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PRELIMINARY THERMAL PROTECTION SYSTEM FOR THE 14-X S SCRAMJET TECHNOLOGICAL DEMONSTRATOR FOR ATMOSPHERIC FLIGHT AT 30 KM ALTITUDE AND SPEED CORRESPONDING TO MACH NUMBER 7

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Abstract. *Aerospace hypersonic vehicles equipped with an airbreathing supersonic propulsion system faces extremely severe environments during hypersonic flight in terms of thermal and aerodynamic loads. In this way, it is necessary to work with materials that meet a thermal and aerodynamic load without compromising the structure of the vehicle and use a thermal management system to reduce the temperature of the vehicle's structure. Through the 14-X S Technological Demonstrator it is possible to highlight methodologies to design a complete thermal protection system, maximizing the efficiency of the vehicle.*

Keywords: *Scramjet, 14-X S, Hypersonic, Thermal Protection System.*

1. INTRODUCTION

14-X S is an Aerospace Hypersonic Vehicle, VHA 14-X S (Figure 1), which uses a scramjet propulsion system to perform atmospheric flight at 30 km altitude at a speed corresponding to Mach 7 (Costa, 2016).

Figure 1. Aerospace Hypersonic Vehicle 14-X S (Costa, 2016)

These aerospace hypersonic vehicles that use scramjet engines face extremely severe environments during super / hypersonic flights in terms of thermal and aerodynamic loads. For this reason, it is necessary to use materials that meet the thermal and aerodynamic loads without compromising the vehicle structure, as well as the embedded systems and the efficiency of the scramjet engine (Costa, 2011).

An important factor to be taken into account during hypersonic flights is the oxidation of the materials used in the vehicles, due to the high thermal loads facilitating the oxidation mechanisms, since these mechanisms are diffusional, therefore they are thermally activated. It is therefore necessary to use a coating to protect such materials against oxidation. Ceramic materials are widely used as thermal protection coatings because of their excellent wear resistance and corrosion resistance at high temperatures. There are several ceramic materials that are used for thermal protection system of vehicles, such as Silica (SiO2) and Zirconia (ZrO2) (Glass, 2008).

In the Photonics Division of the Institute for Advanced Studies (IEAv) in São José dos Campos, there is an ongoing project considering Application of Ceramic Coatings for thermal and chemical protection using lasers. This technique is efficient when applied to the deposition of zirconia powder on substrates of Inconel using CO2 laser beams, so the Inconel 718 used for the scramjet engine should use this process of zirconia deposition on its surface to protect against oxidation (Teleginski, 2015).

In hypersonic aerospace vehicle designs one must also take into consideration what their thermal management will be, so that this vehicle fulfills the desired mission. The most known types of thermal management are: passive, semi-passive and active. Active thermal management consists of convection cooling, where heat is transferred to the coolant, the coolant heats up and carries the heat out, so the structure runs hot but is kept within its limits of temperature use by active cooling (Glass, 2008). Based on the studies already carried out and the purpose of the vehicle it was concluded that the active thermal management will be more effective to be used in the scramjet engine and in the body of the 14-X S vehicle, so now the goal is to design the cooling system using the concepts of active thermal management. For the testing and analysis of the cooling system one can use an equipment called a vitiated air generator. With this equipment it will be possible to simulate the flight conditions and how the material will behave according to the effects generated by those conditions.

2. EXPERIMENTAL PROCEDURE

Based on previous works (Assunção, 2014) (Costa, 2016) that determine the geometric characteristics, flight envelope, design assumptions and aerodynamic heating estimation of the 14-X S Scramjet Technological Demonstrator and similar projects (Harsha, 2005), it is possible to create methodologies to establish criteria for selection of alternative materials, maximizing the desired effects and minimizing the unattractive characteristics of the study materials, through a selection matrix. The materials are selected considering their application and properties. A review of the literature on types of coatings for protection against oxidation has been made and it will be determined later on which coatings and in which regions these coatings will be applied (Glass, 2008).

The continuity of the work consists of making a preliminary design of a cooling system for the 14-X S.

3. RESULTS AND DISCUSSIONS

Firstly, before defining the materials to be used, it was necessary to analyze the aerodynamic heating of the vehicle. Grouping the heat flux data, the aerodynamic heating envelope of the 14-X S inboard was obtained (considering the vehicle regions: compression ramp, combustor, internal and external expansion) for a flight with an altitude of approximately 30.7 Km and velocity corresponding to the number of Mach 7, as shown in Figure 2 (Assunção, 2014).

