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BRAZILIAN 14-X S HYPERSONIC SCRAMJET AEROSPACE VEHICLE DIMENSIONAL DESIGN AT MACH NUMBER 7

Ronaldo de Lima Cardoso
Marcos da Silva e Souza
Faculdade de Tecnologia de São José dos Campos - FATEC Prof. Jessen Vidal - Rodovia Presidente Dutra km 138,7 Eugênio de Melo CEP. 12.247-004 São José dos Campos, SP - Brasil.
ronaldolcardoso@yahoo.com.br
marcos3d@fatec.sp.gov.br

Paulo Gilberto de Paula Toro
Instituto de Estudos Avançados/IEAv - Trevo Coronel Aviador José Alberto Albano do Amarante, nº1 Putim CEP. 12.228-001 São José dos Campos, SP - Brasil.
toro@ieav.cta.br

Abstract. *The Brazilian 14-X S Hypersonic Aerospace Vehicle, VHA 14-X S, is an integrated vehicle with the hypersonic airbreathing propulsion system based on supersonic combustion (scramjet), designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics. The Brazilian VHA 14-X S project goal is to conduct the 1st flight experiments to demonstrate scramjet operability under powered free-flight condition at 30km altitude at Mach number 7. The VHA 14-X S is operational only on hypersonic speeds, then a Brazilian hypersonic vehicle based on solid rocket motors will accelerate, in ballistic trajectory, to flight test at pre-established conditions to operate the scramjet engine, i.e., position (altitude, latitude and longitude), speed (Mach number), dynamic pressure and angle of attack. The Brazilian hypersonic accelerator vehicle which may be composed by two-stage solid rocket engines (S31 and S30), unguided, rail launched, is able to accelerate the VHA 14-X S to the predetermined conditions of the scramjet operation, 30km altitude at Mach number 7 from a Brazilian Launch Center. The external dimensional design of the upper and lower surfaces of the VHA 14-X S is based on the oblique shock wave and Prandtl-Meyer theories for the inlet region and the expansion regions, respectively. Internal configuration of the VHA 14-X S is being studied to determine the structural dimensions of the stringers and ribs considering the dynamic pressure during the free-flight at 30km altitude and Mach number 7. Also, coating materials have being specified considering the aerodynamic heating during the ballistic trajectory for the 1st flight atmospheric experiments.*

Keywords: *VHA 14-X S, waverider, scramjet*

1. THE BRAZILIAN 14-X HYPERSONIC AEROSPACE VEHICLE

The 14-X Hypersonic Aerospace Vehicle (Ricco et al., 2011; Toro et al., 2012), (Fig. 1) named after 14-Bis developed by aviation pioneer Alberto Santos Dumont, designed (Rolim, 2009; Rolim et al., 2009; 2011; Costa, 2011; Costa et al., 2012; 2013) at Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at Institute for Advanced Studies (IEAv), is part of the continuing effort of the Department of Aerospace Science and Technology (DCTA) 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.

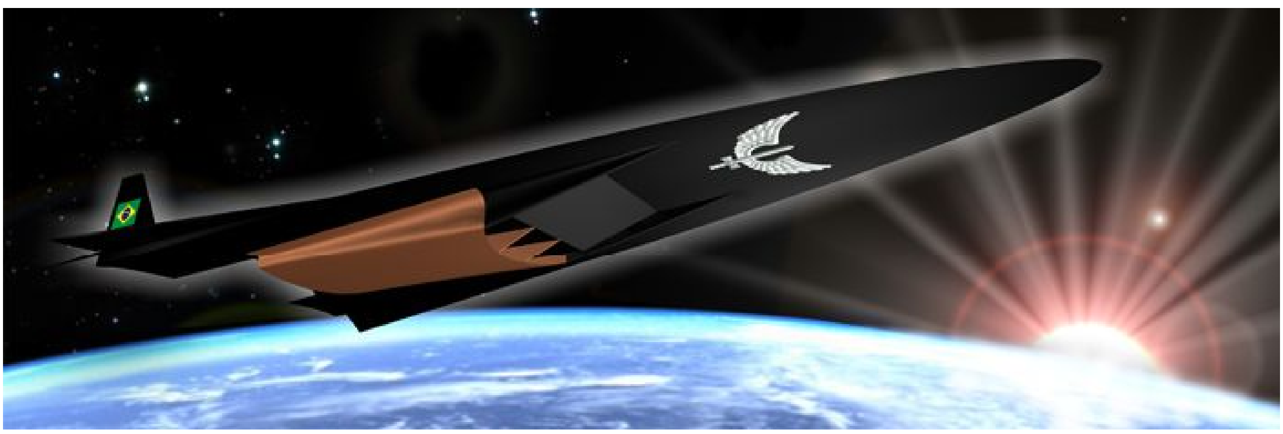

Figure 1: Brazilian 14-X Hypersonic Aerospace Vehicle.

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Analytical theoretical analysis and pressure measurements at pure waverider external upper and lower surfaces (Rolim, 2009; Rolim et al., 2009; 2011) and scramjet power off on internal surfaces (Romanelli Pinto et al., 2013) provide experimental data obtained from the experimental investigation at the T3 Hypersonic Shock Tunnel, Tunnel T3, funded by São Paulo Research Foundation (FAPESP) to design the full 2-m. long 14-X Hypersonic Mach number 10 waverider hydrogen-powered scramjet Aerospace Vehicle to atmospheric flight at 30km altitude.

