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PRELIMINARY AERODYNAMIC HEATING AT STAGNATION POINT APPLIED TO VHA 14-X S

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Abstract. *The Brazilian VHA 14-X is a technological demonstrator of a hypersonic airbreathing propulsion system based on supersonic combustion (scramjet) to fly at Earth's atmosphere at 30km altitude at Mach number 10, designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies. Basically, scramjet is an aeronautical engine, without moving parts, therfore it is necessary another propulsion system to accelerate the scramjet to the operation conditions. Rocket engines is a low-cost solution to launch scramjet integrated vehicle to flight to the test conditions. The Brazilian two-stage rocket engines (S31 and S30) are able to boost the VHA 14-X to the predetermined conditions of the scramjet operation, 30km altitude but at Mach number 7. Therefore, the VHA 14-X S project has being developed to fly at the Earth's atmosphere at 30km altitude at Mach number 7. Analytical theoretical analysis, computational fluid dynamics simulation and experimental investigation are the methodologies used to design the Brazilians technological demonstrators, before flight through Earth's atmosphere. Vehicles flying at high speeds undergo a process of temperature increase at the wall and surrounding. Knowledge of the phenomenon, as well as determining the intensity, is of paramount importance to the material specification to be used for its manufacture, its thermal protection that keeping the wall temperature and in the indoor temperature of vehicle at acceptable levels and also prevent telemetry problems generated by ionization of the air. Aerodynamic heating based on Fay and Riddell methodology is evalueted at the stagnation point of the VHA 14-X B under two models of the gas: calorically perfect (γ=1.4) and equilibrium air. The results show that lower values are found for equilibrium model, because the effects of the molecular vibrational energy are considered. However, the levels of the heating found in both cases are high, in order of MW/m^2.*

Keywords: *VHA 14-X; Aerodynamic Heating; Stagnation Point; Scramjet.*

1. THE BRAZILIAN 14-X HYPERSONIC AEROSPACE VEHICLE

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

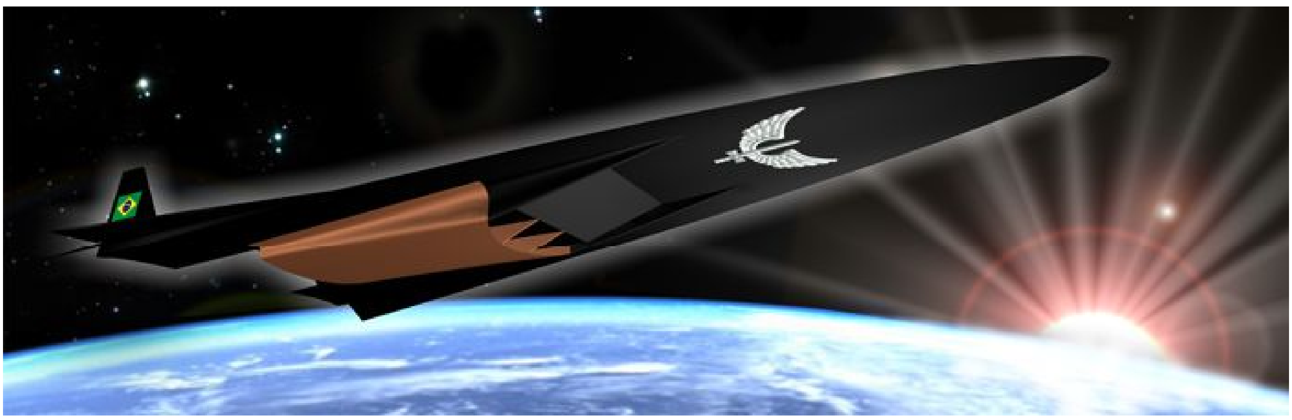

Figure 1: Brazilian 14-X Hypersonic Aerospace Vehicle, VHA 14-X.

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

In fact, the use of atmospheric air as oxidizer allows air breathing propulsion vehicles to substantially increase payload weight. Basically, scramjet is a fully integrated airbreathing aeronautical engine that uses the inlet oblique/conical shock waves generated during the hypersonic flight, to provide compression and deceleration of freestream atmospheric air at the inlet of the scramjet. Fuel, at least sonic speed, may be injected into the supersonic airflow just downstream of the inlet or at the beginning of the combustion chamber. Right after, both oxygen from the atmosphere and on-board hydrogen fuel are mixed. The combination of the high energies of the fuel and of the oncoming hypersonic airflow starts the combustion at supersonic speed. Finally, the divergent exhaust nozzle at the afterbody vehicle accelerates the exhaust gases, generating thrust.

