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DESIGN OF AN ACADEMIC UNPOWERED AXISYMMETRIC SCRAMJET FOR ATMOSPHERIC CAPTIVE FLIGHT AT MACH NUMBER 4.18 USING THE TRAINING ROCKET FTI

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Abstract: An academic unpowered axisymmetric scramjet engine is been developed at the Instituto de Estudos Avançados, to perform atmospheric captive flight at 6.2 km of altitude with speed corresponding to Mach number 4.18. The academic scramjet will be launched by the Foguete de Treinamento Intermediário/FTI released from the Brazilian Launch Centers of Barreira do Inferno (CLBI) or of Alcântara (CLA). The Brazilian Launch Centers CLBI and CLA are the only national institutions that have the proper infrastructure (control center, payload-rocket integration lab, launch platform and tracking radars) and expertise in performing the launch of scramjet demonstrators. The FTI is used by CLBI and CLA for training of local operational teams. The FTI reaches speed close to Mach number 4, just the operating speed of the scramjet, but, it is planned to have no combustion during the first atmospheric captive flight of the academic scramjet. In this present work will be used analytical and numerical methodologies to design the academic unpowered axisymmetric scramjet. Two-dimensional steady state, non-viscous, adiabatic compressible flow applied to the shock and expansion waves may be used as analytical theoretical analysis. The Fluent software may be applied for the numerical simulation considering non viscous calorically airflow for the academic unpowered axisymmetric scramjet. Implicit first order upwind spatial discretization is used to obtain the distributions of the thermodynamic properties and Mach number. Numerical simulation (static pressure, static temperature and static density) results at the inlet compression region are compared to the correspondent properties based on the analytical theoretical analysis.

Keywords: *scramjet, academic scramjet, training rocket, FTI*

1. INTRODUCTION

Several researchers from Instituto de Estudos Avançados/IEAv, Universidade Federal do Rio Grande do Norte/UFRN and Centro de Lançamento da Barreira do Inferno/CLBI have been joined, with the objective to conduct scientific research and technological development for the solution of problems related to the design of an aerospace vehicle using hypersonic airbreathing propulsion system based on supersonic combustion (scramjet).

The proposal involves research and development of a technological scramjet considering the following multi-disciplinary areas: (analytical, numerical and experimental) aerothermodynamics to solve the problems related to the aerodynamic; thermal and structural design of all phases of flight; integration with accelerator vehicle; material definitions; control studies related to the flight dynamics (stability and flight control) of scramjet; establish the study of the trajectory during the phases of flight of the technological scramjet from launch and separation of the hypersonic accelerator vehicle to the free flight of the scramjet engine burning fuel; develop capabilities for the specification and implementation of instrumentation for monitoring the aerothermodynamic phenomena during the flight; the definition and development of the embedded software; the definition and perform of ground testing of the scramjet and of the scramjet coupled to the accelerator vehicle; conducting implementation studies of the flight control, considering the navigation systems and telemetry, post-flight analysis of telemetry data, covering the complete envelope of atmospheric flight from the launch up to hypersonic speeds.

The technological scramjet aims to develop a flight demonstrator to perform atmospheric free flight at 30 km of altitude with speed corresponding to Mach number 7, including prediction of burning fuel in the combustion chamber.

It is important note, the Instituto de Estudos Avançados/IEAv has already designed the technological scramjets, named 14-X waverider "Fig. 1" and 14-X S "Fig. 2", for atmospheric free flight at the altitude of 30 km with speeds corresponding to Mach number 10 and 7, respectively. There is no available Brazilian accelerator vehicle to perform Mach number 10 at 30 km of altitude. The Brazilian two-stage solid rocket engines (S31 and S30), unguided, rail launched, are able to accelerate the 14-X S to the predetermined conditions of the scramjet operation, 30 km of altitude at Mach number 7 (approximately 2100 m/s) from a Brazilian Launch Center.

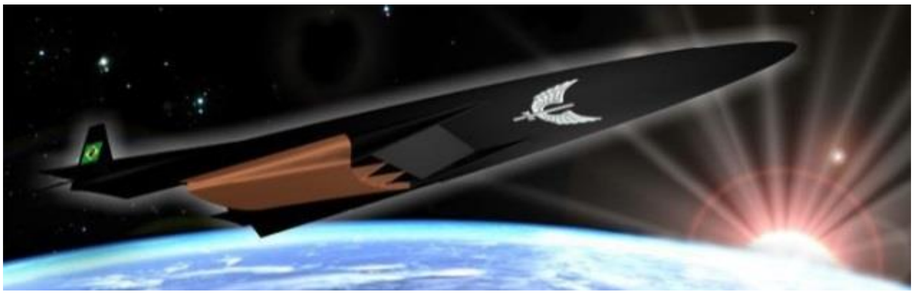

Figure 1: Brazilian technological scramjet 14-X waverider.

