ENC-2020-0805
INFLUENCE OF THE BOUNDARY LAYER ON THE DESIGN OF THE COMPRESSION SECTION OF A GENERIC SCRAMJET

Ramon Carneiro[1]
[1] Instituto Tecnológico de Aeronáutica/ITA - Praça Marechal Eduardo Gomes, nº 50 Vila das Acácias CEP. 12.228-900 São José dos Campos, SP – Brasil
ramon_cgd@hotmail.com

Pedro Paulo Batista de Araújo[2]
Gilvan Luiz Borba[3]
George Santos Marinho[2]
Paulo Gilberto de Paula Toro[2]
[2,3] Universidade Federal do Rio Grande do Norte/UFRN – [2] Centro de Tecnologia. [3] Centro de Ciencias Exatas e da Terra. Av. Senador Salgado Filho, 3000 - Campus Universitário, Lagoa Nova CEP 59.078-970 – Natal/RN - Brasil
araujo.projects@gmail.com;gilvan@geofisica.ufrn.br; gmarinho@ct.ufrn.br; toro11pt@gmail.com

Abstract. The high potential of the scramjet technology to be used in aerospace vehicles has attracted worldwide attention for studies about hypersonic air-breathing propulsion based on supersonic combustion. A key parameter in projects with scramjets is the compression section design. The atmospheric air flow must be compressed to necessaries conditions for supersonic combustion and auto-ignition of the fuel in the combustion chamber. In this work, a theoretical analytical approach was applied to evaluate the thickness and the influence of the boundary layer on the surface of a scramjet projected to fly at an altitude of 30 km with a Mach number equal to 6.8. The geometry of the inlet is based on a compression system composed of three flat compression ramps with deflection angles respectively $\theta_1 = 5.5°$; $\theta_2 = 7.0°$; $\theta_3 = 8.5°$. Computational routines were developed to dimension the thickness of the boundary layer above the three compression ramps using a methodology based on Chapman-Rubesin theory. The results showed that the presence of the boundary layer changed the angles of the incident plane oblique shock waves and, consequently, affects the flow thermodynamic properties like temperature, pressure, density, velocity, and causing air leakage close to the leading edge of the cowl.

Keywords: *Scramjet, Hypersonic airbreathing propulsion, Supersonic combustion, Boundary layer.*

1. INTRODUCTION

The recent successes in proving the supersonic combustion (scramjet technology) to propel aerospace vehicles to hypersonic speeds greater than 5, indicates the scramjet technology is a promising and efficient way of accessing space in the not too distant future.

Despite research on supersonic combustion started in the late 1950's (Weber and Mackay, 1958), it was only in 2002 that Hyshot showed, for the first time, the supersonic combustion was viable as a propulsion system for aerospace vehicles to fly at hypersonic speeds into the Earth's dense atmosphere.

The two HyShot scramjet projects were developed by the Centre for Hypersonics, at The University of Queensland, Australia, to demonstrate the possibility to use the supersonic combustion as Hypersonic Airbreathing Propulsion. Despite the unsuccessful first flight, on 30 October 2001, of the HyShot scramjet, due to the rocket engines, responsible to accelerate the HyShot to the on-design conditions of supersonic combustion, have failed, the first HyShot flight provides a lot of information about the payload, the rocket engines, and the safety issues (Paull et al., 2006). On July 30, 2002, the 2nd flight experiment of the HyShot scramjet was successful. HyShot was flying back, at Mach number 7,8, to the Woomera Prohibited Area (WPA), in Australia, at altitudes ranging continuously from 36 km to 25 km, at the combustion chamber was burning hydrogen/air at supersonic speed, for about 5 seconds (Paull et al., 2006).

The three flights, two for Mach number 7 and one for Mach number 10 planned for the X-43 project is a NASA Hyper-X program, where the primary goals were the development and demonstration of technologies for air-breathing hypersonic flight for space access. On June 2 2001 the first X-43 flight Mach number 7 was unsuccessful. On March 27, 2004, the second flight of the X-43 at Mach number 6,83 and 28,7 km altitude was successfully completed, burning for about 10 seconds, hydrogen with air in supersonic speed at the combustion chamber (Marshall et al., 2005a). The third final X-43 scramjet flight was performed on 16 November 2004, at Mach number 9,68 flight (about 33 km)

demonstration of an airframe-integrated, scramjet-powered, hypersonic vehicle, burning hydrogen for about 10 seconds (Marshall et al., 2005b).

The X-51 scramjet engine demonstrator-waverider vehicle is the flight demonstration of AFRL's Hypersonic Technology (HyTech) program, which had several successful engine ground tests, but the flight demonstration of the X-51 scramjet viability beginning in August 2009, with a series of 4 flight tests. The X-51 was designed to reach between Mach 6 and 6,5, propelled by a JP-7 hydrocarbon fuel-cooled scramjet engine (Hank et al., 2008).

On 26 May 2010, the first flight, X-51 flew about 140 seconds, burning hydrocarbon JP-7 fuel, at Mach number 5, at an altitude of about 21 km, before a seal in the engine failed (Croft, 2010). On 13 June 2011, the second test flight took place, but the flight ended early due to an inlet unstart event after being boosted to Mach number 5 speed, but no hypersonic flight happed (Rosenberg, 2013). On 14 August 2012, the third test X-51 scramjet flight took place, but after X-51 separated from its rocket booster, the X-51 lost control, before the scramjet engine could ignite, and crashed into the Pacific (Weinberger, 2012). On 1 May 2013, the fourth and final flight of the X-51, waverider supersonic combustion ramjet (scramjet) engine demonstrator, was performed its first fully successful flight test. The X-51 ignited its engine and powered at Mach number 4,8, then X-51 accelerated to Mach number 5,1 and burning, hydrocarbon JP-7 fuel, for 210 seconds until running out of fuel. This test was the longest air-breathing hypersonic flight (Rondeau and Jorris, 2013).