Therefore, the VHA 14-X is operational only on supersonic/hypersonic speeds, and a hypersonic accelerator vehicle is needed to take the VHA 14-X to the 30km altitude at Mach number 10.

As a low-cost Brazilian solution to launch scramjet integrated vehicle to flight to the test conditions (30km altitude at Mach number 10) is to use Brazilian rocket engines based on solid propulsion, in ballistic trajectory. Such approach may provide an affordable path for maturing of the Brazilian hypersonic airbreathing components and systems in flight.

The Brazilian hypersonic accelerator vehicle (Fig. 2) which may be composed by two-stage solid rocket engines (S31 and S30), unguided, rail launched, is able to accelerate the VHA 14-X to the predetermined conditions of the scramjet operation, 30km altitude but at Mach number 7 (approximately 2100 m/s) from a Brazilian Launch Center.

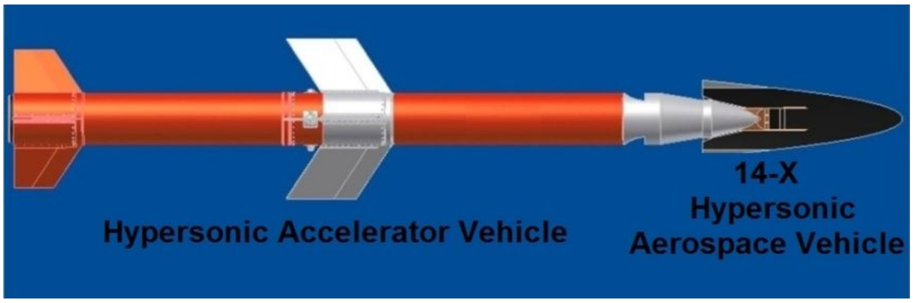

Figure 2: Hypersonic Accelerator Vehicle and 14-X Hypersonic Aerospace Vehicle coupled.

It is planning for the flight test (Ricco et al., 2011), the 14-X Hypersonic Aerospace Vehicle will separate, at 30km altitude, from the 2nd stage rocket engine of the Hypersonic Accelerator Vehicle Fig. 3). The scramjet will be operational for about 4-5 seconds in upward flight of the 14-X Hypersonic Aerospace Vehicle. After scramjet engine demonstration is completed, the 14-X Hypersonic Aerospace Vehicle will follow the ballistic flight. After reaching the apogee, the 14-X Hypersonic Aerospace Vehicle will follow the descending flight to splash into the Atlantic Ocean. Both Hypersonic Accelerator Vehicle and 14-X Hypersonic Vehicle will not be recovered.

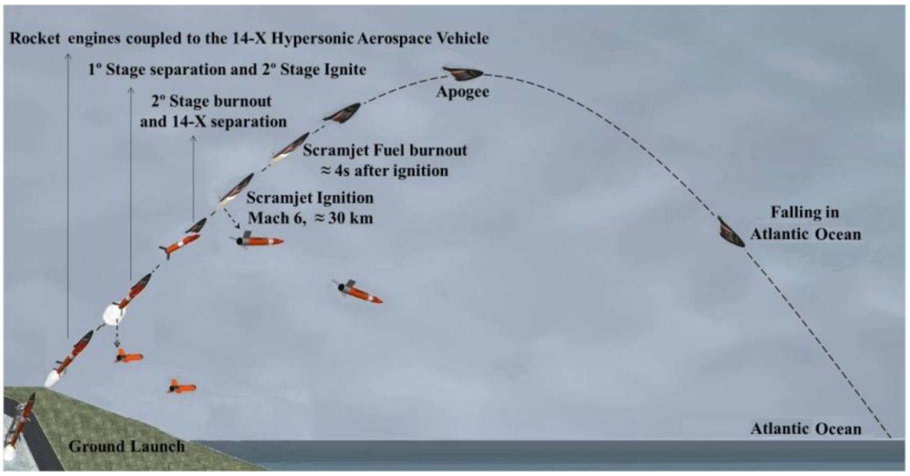

Figure 3: Hypersonic Accelerator Vehicle and 14-X Hypersonic Aerospace Vehicle in ballistic trajectory.