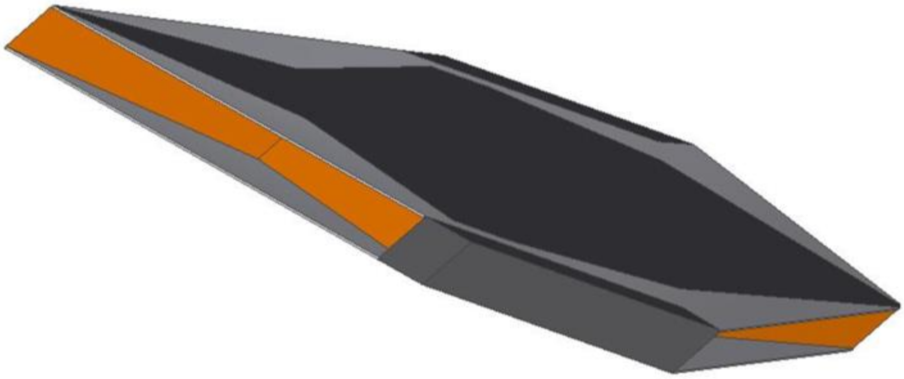

Figure 2: Brazilian technological scramjet 14-X S.

Therefore, in order to accelerate the human resource qualification in this strategic and emerging space area the IEAv proposes transfer the knowledge to the society (Brazilian Universities) and to Brazilian private industries through the design of a new technological scramjet, which involve the research, development and innovation (RD&I) focused on a technological scramjet, with the following tasks: studies of existing scramjet concepts, definition of the appropriate configuration, development and implementation of the necessary methodologies and design of a scramjet to achieve atmospheric flight at the operating conditions, i.e., at the speed corresponding to Mach number 7 in the altitude of 30 km. The proposal considers the use of a hypersonic accelerator vehicle to bring the scramjet from the rest condition, at the CLBI or CLA, up to reaches operating conditions of the scramjet engine, thereby covering the entire atmospheric flight envelope, from subsonic to hypersonic speeds, including burning hydrogen about 4-5 seconds in upward atmospheric ballistic free flight of the technological scramjet.

Finally, before launch the new technological scramjet or the IEAv's 14-X S scramjet and in order to prepare Brazil in this strategic and emerging area, RD&I in all phases, the IEAv proposes the design of an academic scramjet, considering from the configuration conception to the aerothermodynamics, aiming to atmospheric flight at altitude of about 6 km using the Training Intermediate Rocket (FTI). Several sets of academic scramjet would be launched from the CLBI or CLA Brazilian Launch Centers.

The design of the academic scramjet aims to design, using the same methodologies to be applied to the technological scramjet, to manufacture and to perform atmospheric flight, but using Training Intermediate Rocket (FTI) released from the Brazilian Launch Centers CLBI) and CLA.

The FTI is used by CLBI and CLA for training of local operational teams. The FTI reaches speed close to Mach number 4, just the operating speed of the supersonic combustion, but, it is planned to have no combustion during the flight. However, these launch tests will allow the training of undergraduate and graduate students, supervised by researchers or professors, in the following areas: scramjet design, scramjet integration as payload, flight control, telemetry, launch procedures and post-flight analysis of telemetry data.

The Brazilian Launch Centers CLBI and CLA are a satellite launching base of the Brazilian Space Agency (AEB), located on Brazil's northeast and north Atlantic coast, respectively, outside Natal and São Luis cities (capital of Rio Grande do Norte and Maranhão States). Both CLBI and CLA are operated by the Departamento de Ciência e Tecnologia Aeroespacial/DCTA (Department of Aerospace Science and Technology). CLBI and CLA are the world's closest launching base to the equator line, which gives the launch sites a significant advantage in launching geosynchronous satellites, an attribute shared only by the Guiana Space Center (utilized by France), and their position nearer the equator offer an advantage over Cape Canaveral (USA).

