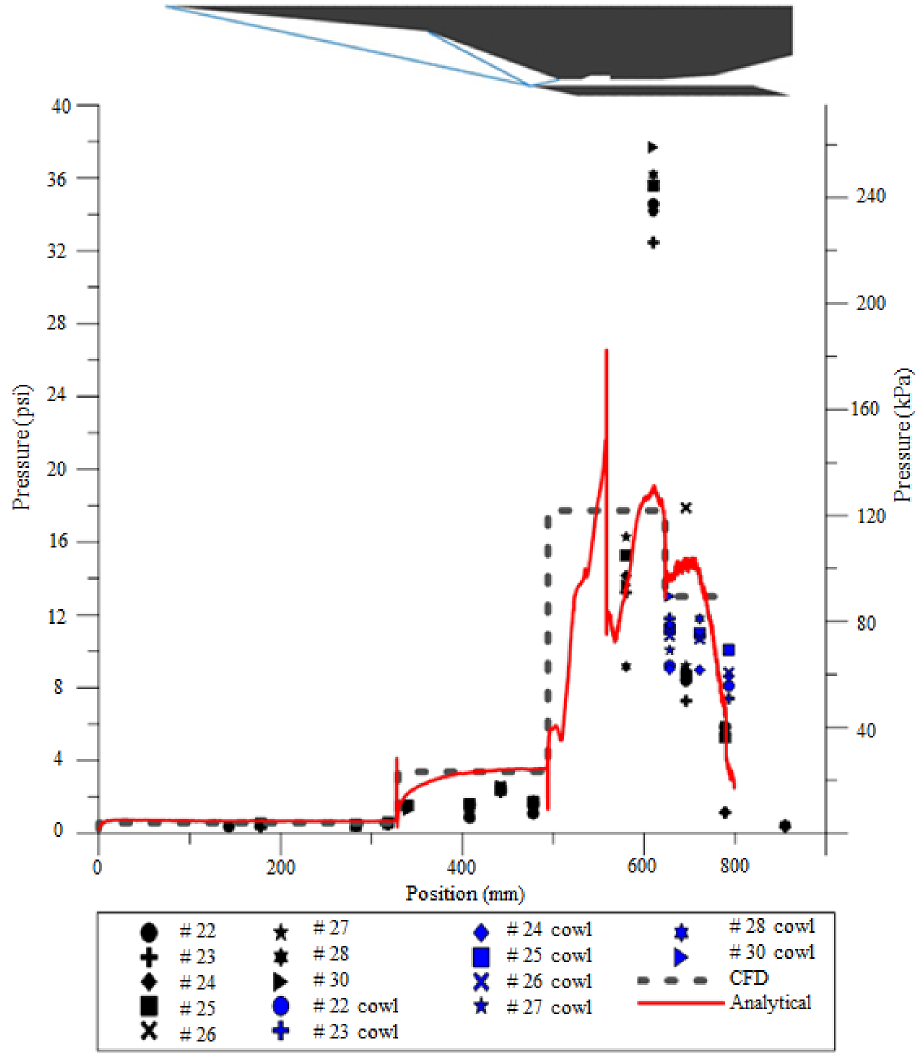

Figure 9. Static pressure measurement of the 14-X B model at Mach number 7.09 real gas.

Schlieren pictures of incident and reflected shock wave angles of the Mach number 7.09 real gas (air in the driver) "Fig. 10", of the 14.5° deflection ramp and reflection at the cowl of 14-X B model in position 2 compared with the correspondents incident shock waves estimate using the oblique shock wave relationships. As expected the shock waves angles are similar with obtained by the theory.

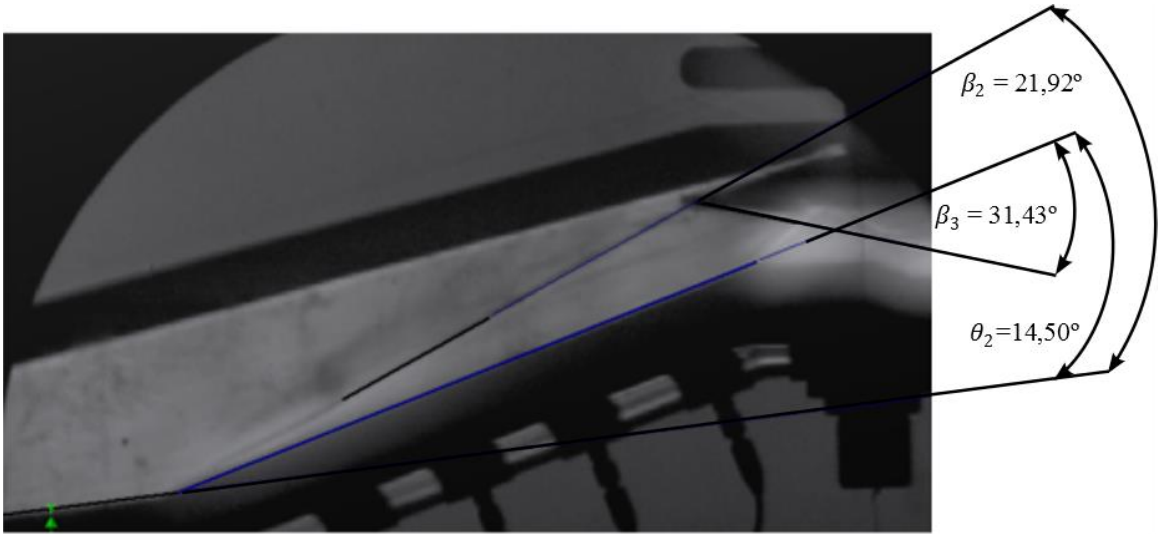

Figure 10. Schlieren picture of run # 25 Mach 7.09 real gas and expected shock wave angles.

The results obtained are qualitatively satisfactory despite there is some quantitatively difference between the experimental data and results obtained by CFD and theoretically. Improves in the data acquisition system and sensors are necessary to reduce errors and better understand of the phenomena involved.

3. CONCLUSION

The T3 0.61-m. nozzle exit diameter Reflected Hypersonic Shock Tunnel, is new Hypersonic High Enthalpy Real Gas Pulsed Reflected Shock Tunnel, funded by The State of São Paulo Research Foundation (FAPESP), and it was designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies (IEAv), primarily, as Research and Development facility for basic investigations in supersonic combustion applied to high-speed advanced airbreathing propulsion. The Brazilian 14-X Hypersonic Aerospace Vehicle, 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 technological demonstrator using: i) waverider technology to provide lift to the aerospace vehicle, and ii) scramjet technology to provide hypersonic airbreathing propulsion system based on supersonic combustion.

The experimental investigation of an integrated scramjet 14-X B was made in the wind tunnel hypersonic pulsed T3 IEAv. Static pressure measurements along with schlieren photographs of high speed were used to investigate the hypersonic flow along the scramjet integrated into the 14-X B model. Pressure measurements along the model were analyzed and compared with the values calculated analytically and by CFD simulations. Despite the quantitative differences in general the experimental and theoretical values are qualitatively exhibit the same behavior, but in a deep analysis the CFD simulations approximate better for the experimental values. Schlieren high speed photographs shows that the structure of hypersonic flow generated over the model is consistent with expected with shock on lip condition for M = 7 as expected in the project. Therefore, it demonstrates the importance of matching these methods in a project of a hypersonic vehicle.

4. RESPONSIBLE NOTICE

The authors are the only responsible for the content in this paper.

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