The Alcântara Launch Center (CLA) is a satellite launching base of the Brazilian Space Agency (AEB), located at the Latitude 2^o 18’ S Longitude 44^o 22’ W, on Brazil’s northern Atlantic coast, outside São Luis city (capital of Maranhão State). The CLA is operated by the Department of Aerospace Science and Technology (DCTA). CLA is the one of the world’s closest launching base to the equator line, which gives the launch site a significant advantage in

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launching geosynchronous satellites, an attribute shared only by the Guiana Space Center (utilized by France), and it's position nearer the equator offers an advantage over Cape Canaveral (USA).

2. THE VHA 14-X S

In March 2012, the coordination of the VHA 14-X proposed new versions based on the VHA 14-X (Toro et al., 2013), where the VHA 14-X S (Fig. 4) has been designed to demonstrate the scramjet technology at 30km altitude with Mach number 7 (using the Brazilian solid rocket engines S31 and S30), which the external configuration is based on VHA 14-X (Fig. 1) 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. 5) consists of a double cross-section of the VHA 14-X B (Fig. 6), where in the upper and lower contours are identical.

Figure 4: VHA 14-X S.

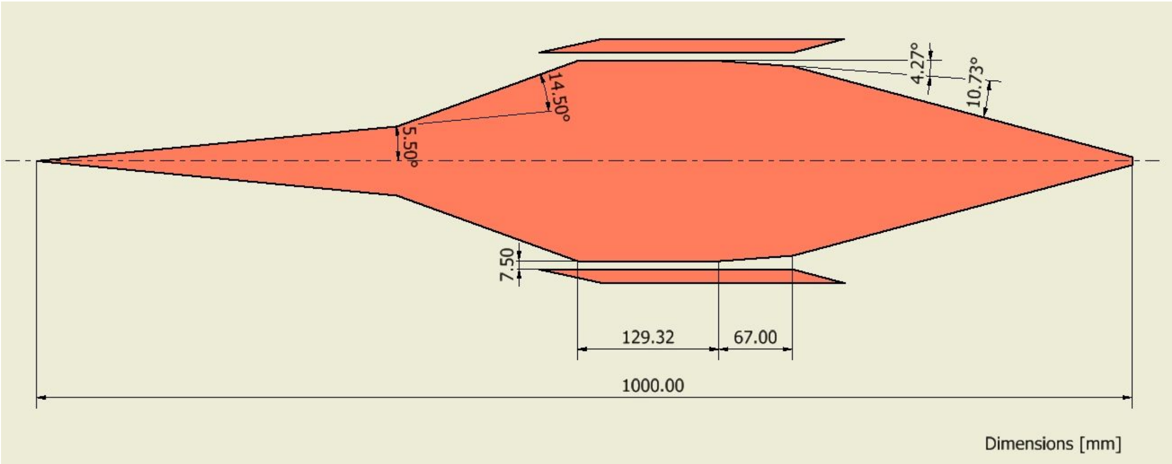

Figure 5: Dimensional for the VHA 14-X S.

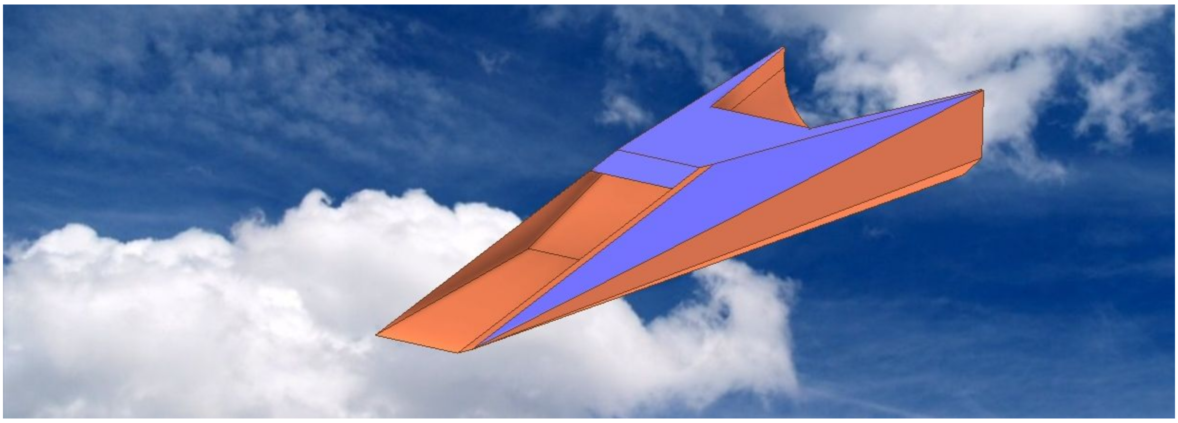

Figure 6: VHA 14-X B.