2. SCRAMJET FEATURES

The recent intensification of international efforts to develop hypersonic propulsion system based on supersonic combustion (scramjet) 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 scramjet 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, temperature 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 scramjet 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 (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.

First, it is necessary to establish a nomenclature to be used in the scramjet design. Following Heiser and Pratt (1994) the scramjet may be divided in three main components and by several stations "Fig. 3": external (stations 0 to 1, governing by incident shock wave) and internal (stations 1 to 3, governing by reflected shock wave) compression section (inlet), combustion chamber (combustor, stations 3 to 4, governing by one-dimensional flow with heat addition, Rayleigh flow) and internal (stations 4 to 9) and external (stations 4 to 9) expansion section (outlet, governing by expansion wave, Prandtl-Meyer Theory and area ratio).

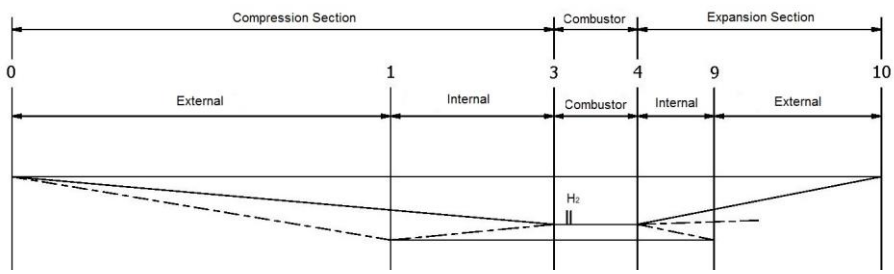

Figure 3: Hypersonic vehicle with airframe-integrated scramjet engine stations and reference terminology.

Analytical theoretical analysis, computational fluid dynamics simulation and experimental investigation are the methodologies used to design any technological demonstrator, before flight throughout Earth's atmosphere.

In general, two-dimensional steady state, non-viscous, adiabatic (no heat conduction) compressible flow is capable to quantify the thermodynamic properties across the incident conical/oblique and reflected shock wave (inlet) and the expansion wave (outlet). Also, the one-dimensional flow with heat addition (Rayleigh flow) is able to simulate the burning of the Hydrogen and Oxygen (existing at the atmospheric air). Available commercial CFD codes are able to investigate numerically the turbulent real gas hypersonic airflow under combustion process.

Reflected hypersonic shock tunnels are ground-based experimental facilities capable to duplicate the scramjet flight conditions close to the altitude of 30 km with speed corresponding to the Mach number 7. Therefore, they are one of the most important methodologies to provide experimental data to design hypersonic aerospace vehicles. The IEAv T3 0.60-m. nozzle exit diameter Reflected Hypersonic Shock Tunnel, funded by São Paulo Research Foundation (FAPESP), designed as Research & Development facility, may be used to simulate supersonic combustion investigation on the scramjet models. Unfortunately, the IEAv T3 Hypersonic Shock Tunnel is able to simulate hypersonic air coming flow from Mach numbers 7 to 25. Therefore, in the present project the experimental investigation will not be used to design the academic unpowered axisymmetric scramjet, that should be design for Mach number 4.18.

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.

Finally, 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.

3. THEORETICAL HYPERSONIC FLOW ANALYSIS APPLIED TO SCRAMJET

Analytical theoretical analysis may be used as first step to calculate the thermodynamic properties (pressure, temperature, density, sound velocities, among others) and Mach number at the flow path from the leading edge to the tail of the hypersonic vehicle with airframe-integrated scramjet engine.

In this analytical theoretical analysis, the subscripts ‘in’ and ‘out’ are used to identify the upstream (in) and the downstream (out) conditions, respectively, of the each station “Fig. 3” of the hypersonic vehicle with airframe-integrated scramjet engine.

It is important to note, there are no available closed form equations to determine the thermodynamic air property ratios and Mach number across an incident conical shock and expansion waves attached to the leading edge and established at the tail of the conical axisymmetric scramjet. Nevertheless, an in-house code was developed based on the conical supersonic/hypersonic steady, no viscous, adiabatic calorically perfect airflow for the incident conical shock wave attached to the leading edge of the conical axisymmetric scramjet, based on the incident oblique shock wave approach, to determine the thermodynamic air properties ratio, the Mach number behind the conical shock wave “Fig. 3, stations 0 to 1” and the shock wave angle (Anderson, 2003).