On 7 September, 2020, the Defence Research and Development Organisation (DRDO), from India, claims they have joined the hypersonic club with a successfully tested a hypersonic scramjet powered vehicle at Mach number 6, named Hypersonic Technology Demonstrator Vehicle (HSTDV), burning kerosene fuel (Newdick, 2020).

A joint between the U.S. Air Force Research Laboratory (AFRL) and the Australian Defence Science and Technology Organisation (DSTO) has the objective to develop hypersonic research activities under the Flight Research and Experimentation (HIFiRE) program (Dolvin, 2008). The HIFiRE program is designed up to 10 flights, where each of the projects will culminate with a flight test at the Woomera Prohibited Area, in South Australia. The HIFiRE investigated the fundamental hypersonic technology and its potential for next generation of aerospace systems. Technology areas include, but are not limited to: aeropropulsion, aerodynamics, aerothermodynamics, high temperature materials and structures, thermal management strategies, guidance, navigation, and control, sensors, and weapon system components (Dolvin, 2008).

The High-Speed Experimental Fly Vehicles – International (Hexafly-Int) is the first project on the international level proposed, under the European Community (EC) with 11 partners from Europe, 4 from the Russian Federation and 3 from Australia. The overall aim is to design, manufacture and flight test a high-speed vehicle, based on the configuration developed in previous EC co-funded projects ATLLAS I & II, LAPCAT I & II, and HEXAFLY (Steelant et al., 2018).

The 14-X project is in developing at the Instituto de Estudos Avançados, in São José dos Campos (São Paulo State), Brazil, proposed to design, to develop, to manufacture and to demonstrate, in flight, supersonic combustion of hydrogen and air in supersonic speed, at the combustion chamber, when the 14-X S (Fig. 1) is flying at 30 km altitude with hypersonic speed, corresponding to Mach number 6,8 (Costa et al., 2016).

Figure 1. Technological Demonstrator 14-X S (Costa et al., 2016).

Although the hypersonic airbreathing propulsion, based on supersonic combustion (scramjet), started in the middle's 1950s, it has been researched intensively and internationally since the 1960s. Only U.S.A. (X-43 and X-51), Australia (HyShot) and India (HSTDV) are the leading countries in scramjet technology, and they have reached a Technology Readiness Levels (TRL) (Mankins, 2009) very close to the operational level TRL 7. The scramjet concept results from the observation that a good part of the flight path towards Earth's orbit occurs in the atmosphere rich in oxygen, which is an oxidizer by nature.

The domain of access to space technology is an objective that has been placed as a State policy of several developed and developing nations, including Brazil. It is an extremely strategic area that moves several segments of the economy,

making possible: the growth of a high-tech industry, the creation of excellence research centers, and the training of specialized professionals to meet the growing demands of the aerospace sector.

Since there is no aerospace vehicle to fly in hypersonic speed at Earth's dense atmosphere using supersonic combustion (scramjet technology), the hypersonic airbreathing propulsion based on supersonic combustion may be considered as a disruptive and strategic technology.

For the preliminary scramjet design, several Researchers from North-American, European, and Australian Universities involved, from the middle-1990's, in the research of the supersonic combustion (scramjet technology) applied many outdated methodologies to estimate not only the boundary layer thickness but also aerodynamic heating.

Most one-dimensional computational codes are called "jump code", where the details of the phenomena that occur and the thermodynamic properties from leading to trailing-edges of the vehicle are not defined.

Clark et al. (2006) present a (two-dimensional) project of a hypersonic vehicle integrated with scramjet (burning hydrogen), under development at the Multidisciplinary Flight Dynamics and Control Laboratory, of California State University, Los Angeles (USA), to carry out missions for both access space and military applications, for flight in the Earth's atmosphere at an altitude of 30 km altitude (geopotential) at hypersonic speed, corresponding to Mach number 10. Studies on aerodynamics (analytical methodology), aerodynamic parameters (numerical methodology) and the system propulsion systems are used to develop the control challenges associated with the scramjet. Theories of plane oblique shockwaves, one-dimensional flow with heat addition (Rayleigh flow) and the expansion (Prandtl-Meyer) waves are applied in the compression, combustion and expansion sections, respectively, considering air as a calorically perfect gas, aiming to estimate the thermodynamic properties (pressure, temperature, density) and velocity (Mach number) of the flow that experienced the establishment of plane oblique shockwaves, the addition of heat and the establishment of the expansion waves. Aerodynamic forces (lift, drag and thrust) are estimated based on the change in Momentum of the flow in the three sections (compression, combustion and expansion).

SPREAD (Scramjet PREliminary Aerothermodynamics Design Code) is a one-dimensional computational code (Bonifacio et al., 2006) applied from the leading edge to the trailing edge for preliminary design in a vehicle integrated with the scramjet. The inlet section uses plane oblique shockwaves considering air as a calorically perfect gas. The combustion and expansion process considers chemically one-dimensional reactive flow of ideal gas mixture.