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The lower surface of the 1-m. long VHA 14-X S (Fig. 5), 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).

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).

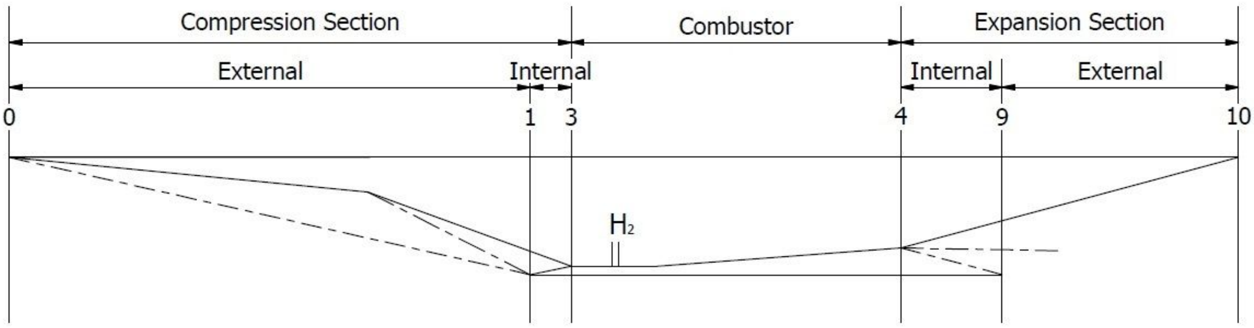

Figure 7: hypersonic vehicle with airframe-integrated scramjet engine stations and reference terminology.

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, Cardoso et al., 2013), 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. The standard atmospheric properties at 30km geometric altitude (U.S. Standard Atmosphere, 1976) are given as $p = 1197\left(Pa\right)$, $T = 226.5\left(K\right)$, $\rho = 0.01841\left(kg/m^3\right)$, $a = 301{,}7\left(m/s\right)$, where a is sound velocity.

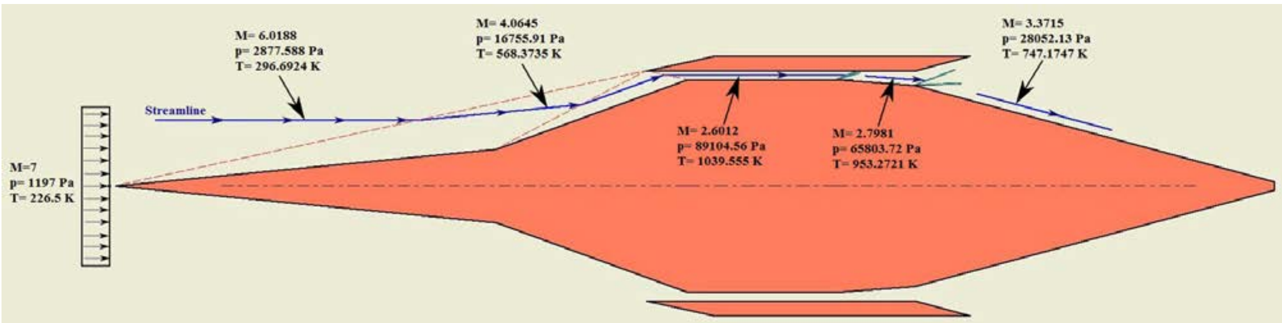

Figure 8: Analytical Theoretical Analysis applied to the VHA 14-X S at 30km altitude Mach number 7.

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.

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3. AERODYNAMIC HEATING OF THE VHA 14-X WAVERIDER SCRAMJET

The feasibility of transatmospheric flight is limited by phenomena such as aerodynamic drag and heating as well as related thermal management problems. Traditional blunt-nosed hypersonic vehicles generate a strong detached normal shock wave in the nose region, which produces high aerodynamic drag. The temperature behind this strong shock wave increases at hypersonic velocities, although the aerodynamic heating rates are reduced compared with that of an attached shock wave on a conical body. On the other hand, a traditional slender body with a sharp leading edge produces a conical weak attached shock wave with low drag coefficient, but extreme heating is created at the tip of the forebody.