Also, there is no plan to burn Hydrogen during the captive flight test of the academic axisymmetric scramjet. Therefore, one may obtain the one-dimensional flow with heat addition (Rayleigh flow) in any gas dynamic textbook (Anderson, 2003).

Therefore, the analytical theoretical analysis will be applied only for the compression region “Fig. 3, stations 1 to 3” of the academic unpowered axisymmetric scramjet “Fig. 4”.

Note for the analytical analysis it was assumed the incident attached conical shock wave generated at the 28° leading-edge deflection angle hits “Fig. 3, station 1” the cylindrical cowl leading-edge (on lip condition) and the reflected shock wave generated at the cylindrical cowl leading-edge hits “Fig. 3, station 3” the entrance of the combustor station (on corner condition), resulting the geometry of the academic unpowered axisymmetric scramjet “Fig. 5”.

Figure 4: Geometry of the Brazilian academic unpowered axisymmetric scramjet.

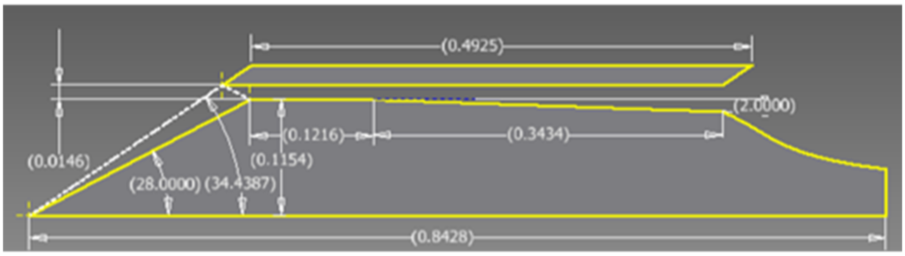

Figure 5: Dimensional of the Brazilian academic unpowered axisymmetric scramjet.

Important to note, the combustor length and the nozzle geometry of the academic scramjet were assumed as 465 mm and a parabolic curve “Fig. 5”.

4. Numerical hypersonic flow analysis applied to scramjet

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.

Axisymmetric, steady state, non-viscous, adiabatic compressible flow using implicit first order upwind spatial discretization are used to nose-to-tail numerical modeling of academic unpowered axisymmetric scramjet “Figs. 4 and 5” geometry.

5. Analytical and numerical hypersonic flow results of the academic scramjet

The analytical and numerical study cases are related to the two-dimensional no viscous flow, calorically perfect air ($\gamma = 1.4$) applied to the configuration of the academic scramjet “Figs. 4 and 5” using the reference terminology “Fig. 3”, flying at 6.2125 geometric km of altitude, where the standard atmospheric thermodynamic properties are given as p = 45,860 (Pa), T = 247.8 (K), $\rho = 0.6447$ (kg/m³), a = 315.6, where ‘a’ is sound velocity (U.S. standard Atmosphere, 1976).

5.1. Analytical results of the thermodynamic properties at the academic axisymmetric unpowered scramjet

Applying the analytical theoretical analysis based on mass, momentum and energy conservation laws, considering air as a calorically or thermally ($p = \rho RT$, γ = constant) perfect gas (Anderson, 2003) applied, as mentioned before, to the conical incident “Fig. 3, stations 0 to 1” and to the oblique reflected shock waves “Fig. 3, stations 1 to 3” one may obtain the thermodynamic airflow properties “Table 1, Fig. 6”.

Table 1: Thermodynamic properties at the inlet of the academic scramjet at 6.2125 km at Mach number 4.18, $\gamma = 1.4$.

		station 0	station 1 (cone deflection 28º)		station 1 (oblique deflection 28º)
M_{in}		4.18	4.18		2.4611
θ_{in}		º	28		28
β_{out}		º	34.4387		57.4317
M_{out}			2.4611		1.1503
T_{out}	K	247.8	average of the properties at the streamline at the conical surface and the properties at the streamline right after the conical incident shock wave	503.6783	880.7318
p_{out}	Pa	45860		305,207.472	1,480,927.696
ρ_{out}	kg/m3	0.6447		2.11	5.8548
a_{out}	m/s	315.6	449.9425		594.9798
u_{out}	m/s	1319.208	1,107.3534		684.4053