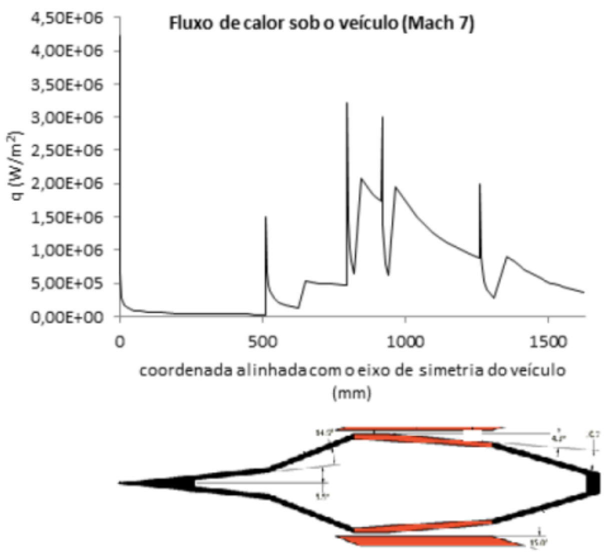

Figure 2: Estimated heat flux under the entire vehicle for the flight condition corresponding to Mach 7 and altitude equal to 30.7 Km (Assunção, 2014).

By the analysis of Figure 2, it can be seen that the heat flux to the 14-X S has a higher value at the stagnation point of the vehicle, revealing that there is a critical region from the point of view of thermal load. It is observed that the second most critical region in terms of convective heating is the combustor region of the vehicle. In these regions there is a need for the use of active thermal management to cooling the engine (Figure 3), as well as the use of materials such as Inconel that are resistant to high temperature and have good thermal conduction. This active thermal management is typically used for high heat flux and for relatively long periods of time. A portion of the cooling will be given by the dissipation of the heat by radiation and the other portion by convection in the propulsion system, where the heat is transferred to the coolant and the coolant heats by carrying the heat outwardly. The structure works hot but is kept within its operating temperature limits. This type of thermal management was used in the "Space Shuttle Main Engine" (Glass, 2008).

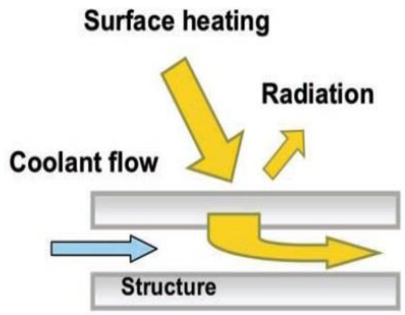

Figure 3. Schematic on Active Thermal Management (Glass, 2008)

In addition, a ceramic coating may be used to reduce the effects of temperature on the engine structure. These coatings, known as Thermal Barrier Coatings (TBC), make up one of the most traditional and effective industrial coatings applications. The TBC concept involves placing a layer of thermal insulation between the metal component and the hot gas of the heat source to reduce the transfer of that heat to the component. Its main applications are in gas turbines and diesel engines, in the aeronautical and automobile industry, respectively, followed by turbines for energy generation. Currently, there is a forecast of use also in fabricated components of ceramic matrix composites (Limar, 2014).

With the heat flux information and the studies carried out with the objective of the selecting vehicle materials (Silva Junior, 2016), the pre-selected materials for the vehicle body 14-X S are in Figure 4.

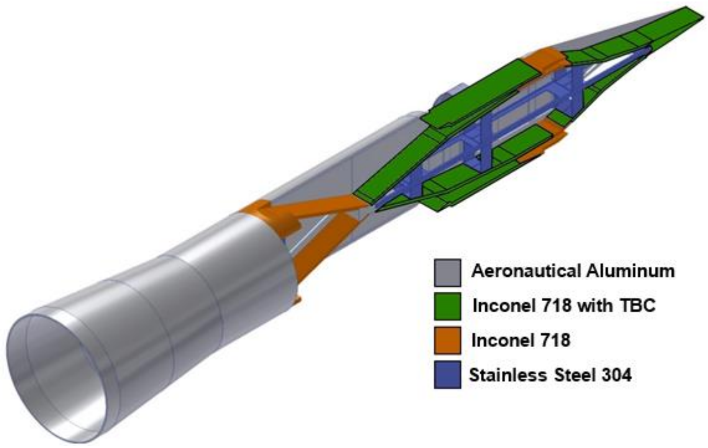

Figure 4. Preliminary specification of the materials of the 14-X S Technological Demonstrator

The high thermal loads facilitate the oxidation mechanisms, since these mechanisms are diffusional, therefore they are thermally activated. Then it is necessary to use coatings that protect the surface of the vehicle to avoid or mitigate the effects of oxidation. One of the best known processes for surface coating against oxidation and thermal protection is Thermal Barrier Coatings (TBC) using Zirconia (ZrO_2) (Teleginski, 2014).