The VHA 14-X pure waverider (Fig. 2) surface (Rolim, 2009; Rolim et al., 2009; 2011) was designed based on Rasmussen and He (1990) concept, which is derived from a supersonic flow past a cone (Fig. 3) with the volumetric efficiency and the viscous high lift-to-drag ratio as optimization parameters. Later, Rolim (2009) and Rolim et al. (2009; 2011) added a compression and expansion ramps to the pure waverider surface in order to simulate the flow on a scramjet engine. The 14.5° deflection compression ramp is designed to capture the entire air flow compressed by the 5.5° waverider leading edge and to provide the ideal conditions for the supersonic combustion of the hydrogen, while the expansion section is assumed a 15° ramp.

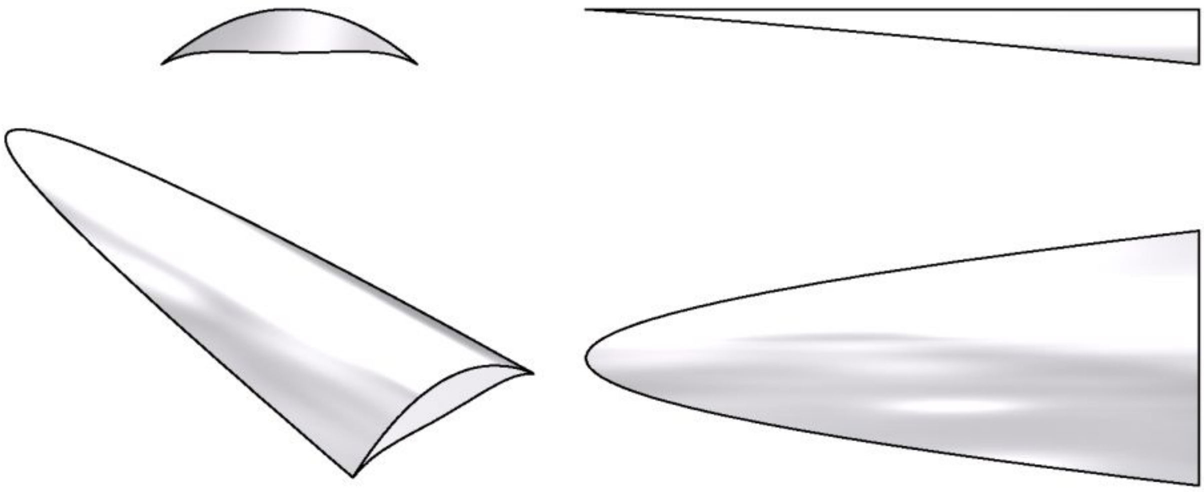

Figure 2: The 14-X pure waverider surface.