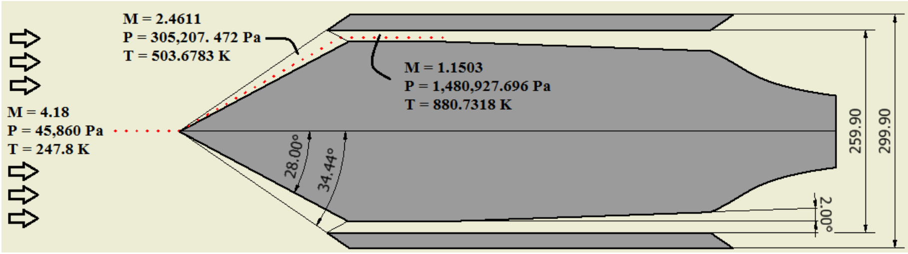

Figure 6: Analytical theoretical results for the academic unpowered axisymmetric scramjet.

The academic unpowered axisymmetric scramjet “Figs. 4 and 5” with 28o leading-edge flying at about 6.2 km of altitude with speed corresponding at Mach number 4.18 is capable to generate a static temperature “Table 1, Fig. 6” higher than 845K, ignition temperature of Hydrogen (Kuchta, 1985), at the combustor. Consequently, it is possible to burn Hydrogen during the atmospheric fhight of the academic axisymmetric scramjet. However, it is plan not to do so.

Note, the supersonic airflow across the conical attached shock wave promotes an increase of temperature, pressure, and density and a decrease of Mach number “Table 1, Fig. 6”. However, it is assumed the conical streamline of the airflow (close to the conical surface) remains supersonic and parallel to the conical surface of the academic scramjet starting at 28o leading-edge deflected angle. Also, the average of the thermodynamic properties at the streamline at the conical (body) surface and the thermodynamic properties at the streamline right after the conical incident 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 incident shock relationships.

Note, the supersonic airflow across the oblique shock wave promotes an increase of pressure, density, temperature, and a decrease of Mach number “Table 1, Fig. 6”. However the flow remains supersonic/hypersonic and parallel to the flat surface of the external and internal compression section “Fig. 4” of the hypersonic vehicle with airframe-integrated scramjet engine lower surface.

5.2. Numerical results of the thermodynamic properties at the academic axisymmetric unpowered scramjet

Axisymmetric, steady state, non-viscous, adiabatic (density-based) compressible flow using implicit first order upwind spatial discretization (with Roe-FDS flux type) are used to nose-to-tail numerical simulation performed considering the academic scramjet flying at Mach number 4.18 at 6.2125 km of altitude.

591,653 numerical cells with 906,693 faces (where 1 cell has 12 faces) and 315,040 nodes “Fig. 7” are used to the nose-to-tail numerical modeling of academic scramjet geometry “Fig. 5”. A high grid resolution was applied to at the region where the presence of the conical and oblique shock waves and expansion wave were expected according to the axisymmetric non viscous calorically perfect hypersonic airflow analytical theoretical analysis. Also, a better high grid resolution was applied to the combustor region than the shock wave and expansion regions.

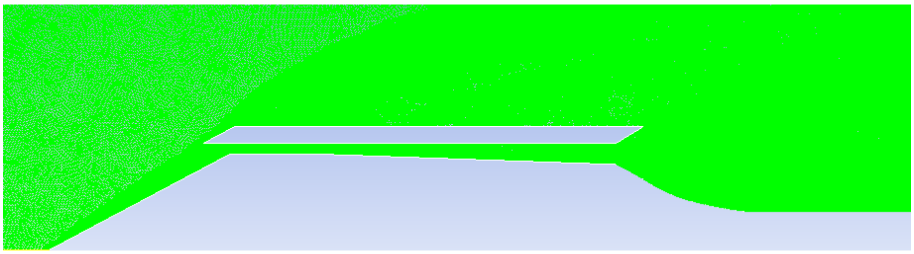

Figure 7: Academic scramjet computacional grid. Details of the high grid resolution at the inlet, combustor and oulet.

Note that the leading-edge attached incident conical shock wave (at the 28° deflection angle) hits closely the cowl leading-edge “Fig. 8”. Also, the reflected oblique shock wave due to the flow after the incident conical shock wave impinges (not too closely) the entrance of the combustor, generating a expansion wave at the corner of the combustor entrance, and establishing a subsonic speed flow (corresponding to Mach number lower than 0.6) next to internal combustor surface “Fig. 8, detail” only.