These vehicles, flying at hypersonic velocities, convert a large amount of the kinetic energy in the thermal energy. The knowledge this phenomenon is important for the design of thermal protection, keeping the structural integrity and the internal temperature in acceptable levels. In this context, this paper has shown an evaluation of the aerodynamic heating suffered by the Aerospace Hypersonic Vehicle (VHA, in Portuguese) 14-X in its stagnation point, under two hypotheses: calorically perfect gas and equilibrium.

For the present study the leading-edge of the VHA 14-X S is blunted and it has a radius of 5-mm.

4. METHODOLOGY

The methodology used in this work will be shown below.

4.1 Calorically Perfect Gas and Thermodynamic Equilibrium Models

A model of air as calorically perfect gas consider that the specific heats are constant, so $\gamma = cte$. ($\gamma = C_P/C_V$). Hence:

$$h = C_P T \tag{1}$$

$$e = C_V T \tag{2}$$

However, a model of equilibrium gas considers that the properties of the gas are function of the two thermodynamic variables. This model is applied when the vibrational energy mode is activated, and for gas at 1 atm this occurs about 800 K. So γ is not constant. Hence:

$$C_P = f_a(T,P) \tag{3}$$

and

$$C_V = f_b(T,P) \tag{4}$$

The polynomial fitting method, developed by Tannehill and Mugge (1974), is used in this work for obtain the properties after a normal shock wave.

4.2 Mathematical Equations

The mathematical model used in this paper is composed by the normal shock relations, demonstrated in Anderson (2003) and the aerodynamic heating technique developed by Fay and Riddell (1958). These equations are shown below.

$$rho_2/rho_1 = (\gamma+1)M_1^2(2+(\gamma-1)\,M_1^2)^{-1} \tag{5}$$

$$P_2/P_1 = 1 + 2\gamma(\gamma+1)^{-1}(M_1^2-1) \tag{6}$$

$$T_2/T_1 = P_2 P_1^{-1} rho_1 rho_2^{-1} \tag{7}$$

The conditions 1 and 2 are before and after normal shock wave, respectively. In order to calculate the heat flux in the stagnation point was used the Fay and Riddell's equation, shown below:

$$q_{sp} = 0.57 P_r^{-0.6}(rho_s \mu_s)^{0.4}(rho_w \mu_w)^{0.1} C_P (T_s - T_w)(du/dx)^{0.5} \tag{8}$$

$$(du/dx)^{0.5} = R^{-1}(2(P_s - P_\infty)/rho_s)^{0.5} \tag{9}$$

The subscripts *s* and *w* corresponds the conditions in the surface and the wall of vehicle, respectively.

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4.3 Trajectory Data

The preliminary trajectory of the VHA 14-X S for Mach number higher than 1 (where the shock wave is established at the leading-edge) was chosen based on the ballistic trajectory of the S31 and S30 solid rocket engines used in the VSB 30 launcher (IAE, 2012).

5. RESULTS

Aerodynamic heating at the leading-edge of the VHA 14-X flying up to about 30km altitude from Mach number 1.23 to 7 is evaluated using the standard atmospheric properties presented by U.S. Standard Atmosphere (1976).

Matlab code was built considering: i) the closed relationships provide by the U.S. Standard Atmosphere (1976) up to 86 km geometric altitude , normal shock relationships (Anderson, 2003) and aerodynamic heating by Fay and Riddell technique (1958).

One may observe the heat flux at the stagnation point of the VHA 14-X S is about the same (Fig. 9) considering the air behaves as a perfect gas or in thermodynamic equilibrium.