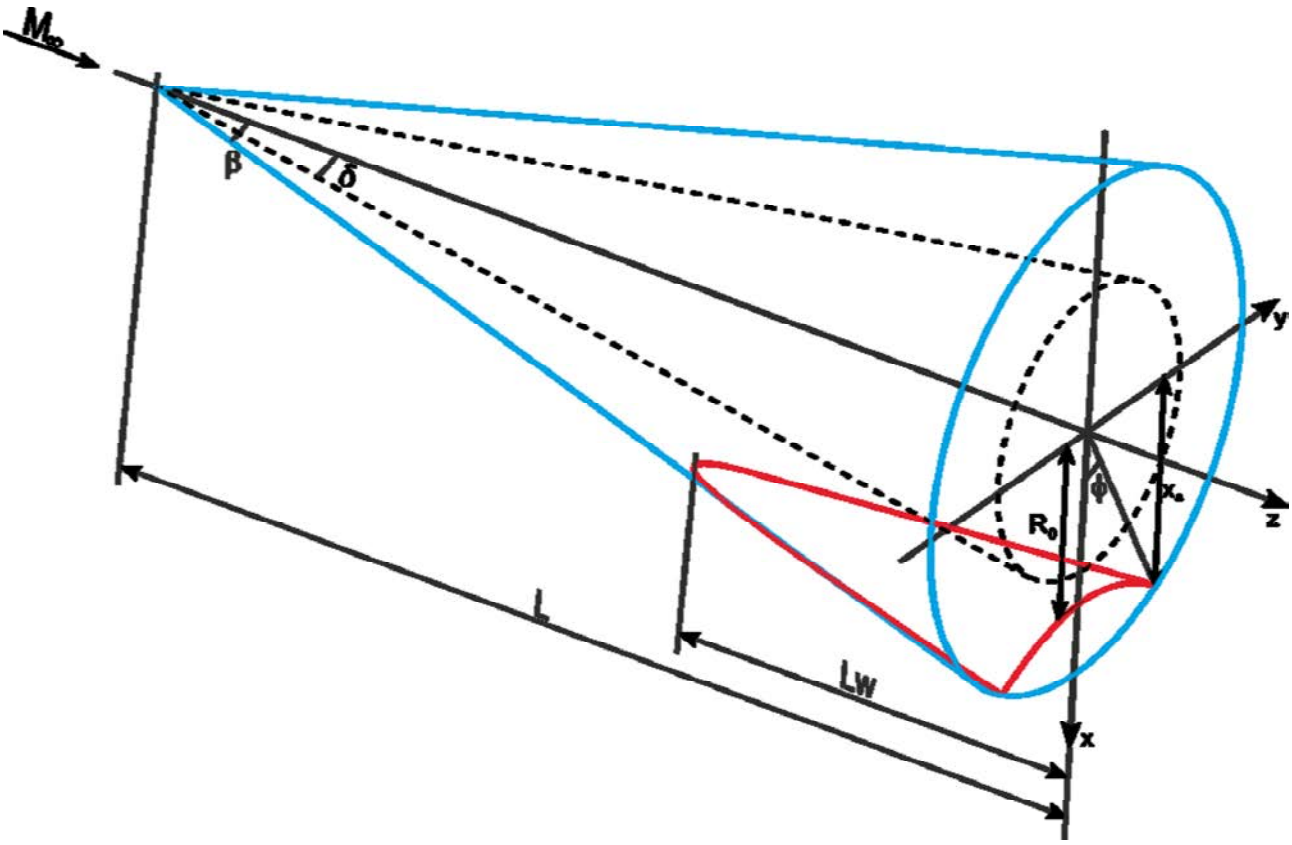

Figure 3: Schematic view of construction of the axisymmetric cone-derived waverider.

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2. THE BRAZILIAN 14-X S HYPERSONIC AEROSPACE VEHICLE

The 14-X S Hypersonic Aerospace Vehicle, VHA 14-X S, (Fig. 4) has been designed to flight at 30km altitude at Mach number 7 for the first experimental flight, in Brazil, based on 14-X Hypersonic waverider (Rolim, 2009; Rolim et al., 2009; 2011) and scramjet engine (Romanelli Pinto et al., 2013) experimental data as well as on the one-dimensional theoretical analysis, based on oblique shock wave flow and Prandtl-Meyer expansion wave flow theories (Anderson, 2003) applied to the external and internal compression surfaces and to the internal and external expansion surfaces, respectively. The cross-section of the VHA 14-X S (Fig. 4) consists of a double cross-section of the VHA 14-X B (Fig. 5), where in the upper and lower contours are identical (Fig. 6).

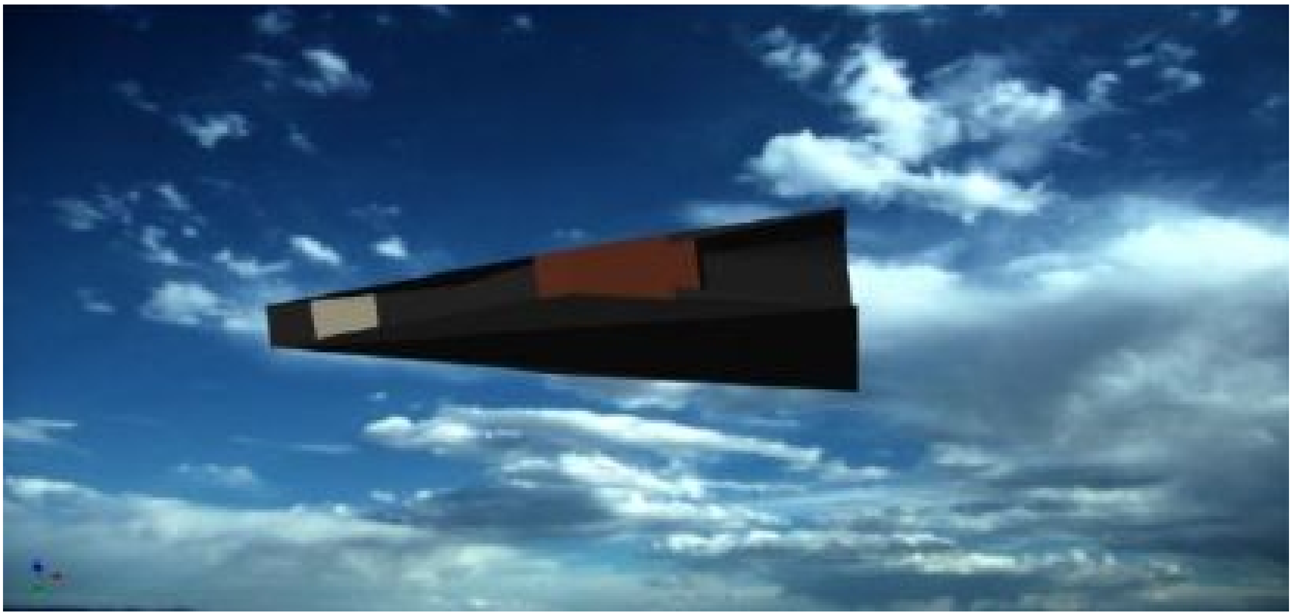

Figure 4: VHA 14-X S.