Bonelli et al. (2011) estimate the influence of the viscous effects by predicting the displacement thickness, considering as a new slope of the wall ramp, as described in the Chapman et al. (1958), where the air is considering as a calorically perfect gas. SPREAD 2.0 is a real time solver that drastically reduces the time and costs associated with excessive use of Computational Fluid Dynamics (CFD) and/or experimental tests. Also, SPREAD 2.0 may be used to guide the selection of the optimal parameters for preliminary design of hypersonic aerospace vehicle, and it has been used to address the influence of air/fuel equivalence ratios and of scramjet angles of attack on the thermodynamic variables.

Piscitelli et al. (2017) use the SPREAD, which can provide a preliminary estimation of the performance of engine/aeroshape for airbreathing aerospace vehicle configurations. It is especially useful to design scramjet engines, for which the strong coupling, between the aerothermodynamics (external) and propulsive (internal) flowfields, requires real-time screening of several engine/aeroshape configurations and the identification of the most promising scramjet configurations with respect to user-defined constraints and requirements. The results demonstrate SPREAD capability to quickly predict reliable values of aero-propulsive balance (net-thrust) and aerodynamic efficiency in a preliminary design phase. Also, to determine the thermodynamic properties after the incident oblique shockwaves they consider air behaves as a calorically perfect gas.

Barth et al. (2013) chose Van Driest's (1951; 1956) compressible turbulent boundary layer models, which allow estimating the effect on skin friction caused by temperature-induced density changes in a turbulent boundary layer, and successfully predicted the friction of the skin on flat plates in hypersonic flows. In addition, they consider that hydrogen and air have specific heat at constant pressure and constant volume of ($\gamma \approx$) 7⁄5 (1.4) and, therefore, significant variations in γ occur only in the vicinity of the front of the flame, where the concentrations of the product species are high.

A 2-D generic scramjet design, to fly at approximately 2050 m/s (corresponding to Mach number 6.8) at 30 km geometric altitude (Fig. 2), is being developed at the Universidade Federal do Rio Grande do Norte (UFRN), to demonstrate in atmospheric flight the supersonic combustion, of atmospheric air with hydrogen in supersonic speed, at the combustion chamber. Plane oblique shockwave theory, one-dimensional flow with heat addition (Rayleigh) theory, plane expansion wave (Prandtl-Meyer) theory coupled to the ratio area theory, are applying to the compression, combustion chamber and expansion sections, respectively.
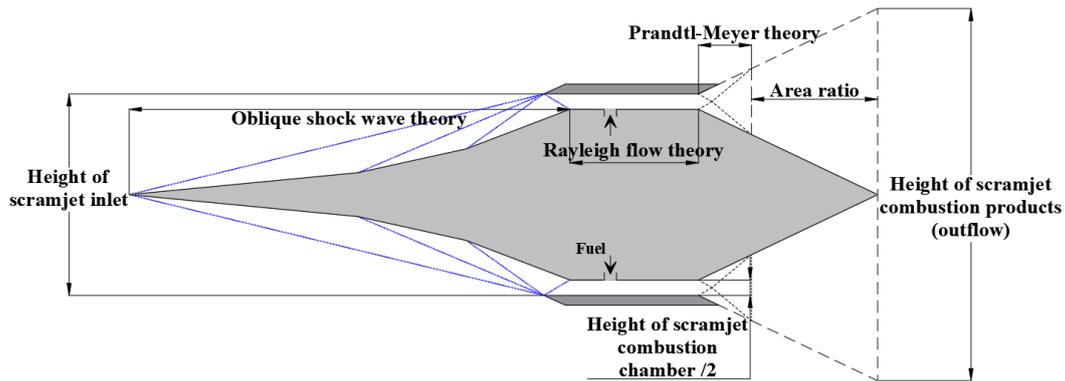
Figure 2. Two-Dimensional generic scramjet and analytical theories used (Carneiro, 2020).

Analytical studies, using engineering approach (Toro et al., 2018a) and numerical, using fluent commercial code (Toro et al., 2018b), applied to the inlet of the generic symmetric planar scramjet (Fig. 3), with three compression ramps (with deflection angles of, respectively, $\theta_1 = 5,5°$; $\theta_2 = 7,0°$; $\theta_3 = 8,5°$), to demonstrate supersonic combustion (scramjet technology), in Earth's atmospheric flight at 30 km altitude at hypersonic speed, corresponding at Mach number 6.8. Two-dimensional steady-state, non-viscous, adiabatic calorically perfect airflow are the hypothesis used to the preliminary design of the scramjet inlet. Numerical simulation the analytical analysis results are comparable and the airflow entering the combustion chamber provides temperature about 1000 K, higher than the spontaneous ignition temperature of hydrogen (845,45 K) and Mach number about 2,55, to promote supersonic combustion, at the combustion chamber.
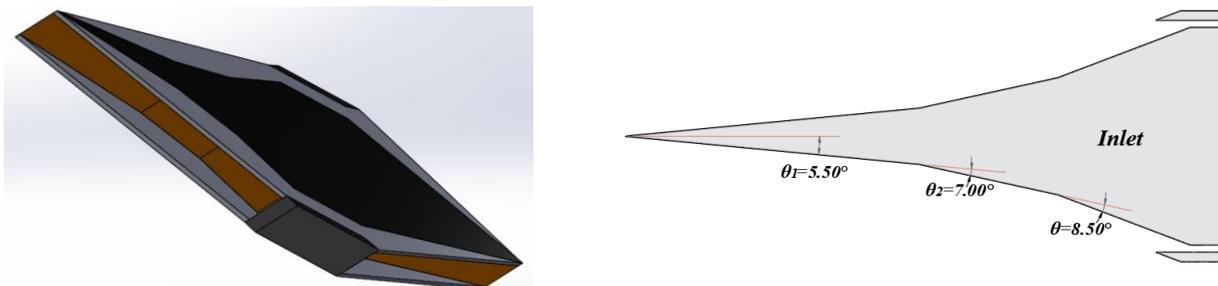

Figure 3. Artistic conception of the generic scramjet vehicle (Toro et al., 2018a).