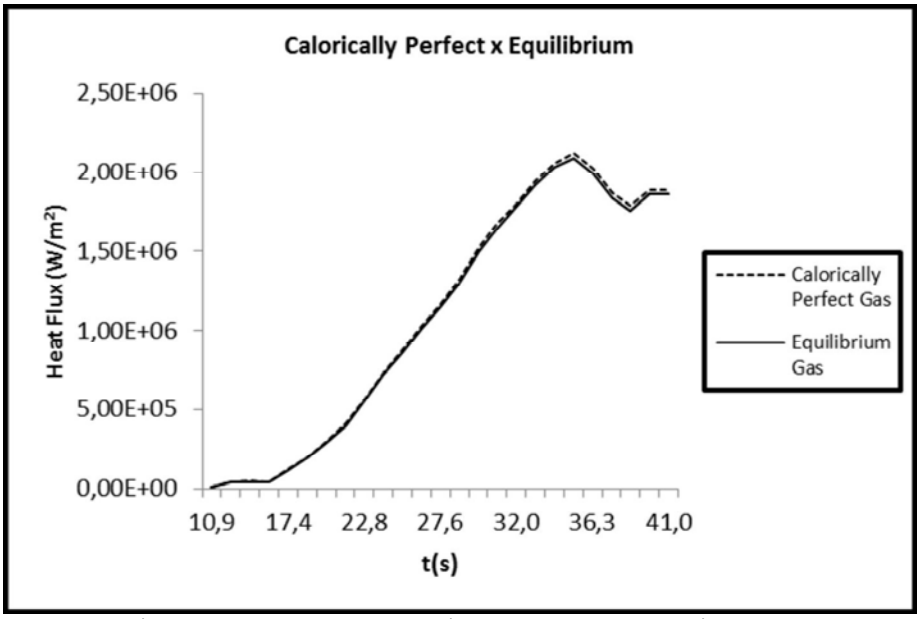

Figure 9: heat flux in the stagnation point of vehicle calorically perfect gas x equilibrium.

Figure 10 shows up to aproximatly Mach number 8 (about 2.4km/s) and up to about 40km geometric altitude the air behaves as a thermally perfec gas, therefore there is no dissociation of the Oxigen (Koppenwallner, 1984).

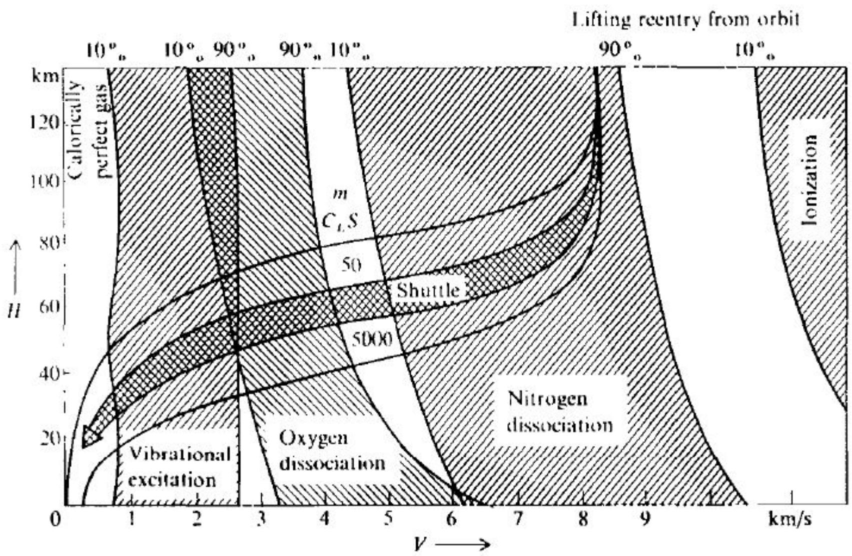

Figure 10: Velocy map with supperimposed regions of vibration, excitation, dissociation and ionization.

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6. CONCLUSION

The primary objective of this work is to present the aerodynamic heating from Mach number higher than 1 up to Mach number 7 and up to 30km altitude, of the hypersonic vehicle with airframe-integrated scramjet engine, named VHA 14-X S, where air behaves as calorically and thermodynamic equilibrium.

Indeed, the Brazilian VHA 14-X S is a technological demonstrator of a hypersonic airbreathing propulsion system based on supersonic combustion (scramjet) to fly at Earth's atmosphere at 30km altitude at Mach number 7, designed at the Prof. Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonics, at the Institute for Advanced Studies. Basically, scramjet is an aeronautical engine, without moving parts, therefore it is necessary another propulsion system to accelerate the scramjet to the operation conditions. Rocket engines are a low-cost solution to launch scramjet integrated vehicle to flight to the test conditions. It is intent, in the near future to use the Brazilian two-stage rocket engines (S31 and S30) to boost the VHA 14-X B to the predetermined conditions of the scramjet operation, 30km altitude at Mach number 7.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Anderson Jr., J. A., 2003, "Modern Compressible Flow, The Historical Perspective" McGraw-Hill, Inc.

Cardoso, R. L., "Estudo Aerodinâmico E Dimensional Para Manufatura Do Veículo Hipersônico Aeroespacial 14-X BS", (in Portuguese). Undergraduate Work, FATEC de São José dos Campos: Professor Jessen Vidal, Brazil, 2012.