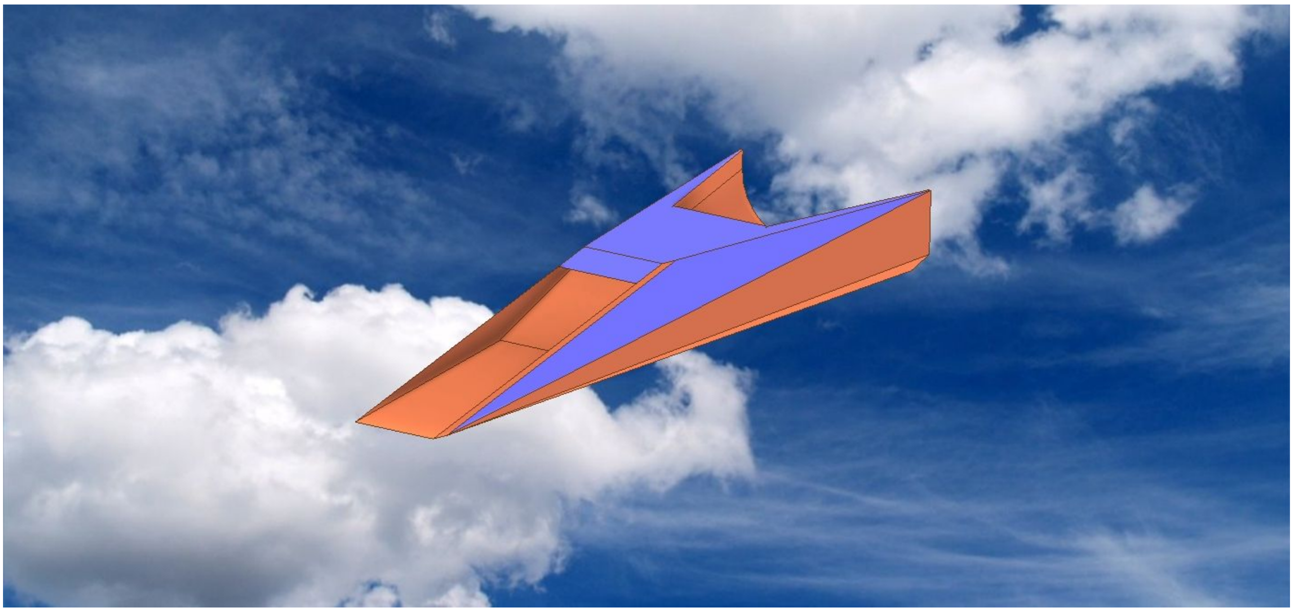

Figure 5: VHA 14-X B.

The lower surface of the 1-m. long VHA 14-X S (Fig. 6), taken from the VHA 14-X waverider external configuration (Rolim, 2009; Rolim et al., 2009; Rolim et al., 2011; Costa, 2011; Costa et al., 2012; Costa et al., 2013) consists of a frontal surface with a leading edge angle of 5.5^o, compression ramp angle of 14.5^o (related to the angle of the leading edge), the internal expansion chamber combustion angle of 4.27^o and external expansion angle of 10.73^o (related to the angle of internal expansion). The cross-section height is 224.35-mm.. The combustor chamber 129.32-mm. long with constant area, following by 67-mm. long with 4.27^o (to accommodate the boundary layer and expansion due H_2 and O_2 combustion) was defined by research of the Hyslop (1998) and Kasal et al. (2002), respectively. The constant area combustion chamber is 7.5-mm. high (to accommodate the airflow captured by the VHA 14-X B frontal area).

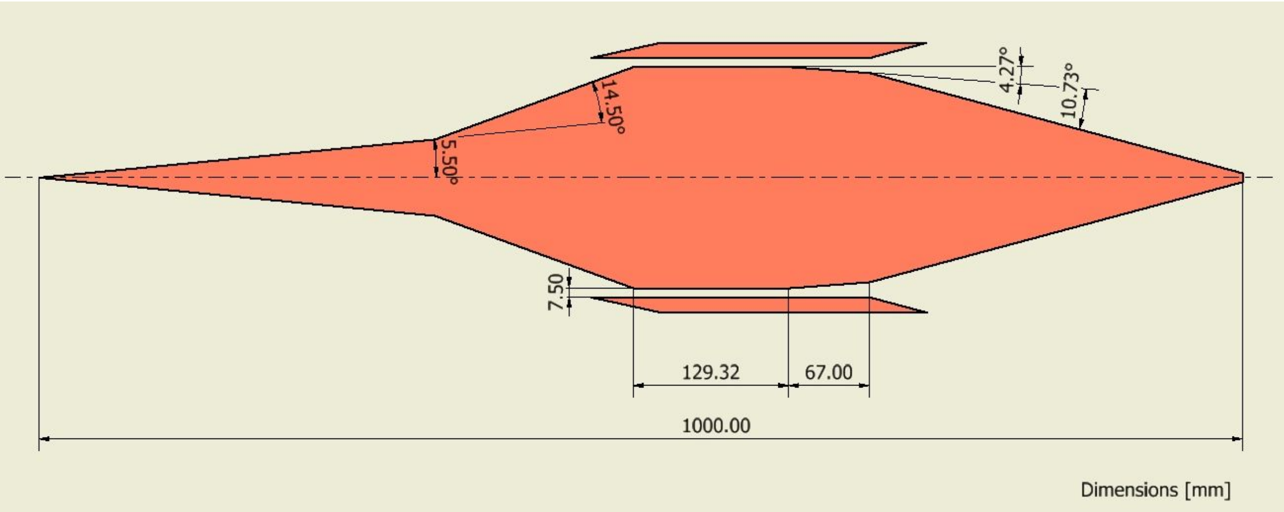

Figure 6: A side view of the plane VHA 14-X S.