Typically, these coatings are deposited by techniques such as atmospheric plasma spray (APS). However, the main adhesion of these coatings is mechanical and chemical. This technique consists of using laser irradiation to treat coatings deposited by APS, remelting the material, homogenizing its structure and forming a metallurgical bond with the substrate, Figure 5 (Teleginski, 2014).

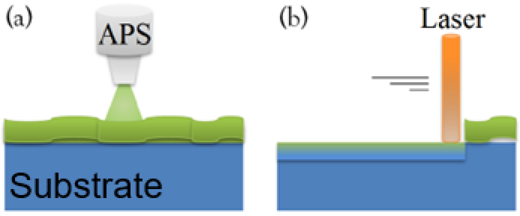

Figure 5. (a) APS coating application and (b) laser treatment (Teleginski, 2014)

The laser treatment plasma thermal spray coating process proved to be efficient for use in hypersonic aerospace vehicles when applied to the deposition of zirconia powder on Inconel substrates using CO2 laser beams. Therefore, the Inconel 718 used for the scramjet engine must use this process of zirconia deposition on its surface to protect against oxidation (Silva Junior, 2016). This process has a better adhesion between the layers and the surface is less rough and more homogeneous than the other two types of processing presented, but it has a dimensional limitation, that is, the process is not feasible for large parts, so a new study with the scramjet engine dimensions to evaluate the viability of this type of processing is still going on (Figure 6).

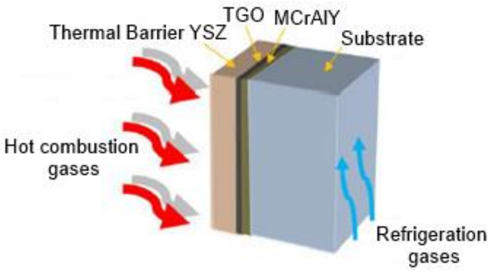

Figure 6. Schematic drawing showing the engineering of surface coatings against oxidation and thermal protection system (TBC) (Teleginski, 2014)

After completion of the cooling system design it will be necessary to make a practical analysis of the whole system and the materials used. For this analysis, an experimental system coupled to the additive air generator (Leite, 2006) will be used, as it will simulate the flight conditions and it will be possible to analyze the entire design of the cooling system as well as the materials used on this design.

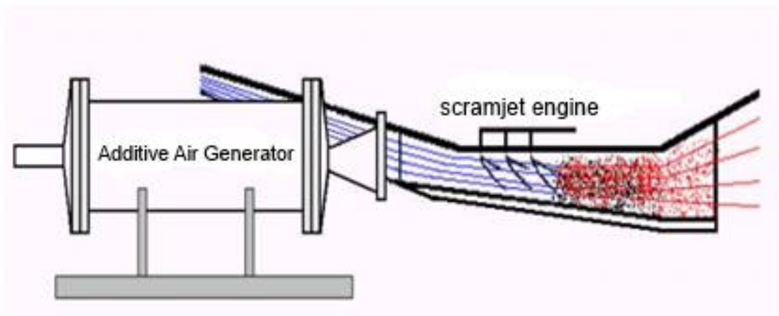

Figure 7. Schematic of the test conditions that must be generated in the test bench of the additive air generator (Adapted from Leite, 2006)

In order to simulate the same conditions at the entrance of the scramjet engine in real flight, the air is enriched with oxygen before entering the combustion chamber of the Additive Air Generator (GAV), to replace the O2 that will be consumed in the process of combustion of air heating and continues to have 21% oxygen, relative to atmospheric air, at the outlet of the supersonic or hypersonic nozzle. The fuel used in the process of heating the atmospheric air is injected into the combustion chamber by the injection plate, located at the entrance of the GAV, through "swirlers" (vertical flame anchors). This generated final flow, the "junk air", will feed the engine to be tested. Such vitiated air must contain the desired test conditions, ie the flow conditions (primarily Mach number and temperature) behind the conical or oblique shock waves, plus the combustion products, in addition to maintaining the same oxygen ratio of the atmospheric air. Due to the fact that it is not possible to eliminate the combustion products obtained in the air heating process, it is called air additive to the flow generated by the test bench (Leite, 2006).