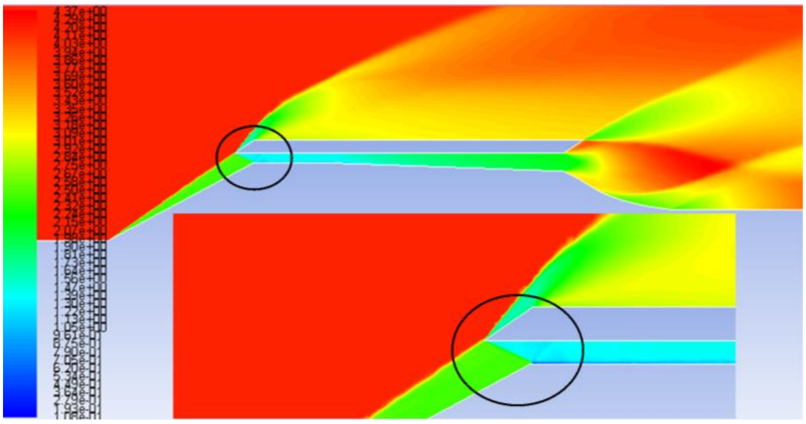

Figure 8: Mach number countor plot related to the academic scramjet based on analytical theoretical analysis "Figs. 4 and 5". Detail close to the cowl leading edge and entrance of the combustor.

In order to assure the on lip condition (the incident conical shock wave attached to the leading edge generated at the 28° deflection angle hits the cylindrical cowl leading-edge) and on corner condition (reflected oblique shock wave generated at the cylindrical cowl leading-edge hits the entrance of the combustor station) the cowl leading-edge was re-positioned "Fig. 9", decreasing the height of the combustor from the 0.0146 mm "Fig. 5" to 0.0134 mm "Fig. 9" and bring the cowl leading edge matches to the incident conical shock wave attached to the leading edge. Also, the deflection angle of the cowl leading edge was modified "Fig. 9" to be the same (28º) deflection angle of the academic scramjet conical leading edge.

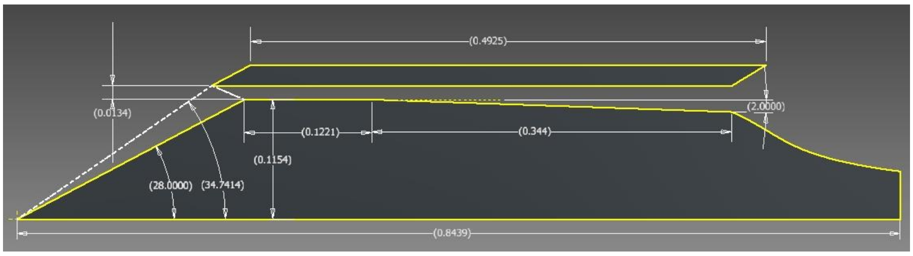

Figure 9: External configuration of the academic scramjet based on numerical simulation, considering on lip and on corner conditions.

For the academic scramjet on lip on corner numerical case, the flow from the external and internal compression section are deflected to the combustor entrance "Fig. 10" at supersonic speed (at constant temperature, at constant pressure, constant density, and constant Mach number) and remains constant up to the constant cross section (with the 0.1221 mm long) of the combustor.

Note that the incident attached conical shock waves (at the 28° leading-edge deflection angle) hits (very closely) the cowl leading-edge "Fig. 10" conforms the inlet design criteria (on lip) of the academic scramjet. Also, the reflected oblique shock wave due to (on corner criteria) the incident conical shock waves impinges (very closely) the entrance of the combustor "Fig. 10", showing a supersonic speed airflow in the entire combustor section.

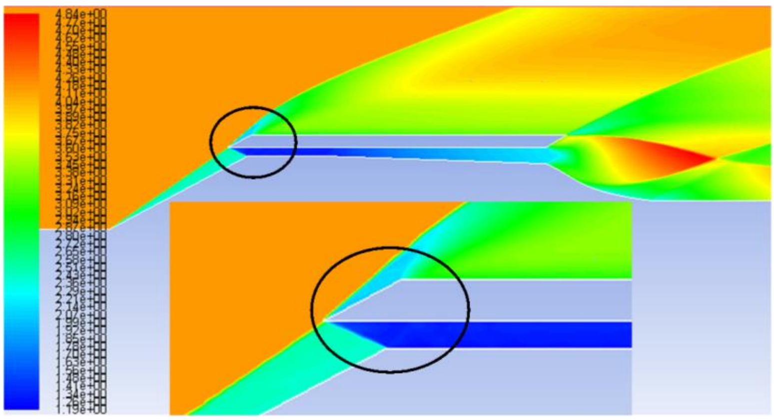

Figure 10: Mach number countor plot related to the academic scramjet based on numerical on lip on corner criteria "Fig. 9". Detail close to the cowl leading edge and entrance of the combustor.