Firstly, a nomenclature was defined to be used in the analytical theoretical analysis. Following Heiser and Pratt (1994) the VHA 14-X S may be divided in three (Fig. 7) main components: external and internal compression section (inlet), combustion chamber (combustor) and internal and external expansion section (outlet). Also, the hypersonic vehicle with airframe-integrated scramjet engine lower surface may be divided by several stations (Fig.7).

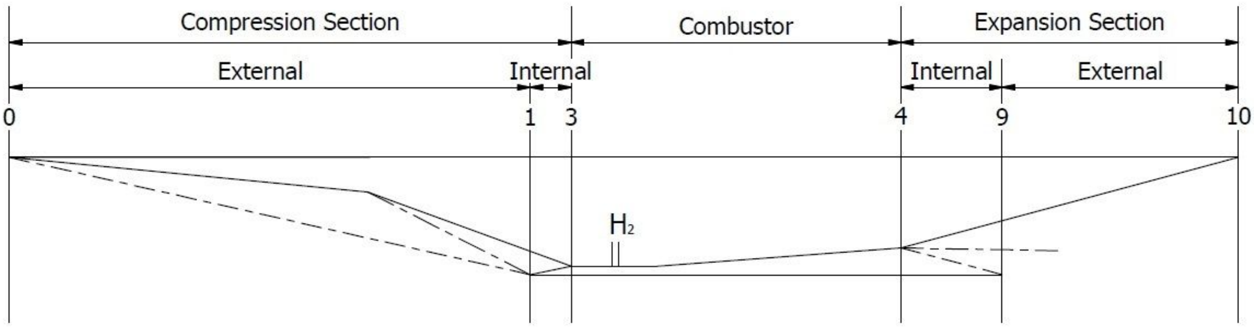

Figure 7: hypersonic vehicle with airframe-integrated scramjet engine stations and reference terminology.

Analytical theoretical analysis (Fig. 8), using the reference terminology (Fig. 7), applied to the nose-to-tail VHA 14-X S flying at 30km altitude at Mach number 7 (Cardoso, 2012), where at the lower surface was considering the simplest case, i. e., no viscous flow, calorically perfect air ($\gamma = 1.4$) and scramjet engine with power off (Table 1). The standard atmospheric properties at 30km geometric altitude (U.S. Standard Atmosphere, 1976) are given as $p = 1197(Pa)$, $T = 226.5(K)$, $\rho = 0.01841\left(kg/m^3\right)$, $a = 301{,}7\,(m/s)$, where a is sound velocity.

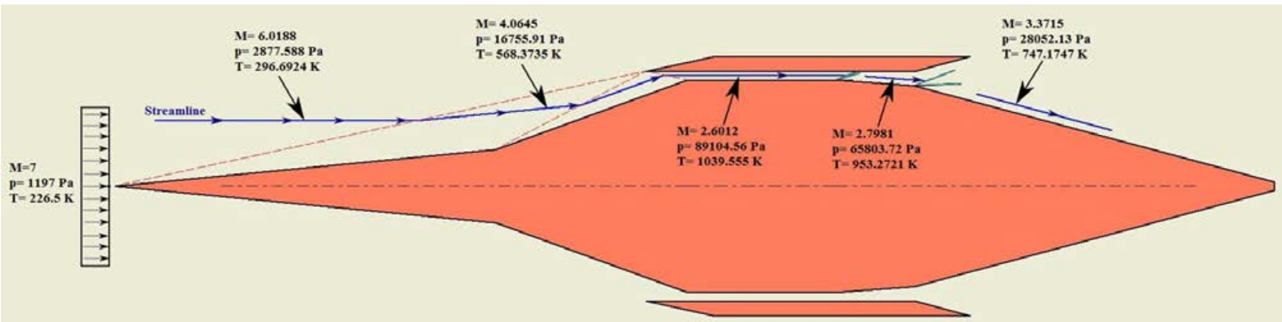

Figure 8: Analytical Theoretical Analysis applied to the VHA 14-X S at 30km altitude Mach number 7.

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Note that, the incident shock waves generated at the 5.5° attached leading-edge deflection angle and at the 14.5° deflection (following the leading-edge deflection) hit the cowl leading-edge. The reflected shock wave generated at the cowl leading-edge hits the entrance of the combustor station (Fig. 8).

Also, the flow from the external and internal compression section are deflected to the combustor entrance (Fig. 8) at supersonic speed (constant pressure, constant density, constant temperature and constant Mach number) and remains constant at the exit of the combustor.

Finally, the closed form of the thermodynamic property (pressure, density and temperature) ratios and Mach number across the oblique shock waves and expansion waves are applied to the external and internal compression section and the internal and external expansion section (Fig. 8), respectively.

Table 1: Thermodynamic properties at the VHA 14-X S, 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		12.2429	22.1143	32.2384		
M_{out}			6.0188	4.0645	2.6012	2.7981	3.3715
T_{out}	K	226.5	296.6924	568.3735	1039.555	953.2721	747.1747
p_{out}	Pa	1197	2877.588	16755.91	89104.56	65803.72	28052.13
ρ_{out}	kg/m^3	0.01841	0.033788	0.102702	0.298605	0.240467	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	20.9405
μ_{tail}	o					20.9394	17.2536

Also, numerical test case, with power-off scramjet engine of the VHA 14-X B at 30km altitude and at Mach number 7 (Carvalhal et al, 2013), the flow from the external and internal compression section are deflected to the combustor entrance (Fig. 9) at supersonic speed (at constant pressure, constant density, constant temperature and constant Mach number) and remains constant at the exit of the combustor.