Studies on hypersonic airbreathing propulsion based on supersonic combustion ramjet (scramjet) technology aims to design an aerospace vehicle that uses, in some propulsion stages, the scramjet engine. Using the atmospheric air as a working fluid and oxygen source, this technology can significantly reduce the weight and costs of space access vehicles.

The scramjet engines are highly integrated with the aerospace vehicle so that there are no moving parts. The supersonic combustion in the combustion chamber depends on the interaction of the flow at hypersonic speed and the frontal geometry of capturing atmospheric air. Scramjets are essentially composed of three components (Fig. 4): the convergent compression section (inlet), the combustion chamber and the divergent expansion section (outlet). The scramjet engine works according to the opened Brayton cycle (Heiser and Pratt, 1994).
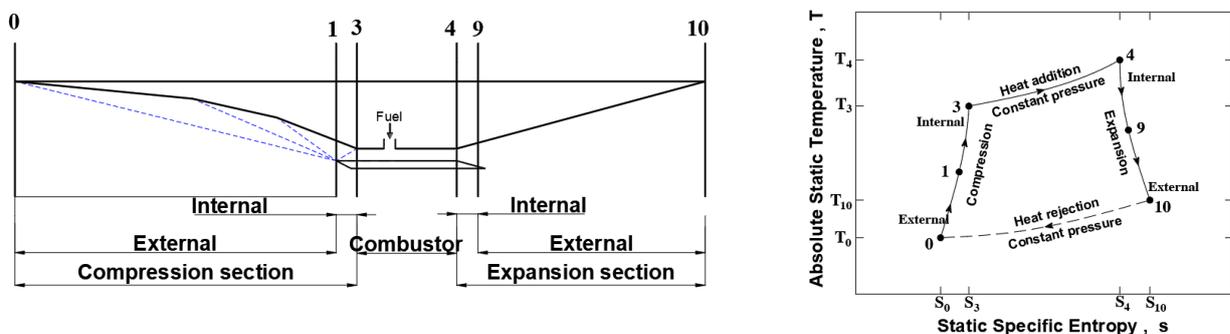

Figure 4. Components and thermodynamic cycle of scramjet engines, adapted from Heiser and Pratt (1994).

A key parameter in projects with scramjets is the design of a compression section that should be able to compress the flow, at hypersonic speed, up to necessary conditions for the auto-ignition of the fuel and supersonic combustion in the combustion chamber. The isentropic compression process is configured as the most efficient option for the engine, this case is approximated when the physical surface of the compression section is manufactured to obey the profile of an isentropic curve. However, the manufacturing difficulties inherent to the more complex profile result the design of alternative and practical geometries, such as a planar profile of compression ramps, similar to the configuration shown in Fig. 1 on the left.

The present work emphasizes the design of the compression section of the scramjet (Fig. 3), considering the viscous effects, which may be estimate the growth of the boundary layer using the analytical method applied by Bonelli et al. (2011), first proposed by Chapman et al. (1958) and evaluate its influence on the plane oblique shockwaves and thermodynamic properties in the vehicle's compression section.

2. METHODOLOGY

The plane oblique shockwave theory quantify the thermodynamic properties and the velocity of the airflow in the external and internal compression section*s*, respectively (Anderson, 1990). The model to describe the growth of the boundary layer on the vehicle surface is based on Chapman et al. (1958), which are used by Bonelli et al. (2011) and adapted to a system with three flat compression ramps. As initial considerations, the viscous effects were considered and the air was modeled as a calorically perfect gas. Also, the indices *in* and *out* were used to identify the upstream and downstream flows, respectively.

2.1 Viscous effects - Chapman-Rubesin model

When the airflow is forced against the surface of the scramjet, the viscosity μ of the fluid, associated with the non-slip condition, results on the boundary layer formation that tends to grow in the flow direction. Chapman et al. (1958) proposed a methodology to estimate the thickness of the boundary layer, at supersonic velocity, from parameters such as Reynolds number, temperature and velocity, according to the following equation.

$$\frac{\delta^*}{x} = \sqrt{\frac{C^*}{\mathrm{Re}_{\infty,x}}} \left(1{,}72 + 2{,}21\frac{\gamma-1}{2}M_\infty^2 + 1{,}93\frac{T_w - T_{aw}}{T_\infty}\right) \tag{1}$$