The same behavior the incident attached conical shock waves hits the cowl leading-edge (on lip) and hits back to the entrance of the combustor entrance (on corner) are showing at the countor plots of the temperature “Fig. 11”, pressure “Fig. 12” and density “Fig. 13”.

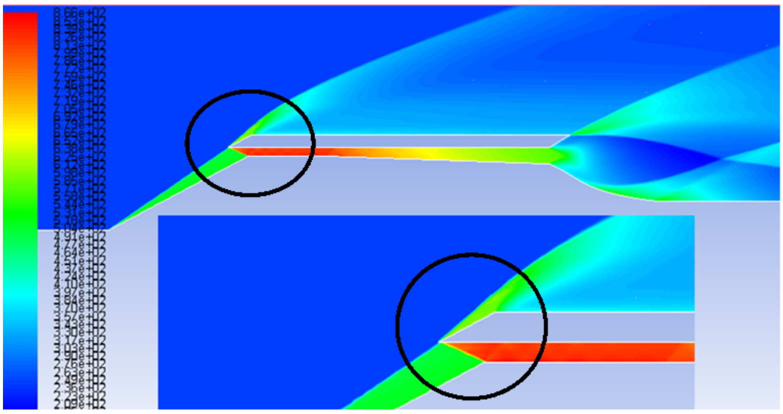

Figure 11: Temperature (top), pressure (left bottom) and density (right bottom) countor plots of the academic scramjet based on numerical on lip on corner criteria “Fig. 7”.

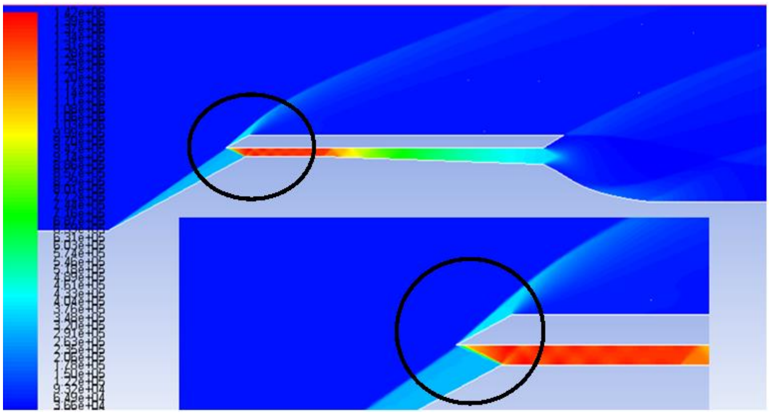

Figure 12: Temperature (top), pressure (left bottom) and density (right bottom) countor plots of the academic scramjet based on numerical on lip on corner criteria “Fig. 7”.

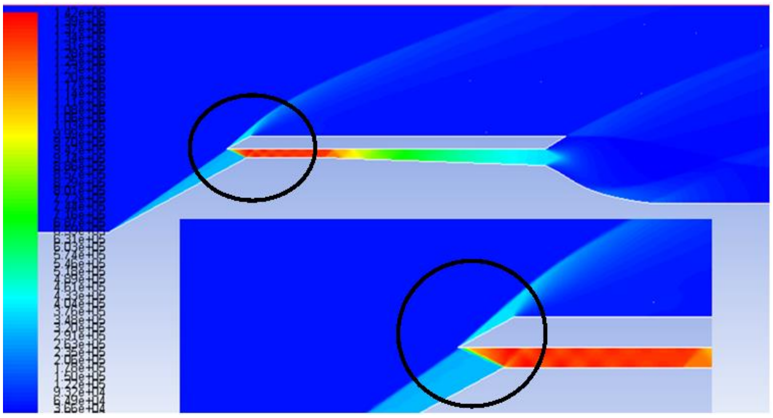

Figure 13: Temperature (top), pressure (left bottom) and density (right bottom) countor plots of the academic scramjet based on numerical on lip on corner criteria “Fig. 7”.