Cardoso, R. L., Sousa, M. S., Toro, P.G.P., Porto, B. F., "Dimensional Design of the Brazilian 14-X S Hypersonic Aerospace Vehicle for Flight Experimentation", to be presented at the 22nd Brazilian Congress of Mechanical Engineering, November 3-7, 2013, Ribeirão Preto, SP, Brazil.

Costa, F. J. "Projeto Dimensional para Manufatura do Veículo Hipersônico Aeroespacial 14-X" (in Portuguese). Undergraduate Work, FATEC de São José dos Campos: Professor Jessen Vidal, Brazil, 2011.

Costa, F. J., Toro, P.G.P., Rolim. T.C., Camilo, G.C., Follador, R.C., Minucci, M.A.S., "Design of the Brazilian Hypersonic waverider Aerospace Vehicle", 14th Brazilian Congress of Thermal Sciences and Engineering, October 18-22, 2012, Rio de Janeiro, RJ, Brazil.

Costa, F. J., Toro, P. G. P., Camillo, G. P., Pivetta, A. F. S. "Structural Analysis of waverider hypersonic aerospace vehicle unpowered scramjet at Mach number 10", to be presented at the 22nd Brazilian Congress of Mechanical Engineering, November 3-7, 2013, Ribeirão Preto, SP, Brazil.

Fay,J.A. and Riddell, F. R., 1958.,"Theory of Stagnation Point Heat Transfer in Dissociated Air". Journal of the Aeronautical Sciences, Vol. 25, nº 2, pp. 73-85.

Heiser, H. W. and Pratt, D. T (with Daley, D. H. and Mehta, U. B.). Hypersonic Airbreathing Propulsion. Education Series. EUA. AIAA. 1994.

Hyslop, P. "CFD Modeling of Supersonic Combustion in a scramjet Engine". Doctoral Thesis. The Australian National University, 1998.

IAE, 2012, Private communication.

Kasal, P, Gerlinger, P., Walther, R., Wolfersdorf, J. V. and Weigand, B. "Supersonic Combustion: Fundamental Investigations of Aerothermodynamic Key Problems". AIAA-2002-5119, 2002.

Ricco, M.F.F., Funari, P.P., Carvalho, A.V., Espaço, Tecnologia, Ambiente e Sociedade (in Portuguese), 1st Ed., Habilis Editora Erechim, RS, Brazil, 2011, Chapter 8, 161.

Rolim, T. C., "Experimental Analysis of a Hypersonic Waverider", M.Sc. Thesis (in English), Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil, 2009.

Rolim, T. C., Minucci, M. A. S., Toro, P. G. P., and Soviero, P. A. O., "Experimental Results of a Mach 10 Conical-Flow Derived Waverider". 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference. AIAA 2009-7433, 2009.

Rolim, T.C., Toro, P.G.P., Minucci, M.A.S, Oliveira, A.C., Follador, R.C., 2011, "Experimental results of a Mach 10 conical-flow derived waverider to 14-X hypersonic aerospace vehicle". Journal of Aerospace Technology and Management, São José dos Campos, Vol.3, No.2, pp. 127-136, May-Aug., 2011.

Romanelli Pinto, D., Toro, P. G. P., Marcos, T., V. C., Camillo, G. P., Galvão, V. A. B., Cruzelles, S. B., Assunção, T. L. "Experimental Investigation of the 14-X waverider unpowered scramjet Mach number 10", to be presented at the 22nd Brazilian Congress of Mechanical Engineering, November 3-7, 2013, Ribeirão Preto, SP, Brazil

ISSN 2176-5480

Toro, P. G. P., Minucci, M. A. S., Rolim, T. C., Follador, R. C., Santos, A. M., Camillo, G. P., Barreta, L. G.. "Brazilian 14-X Hypersonic Aerospace Vehicle Project". 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 22-28 Set,Tours, France 2012.

Toro, P. G. P., Santos, A. M., Rolim, T. C., Camillo, G. P., Porto, B. F., Assunção, T. L., Follador, R. C. "Scramjet Research at the Institute for Advanced Studies". To be submitted.

Tannehill,J.C. and Mugge, P.H., "Improved Curve Fits for the Thermodynamic Properties of Equilibrium Air Suitable for Numerical Computation Using Time-Dependent or Shock-Capturing Methods," NASA CR-2470.

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

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