It is observed that x is the coordinate in the flow direction, C^* is the Chapman-Rubesin constant. Re is the Reynolds number. The subscripts ∞, w and aw represent free flow, wall and adiabatic wall conditions, respectively. The Chapman-Rubesin constant is given by:

$$C^* = \frac{T_\infty \mu^*}{T^* \mu_\infty} = \left(\frac{T^*}{T_\infty}\right)^{-(1-w)n} \tag{2}$$

where n is equal to 0.5 and 0.2 for the laminar and turbulent flow condition, respectively; w is a parameter that varies in the range 0,75-1. T^* is the temperature that corresponds to the reference enthalpy condition, which is given, considering calorically perfect gas:

$$\frac{T^*}{T_\infty} = 0{,}28\frac{T_e}{T_\infty} + 0{,}5\frac{T_w}{T_\infty} + 0{,}22\frac{T_{aw}}{T_\infty} \tag{3}$$

The subscript e represents the properties of the edge of the boundary layer and r is the recovery factor, which the recovery temperature (adiabatic wall) is defined by:

$$\frac{T_{aw}}{T_\infty} = 1 + r\frac{\gamma-1}{2}M_\infty^2 \tag{4}$$

Bonelli et al. (2011) represent the thickness of the boundary layer (δ^*) at linearized form (Fig. 5), where θ is the flow deflection angle with correspond to the physical surface of the compression ramp; θ' is the deflection angle in relation to the virtual surface. For a system of n compression ramps the methodology is also valid, in this case, the reference system for the construction of the limit layer of the consecutive ramps must consider the limit layer of the previous ramp (Fig. 5).
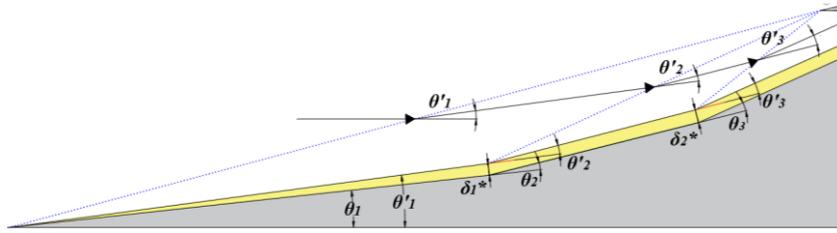
Figure 5. Schematic representation of the growth of the boundary layer between consecutive compression ramps.

3. RESULTS AND COMMENTARIES

Figure 6 shows a sectional view with the main dimensions of the projected vehicle inlet with three compression ramps with angles respectively equal to $\theta_1 = 5.5°$; $\theta_2 = 7.0°$; $\theta_3 = 8.5°$. It is observed that the height and width of the scramjet are given by a design constraint – dimensional compatibility with the rocket engine.

Toro et al. (2018a) presented the analytical results disregarding the boundary layer. For this case, the incident oblique shockwaves established on the leading edge of the vehicle and the compression ramp intersections incident on the leading edge of the cowl (shock on-lip) and the reflected shockwave hits on the entrance of the combustion chamber (shock on-corner), guaranteeing the maximum airbreathing air capture (Fig. 6).
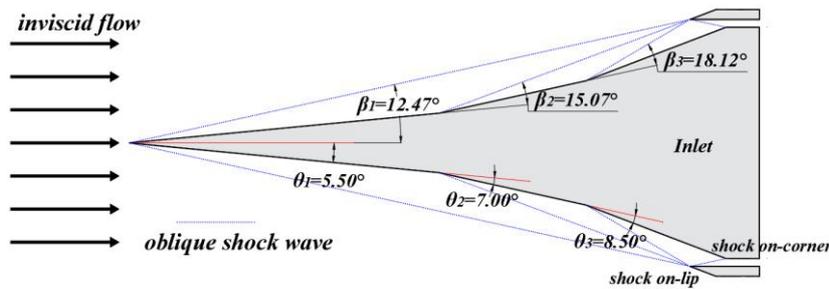

Figure 6. Oblique shockwaves in the generic scramjet with no viscous effects, adapted from Toro et al. (2018a).

The methodology presented was used to estimate the behavior of the boundary layer due to the viscous effects of supersonic flow on the compression ramps. The scramjet wall temperature was considered to be constant and equal to 300 K in all sections of the vehicle (Tw = 300 K). The number of Prandtl used was 0.7225. For a more conservative analysis, the Chapman-Rubesin constant was obtained considering the variable w equal to 1. Also, a Reynolds number was used as a reference for the transition from laminar to turbulent flow equal 5×10^6.

The growth behavior of the boundary layer on the vehicle inlet wall as a function of the length parallel to the compression section (X') was plotted in Fig. 7. It was observed that at the 195 mm distance from the leading edge, the transition from laminar boundary to turbulent layer. The boundary layer showed growth in the three compression ramps, reducing its growth rate according to the increase of temperature and decrease of velocity.
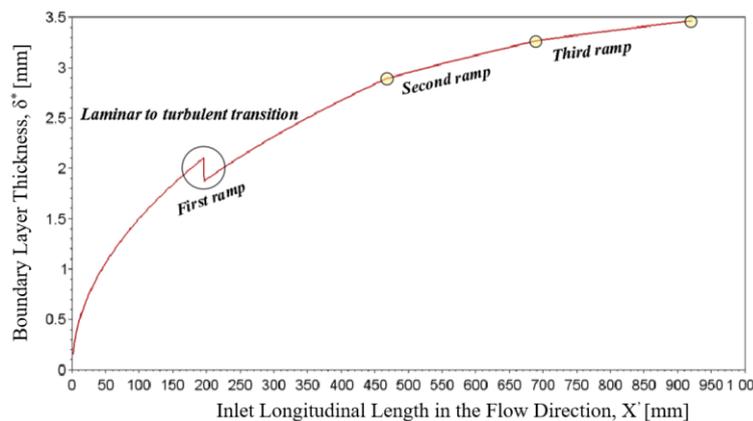

Figure 7. Thickness of the boundary layer in the external compression section of the generic scramjet.