Numerical simulation results (Fig. 9) (Carvalhal et al, 2013) obtained for VHA 14-X B (Fig. 5) are comparable with the analytical theoretical analysis applied to the VHA 14-X B (Galvão and Toro, 2013; Silva et al., 2013), respectively and VHA 14-X S (Fig. 8, Table 1).

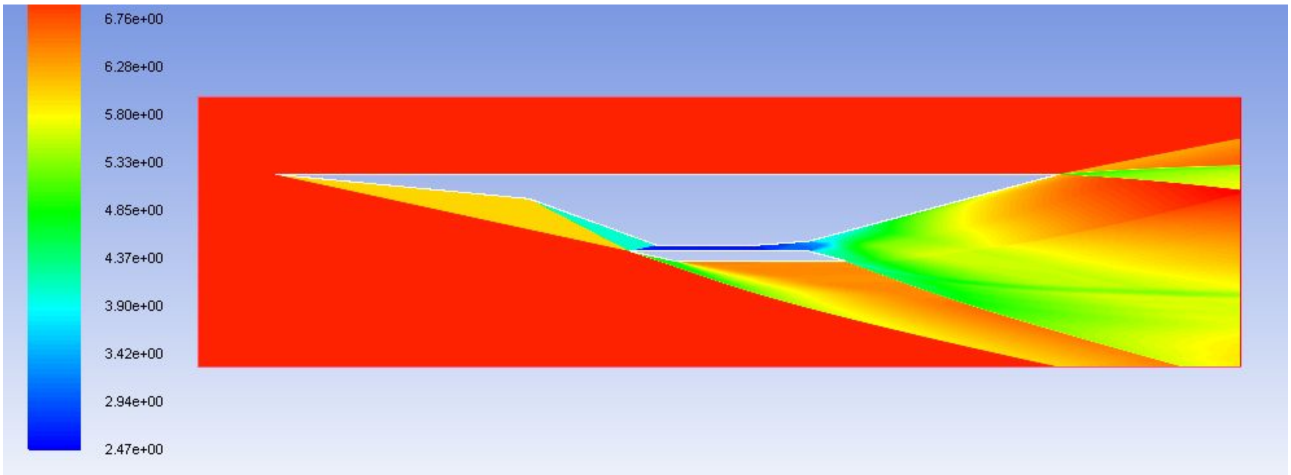

Figure 9: Computational Fluid Dynamics results for VHA 14-X B at 30km altitude Mach number 7.

Structural Analysis of the VHA 14-X S unpowered scramjet at Mach number 7 at 30km altitude (Pivetta et al., 2013) has been studied based on the external configuration (Fig. 6), pressure distribution (Fig. 8, Table 1) and dynamic pressure at Mach number 7 at 30km altitude, internal configuration and coating material dimensional specification (Fig. 10), structural dimensions (Fig. 11) and the material specification of the stringers and ribs (Fig. 12).

6-mm. thickness (Fig. 10) of coating materials (Fig. 12) used for the thermal protection systems (which define the internal volume) and structural materials (Fig. 12) for the stringers and ribs as well as structural materials for the scramjet engine (Fig. 12) were specified (Cardoso, 2012) based on preliminary studies of the VHA 14-X waverider scramjet Mach number 10 at 30km altitude (Costa, 2011; Costa et al., 2012; Costa et al., 2013) to support the aerodynamic loads during the atmospheric hypersonic flight.

77.44-mm. long of the 5.5^o leading edge will be made from Carbon-Carbon material following by 108.35-mm. long Tungsten SD 180. The rest of the 5.5^o ramp, the 14.5^o ramp and the external expansion section while the scramjet engine will be made using Carbon-Carbon and Inconel 718, respectively (Cardoso, 2012).