5.3. Analytical and numerical flow analysis applied to academic scramjet

The numerical static temperature “Fig. 14” and numerical static pressure “Fig. 15” at the conical section agree very closely with the correspondent analytical static temperature and numerical static pressure. However, at the scramjet’s interior, there is a significant difference between numerical and analytical, probably because in the analytical analysis it was considered the reflected oblique shock wave and in the numerical simulation it is assumed a combination between oblique and conical shock wave approach.

Also, the numerical simulation results show the expansion section must be re-design to obtain at least a (probably) constant thermodynamic properties (pressure, temperature) close to the thermodynamic properties at the freestream airflow, i.e. close to undisturbed Earth's atmosphere at desired (in this case) 6.2125 km of altitude.

The 28° leading-edge conical deflection angle "Fig. 7" provides a (numerical) combustor temperature of 830 K "Fig. 10", which is lower than the ignition temperature (Kuchta, 1985) of 845 K for Hydrogen. Therefore, in this numerical case the supersonic Mach number close to 1.4 "Fig. 8" at the combustor will no be able to burn the Hydrogen.

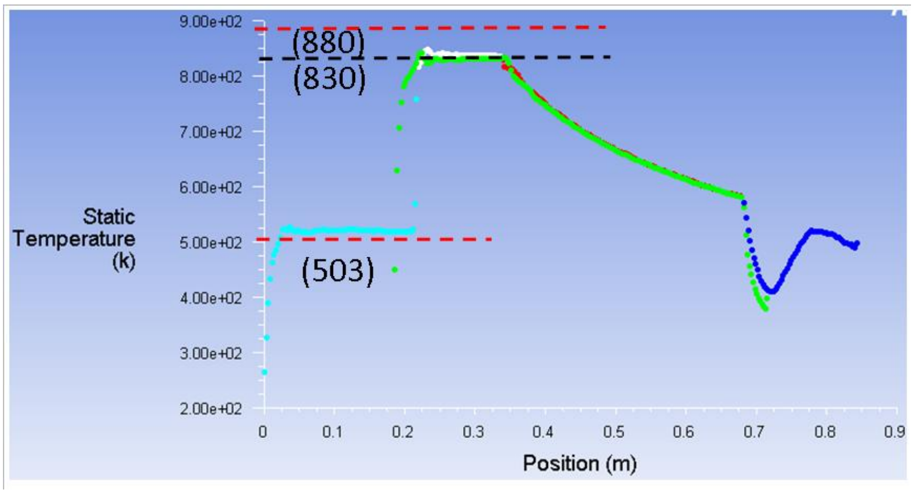

Figure 14: Numerical and analytical temperature distribution at the academic scramjet.

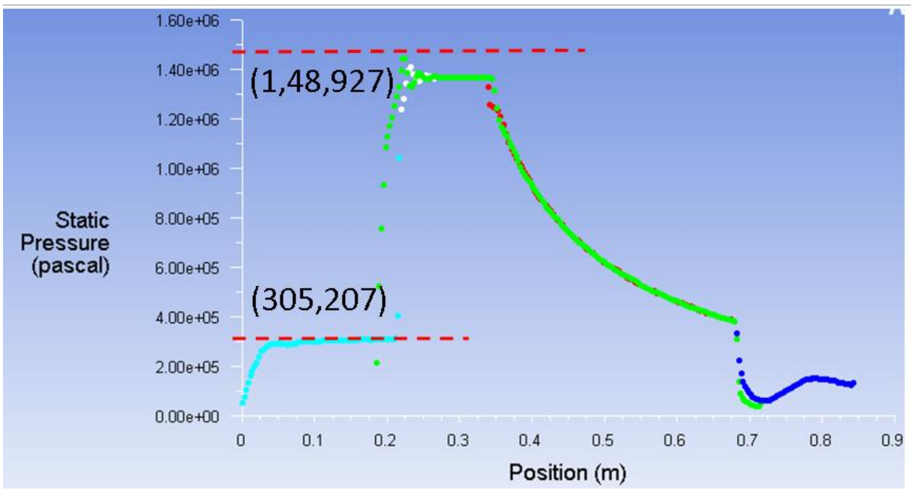

Figure 15: Numerical and analytical pressure distribution at the academic scramjet.

6. Acknowledgements

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