The profile of the boundary layer was linearized and plotted on the surface of the compression section, as shown in Fig. 8.a. Due to the small dimensions of the boundary layer, the figure is out of scale. It is noticed that the viscous effects produced a boundary layer that behaves as a virtual/apparent surface on the scramjet wall, similarly the assumption made by Bonelli et al. (2011). Note that the boundary layer on the cowl surface was ignored due to its small thickness in the region near the entrance of the combustion chamber.
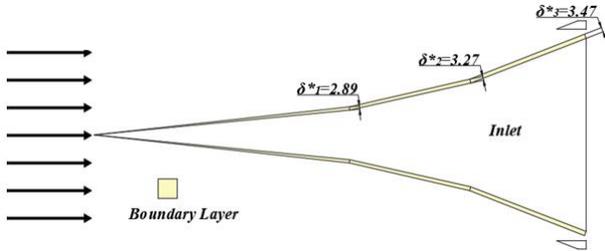
Figure 8.a. Linearized profile of the boundary layer in the external compression section of the generic scramjet.
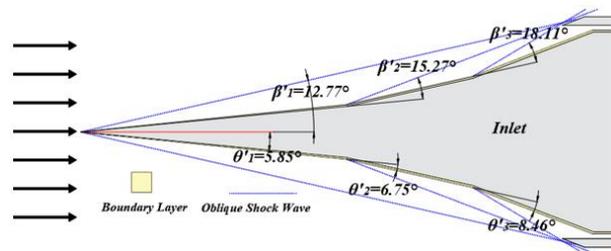
Figure 8.b. Configuration of shock waves in the generic scramjet considering viscous effects.

The thickness of the boundary layer directly influenced the behavior of the scramjet compression system. It modified the deflection angles of the ramps and the angle of the oblique shockwaves (Fig. 8.b) and causing air leakage close to the leading edge of the cowl (Fig. 9). It was possible to notice a distance from the oblique shock waves in relation to the cowl (Fig. 9). Consequently, It was not possible to establish the reflected oblique shock wave (internal compression stage). Also, the boundary layer at the entrance of the combustion chamber represented an obstruction to the flow, reducing the height of the combustion chamber.
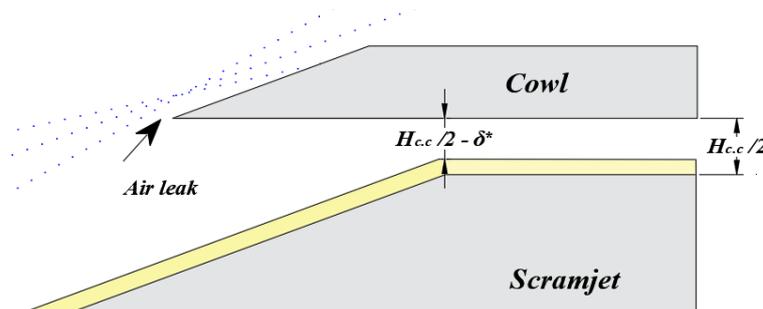

Figure 9. Distancing of oblique shock waves with respect to cowl and obstruction of the combustion chamber entrance due to the thickness of the boundary layer.

The property ratios and thermodynamic properties at the scramjet inlet are presented in Tab. 1. The thermodynamic conditions of the freestream at an altitude of 30 km were obtained from the U.S Standart Atmosphere (1976). One may observe the pressure, temperture and density increase and Mach numbers (and velocities) decrese at the compression section.

Table 1. Thermodynamic properties comparison of the flow in the external compression section, flow with and without boundary layer, calorically perfect gas ($p = \rho RT$, $\gamma = 1.4$).

		$\frac{p_n+1}{p_n}$	$\frac{\rho_n+1}{\rho_n}$	$\frac{T_n+1}{T_n}$	Mach	p (Pa)	ρ (kg/m³)	T (K)	V (m/s)
without boundary layer (Toro et al,. 2018a)	Freestream	-	-	-	6,8	1197	0,0184	226,5	2051,39
	1° Ramp	2,35	1,81	1,30	5,86	2813,16	0,0333	294,35	2018,08
	2° Ramp	2,54	1,90	1,33	4,95	7145,51	0,0633	393.16	1968,30
	3°Ramp	2,60	1,93	1,35	4,11	18582,97	0,1222	529,62	1897,37
with boundary layer	Freestream	-	-	-	6,8	1197	0,0184	226,5	2051,39
	1° Ramp	2,47	1,87	1,32	5,810	2955,62	0,0344	299,50	2015,33
	2° Ramp	2,45	1,86	1,32	4,941	7225,82	0,0638	394,63	1967,53
	3°Ramp	2,59	1,92	1,34	4,109	18683,10	0,1227	530,49	1896,85