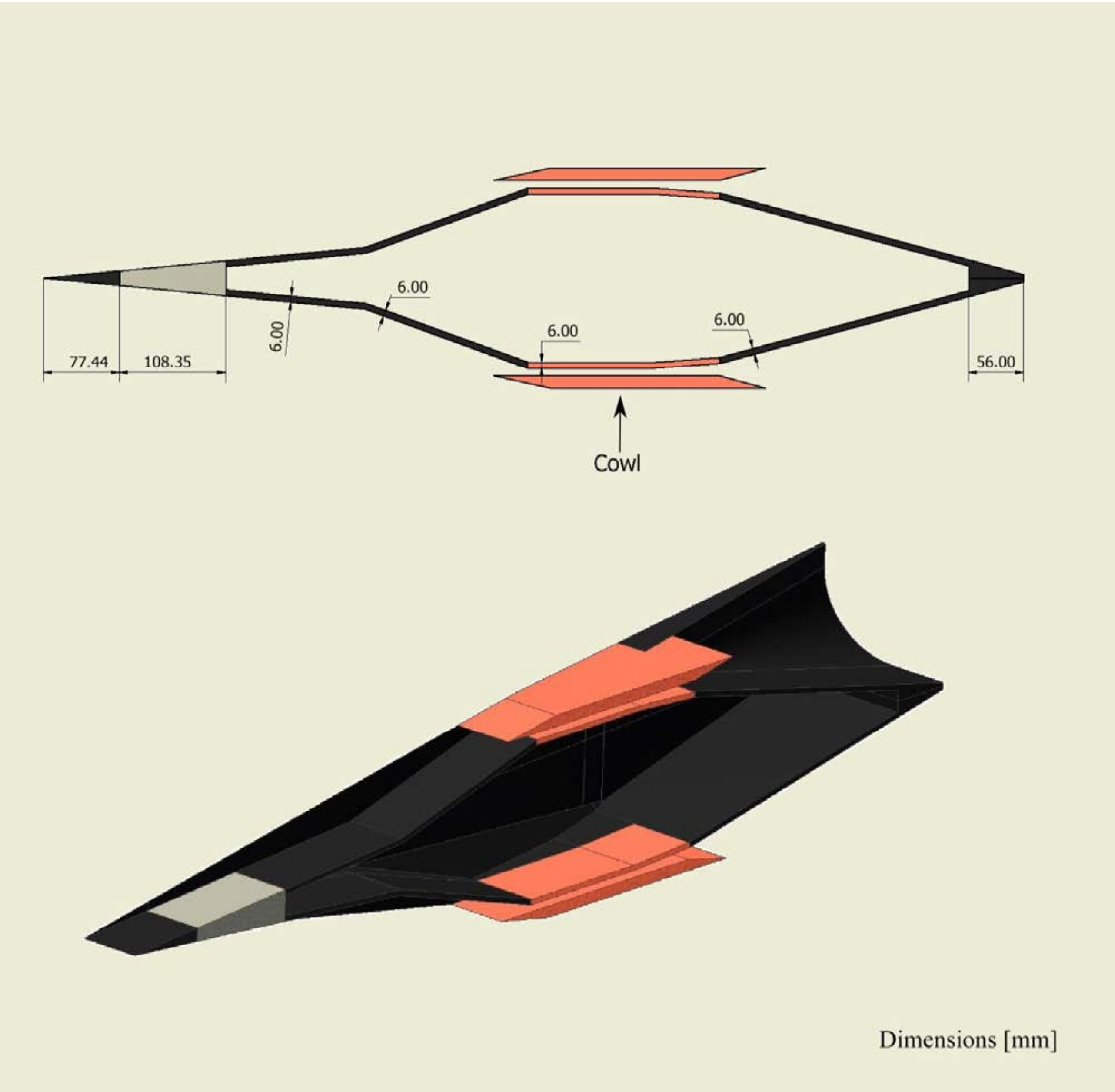

Figure 10: VHA 14-X S scramjet internal configuration.

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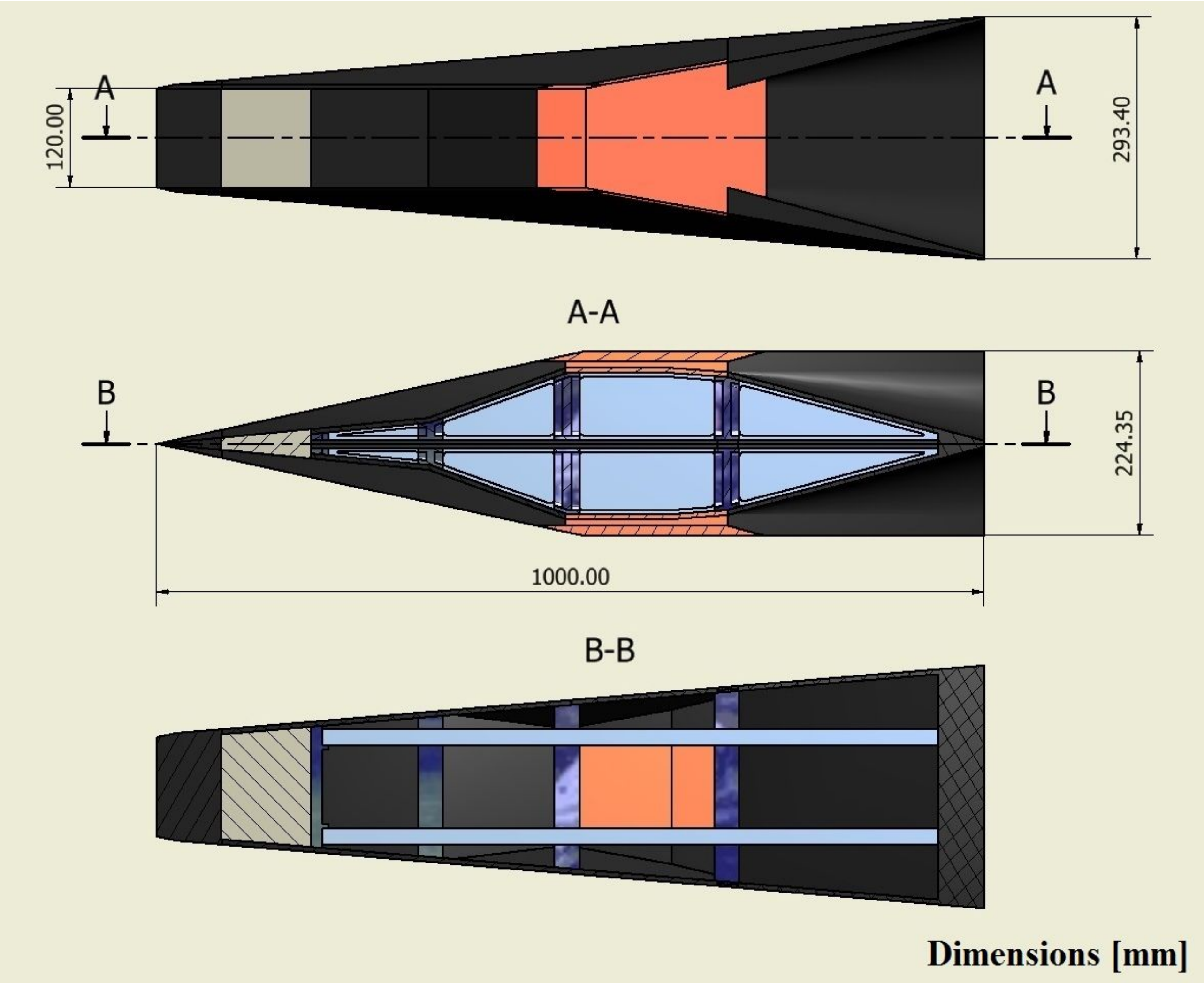