At Figure 10, the initial region (between 0 and 100 mm) corresponds to the conditions of the freestream. The three jumps in the analyzed variables occur due to the vehicle's external compression system, related to the incident oblique shock waves established in the three compression ramps. According to the shock wave theory, pressure, density and temperature must increase, while the Mach number and flow velocity decrease, as observed in the results obtained. The graphs of the behavior of the properties are shown in Figure 10. The properties are plotted using red color (continuous line) for the compression section considering the boundary layer, and using blue color (dash line) to properties for the compression section disregarding the boundary effects. Note that the presence of the boundary layer increases the thermodynamics properties and reduce the Mach number and velocity of the inlet airflow when compared to the inviscid flow.
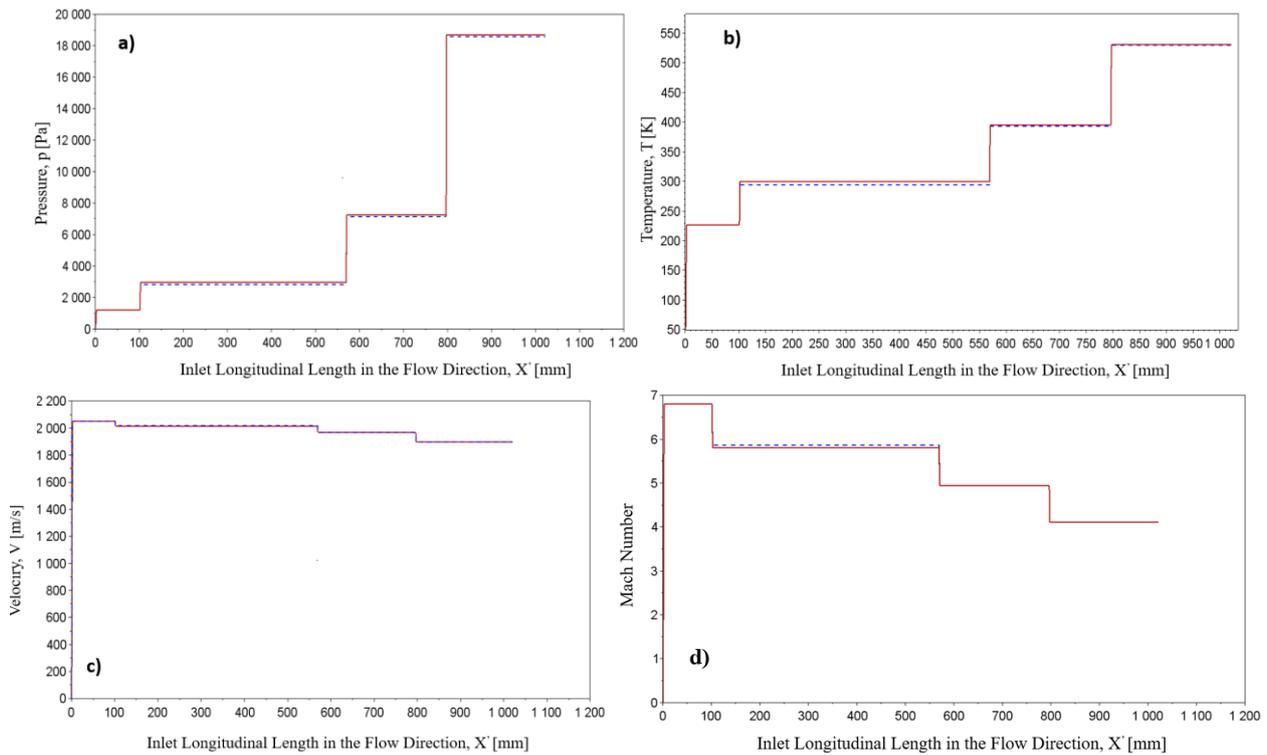

Figure 10. The behavior of flow properties in the compression section of the generic scramjet. a) pressure; b) temperature; c) velocity; d) Mach number.

4. CONCLUSION

An analytical model was applied to calculate the thickness of the boundary layer on the surface of the compression section of a generic scramjet engine that is being researched at the Federal University of Rio Grande do Norte (UFRN). It is concluded that the boundary layer behaves like a virtual ramp in which it significantly changed the configuration of the compression system, modifying the deflection angles and flat oblique shock wave and causing air leakage close to the leading edge of the cowl. The thickness of the boundary layer at the entrance of the combustion chamber represented an obstruction that can clog the combustion chamber. The evaluations of the flow properties showed that the presence of the limit layer increased the temperature, pressure and density while reducing the velocity when compared with the analytical results without boundary layer. It is concluded that modifications in the compression system are necessary to accommodate the boundary layer and guarantee operating parameter keys of the scramjet engine. For future work it is suggest to make geometric modifications on the scramjet inlet, changing the deflection angles, the length of the last compression ramp and making a cowl repositioning.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Anderson, J. D., Modern Compressible Flow, The Historical Perspective. McGraw-Hill, Inc., ed. 2nd, 1990.

Barth, J.; Wheatley, V.; Smart, M. Hypersonic Turbulent Boundary-Layer Fuel Injection and Combustion: Skin-Friction Reduction Mechanisms. AIAA Journal, Vol. 51. No. 9. 2013.

Bonelli, F.; Cutrone, L.; Votta, R.; Viggiano, A.; Magi, V. Preliminary Design of a Hypersonic Air-breathing Vehicle. 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, California, 2011.

Bonifacio, S.; Borreca, S.; Ranuzzi, G.; Salvatore, V. SPREAD: a scramjet PRELiminary aerothermodynamic design code. 14th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. Australia. (AIAA 2006-7910). 2006.

Chapman D.R., Kuehn D.M. and Larson H.K., Investigation of Separated Flows in Supersonic and Subsonic Streams with Emphasis on the Effect of Transition, NACA report No. 1356, 1958.

Clark, A.; Wu, C.; Mirmirani, M.; Sangbum, C.; Kuipers, M. Development of an Airframe-Propulsion Integrated Hypersonic Vehicle Model. 44th AIAA Aerospace Sciences Meeting and Exhibit. Nevada/EUA. (AIAA 2006-218). 2006.

Costa, G. J., Costa, F. J.; Coelho, B. L.; Laiton, S. N.; Cardoso, R. L.; Santos, R. O.; Minucci, M. A. S., Oliveira, A. C.; Rego, I. S.; Toro, P. G. P. Projeto preliminar de uma proteção aerodinâmica para a entrada de ar do motors sramjet do demonstrador tecnológico 14-X S. IV Congreso Argentino de Ingeniería Aeronáutica, 2016.

Croft, J. X-51A Waverider reaches Mach 5 in 140s scramjet flight. Flight global, 27 may. 2010. Available from: https://www.flightglobal.com/pictures-and-animation-x-51a-waverider-reaches-mach-5-in-140s-scramjet-flight/93720.article.

Dolvin, D. Hypersonic International Flight Research and Experimentation (HIFiRE) Fundamental Science and Technology Development Strategy. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. Ohio/EUA. (AIAA 2008-2581). 2008.

Hank, J. M.; Murphy, J. S.; Mutzman, R. C. The X-51A scramjet engine flight demonstration program. 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference. Ohio/EUA. (AIAA 2008-2540). 2008.

Heiser, W. H.; Pratt, D. T. Hypersonic Airbreathing Propulsion. Washington, D.C, American Institute of Aeronautics and Astronautics, 1994.

Mankins, J. C. Technology readiness assessmentes: a retrospective. Acta Astronautica, Vol. 65. 2009.

Marshall, L. A.; Bahm, C.; Corpening, G. P.; Sherrill, R. Overview with results and lessons learned of the X-43A Mach 10 flight. AIAA/CIRA 13th International Space Planes and Hypersonic Systems and Technologies Conference. Capua/Italy. (AIAA 2005-3336). 2005a.

Marshall, L. A.; Corpening, G. P.; Sherrill, R. A. Chief engineer's view of the NASA X-43A scramjet flight test. AIAA/CIRA 13th International Space Planes and Hypersonic Systems and Technologies Conference. Capua/Italy. (AIAA 2005-3332). 2005b.

Newdick, T. India Claims To Have Successfully Tested a Hypersonic Scramjet Powered Vehicle. 7 September. 2020. Available from: https://www.thedrive.com/author/thomas-newdick.

Paull, A.; Hass, N. E.; Smart, M. K. Flight data analysis of HyShot 2 scramjet flight experiment. AIAA Journal. Vol. 44. No. 10. 2006.

Piscitelli, F.; Cutrone, L.; Pezzella, G.; Roncione, P.; Marini, M. Nose-to-tail analysis of an airbreathing hypersonic vehicle using an in-house simplified tool. Acta Astronautica, Vol. 136. No 15. 2017.

Rondeau, C. M.; Jorris, T. R. X-51A scramjet demonstrator program: waverider ground and flight test. SFTE 44th International / SETP Southwest Flight Test Symposium, Fort Worth, Texas/EUA. 2013.

Rosenberg, Z. Hypersonic X-51 program ends in success. Flight Global, 3 may. 2013. Available from: https://www.flightglobal.com/hypersonic-x-51-programme-ends-in-success/109619.article/.

Steelant, J.; Villace, V.; Kallenbach A.; Wagner, A.; ANDRO, J.; Benedetto, S.; et al. Flight testing designs in HEXAFLY-INT for high-speed transportation. HISST 2018. Moscou/Russia. (hal- 01978022). 2018.

Toro, P. G. P.; Carneiro, R.; Araújo J. W. S.; Marinho, G. S.; Borba, G. L.; Rego, I. S.; Martos, J. F. A., "Design and Analysis of a generic scramjet air inlet". 17th Brazilian Congress of Thermal Sciences and Engineering (ENCIT 2018). November 25th-28th, 2018, Águas de Lindóia, SP, Brazil.

Toro, P. G. P.; Araújo J. W. S.; Mendes, E ; Souza, S ; Rêgo, I. Numerical Analysis of a Generic Scramjet air Inlet. 17th Brazilian Congress of Thermal Sciences and Engineering (ENCIT 2018). November 25th-28th, 2018, Águas de Lindóia, SP, Brazil.

Van Driest, E. R. Turbulent Bundary Layer in Compressible Fluids. Journal of the Aeronautical Sciences. Vol. 18, No. 3, 1951.

Van Driest, E. R. The Problem of Aerodynamic Heating. Aeronautical Engineering Review. Vol. 15, No. 10, 1956.

U.S. Standard Atmosphere. NASA TM-X 74335. National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration and United States Air Force. 1976.

Weber, R. J., and Mackay, J. S. An Analysis of Ramjet Engines Using Supersonic Combustion, NACA TN-4386, 1958.

Weinberger, S. X-51 Waverider: Hypersonic jet ambitions fall short. BBC Future, 14 August. 2012. Available from: https://www.bbc.com/future/article/20120815-hypersonic-ambitions-fall-short.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this scientific article.
The authors declare there is no conflict of interest regarding the publication of this scientific article.