Figure 11: Internal View showing the stringers and ribs for the VHA 14-X S.

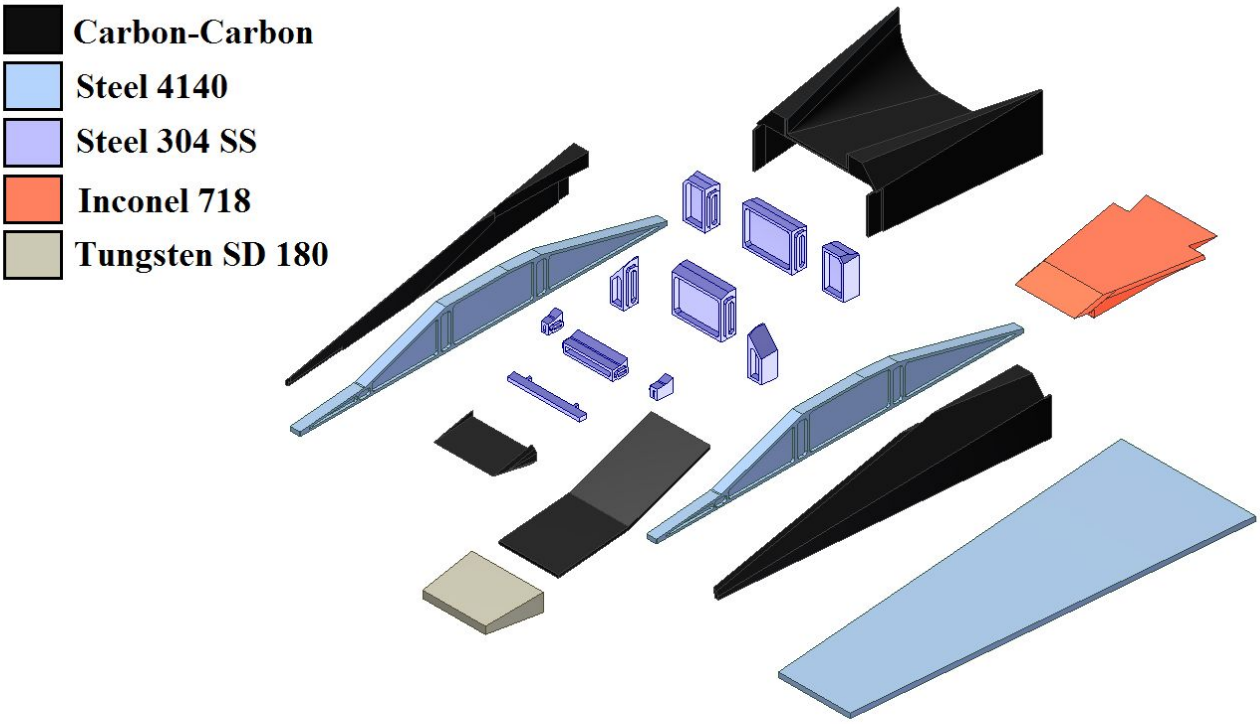

Figure 12: Material specification for the VHA 14-X S.

3. CONCLUSION

The primary objective of the present work is to present the dimensional design of the 14-X S Hypersonic Aerospace Vehicle, VHA 14-X S, designed as an option of a new generation of scientific aerospace vehicle to replace not in a too distant future the conventional 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.

The VHA 14-X S is an integrated vehicle with the hypersonic airbreathing propulsion system based on supersonic combustion (scramjet), designed to demonstrate scramjet operability under powered free-flight condition at 30km altitude at Mach number 7.

The external dimensional design of the upper and lower surfaces of the VHA 14-X S is based on the oblique shock wave and Prandtl-Meyer theories for the inlet region and the expansion regions, respectively.

Internal configuration of the VHA 14-X S is being studied to determine the structural dimensions of the stringers and ribs considering the dynamic pressure during the free-flight at 30km altitude and Mach number 7. Also, coating materials have being specified considering the aerodynamic heating during the ballistic trajectory for the 1st flight atmospheric experiments.

4. ACKNOWLEDGEMENTS

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