Another important factor is the possibility of using the fuel itself, in this case hydrogen, as a coolant, causing it to travel the structure in the direction in favor of the airflow (Figure 8), where under these conditions the injection temperature will be something around of 300 K. When used counter flow the injection temperature will be around 1000K. Due to the higher input temperature, assumed to be 1000 K, the entire structure reaches a higher equilibrium temperature, and the lower temperature gradients, so the fuel must be used by driving the structure in the direction in favor of the airflow so that the entire structure reaches a lower equilibrium temperature (Messe, 2010).

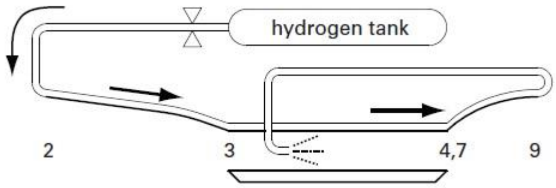

Figure 8. Coolant (hydrogen) in favor of the airflow (Messe, 2010)

From the selection of materials and types of thermal protection it was possible to determine the regions of the vehicle that will be used Inconel with a cooling system or with TBC. These regions are represented in Figure 9.

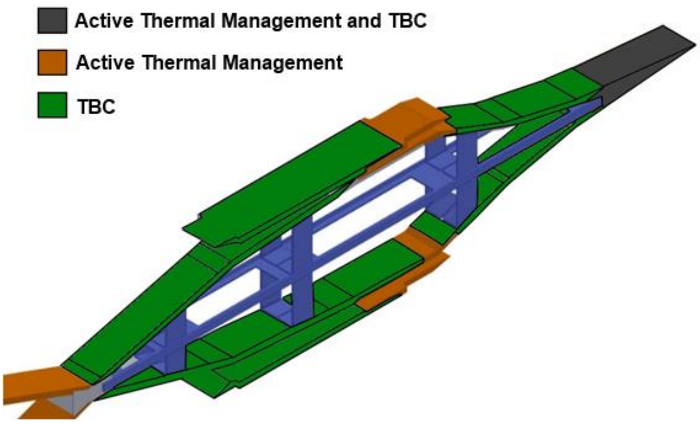

Figure 9. Regions of the vehicle that require an Active Thermal Management or Thermal Protection

For regions where there is a need for active thermal management, it is necessary to make piping through the structure of the vehicle in order to transport the coolant, removing heat from the structure and reducing the temperature. Figure 10 shows a schematic depicting such pipes.

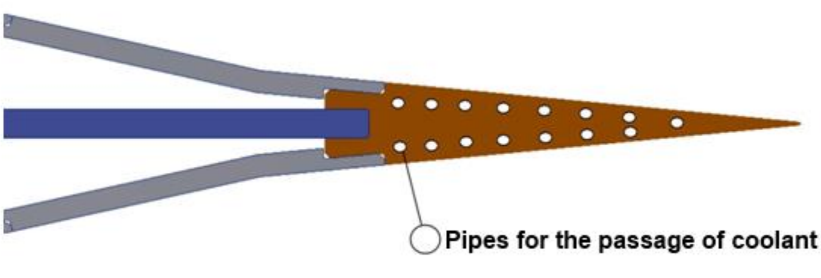

Figure 10. Piping schematic in Active Thermal Management

Due to the geometric limitations of the vehicle and the need for a longer time of interaction between the fluid and the material of the structure, the schematic above differs from that presented by Messe (2010). The schematic shows a series of interconnected pipes with the objective of increasing the contact time of the liquid with the structure and consequently a greater efficiency in the withdrawal of heat from this structure It will be evaluated later if this distribution of pipes is efficient for application in the regions that have higher load thermal.

From this stage the study will be directed to the design of the cooling system taking into consideration some variables such as: pipe diameter and length, coolant flow, mechanical resistance of the structure after the installation of the pipes, need for a coating of the pipe, flow system (pump, valve, etc.) and also the thickness of the coating for thermal protection in TBC.

4. CONCLUSIONS

With the development of new aerospace vehicles, such as the hypersonic ones, there was a need to search for new materials and cooling systems, since the flight environment of these vehicles is extremely severe from a mechanical and thermal point of view. Through the preliminary selection made in previous works it was possible to design the structure of the vehicle, but there was a need for a system for vehicle cooling. The first step in designing the cooling system was to perform a literature review of the thermal loading during hypersonic flights. According to Assunção (2014) there are critical regions in terms of thermal loading, so there will be a need for a coating and / or a cooling system to prevent this region of the vehicle from suffering irreversible damages during the flight.

After the study of the thermal loads and the verification of the need for a coating in some regions, the research was directed to the determination of the type of coating, the regions that will need and suitable processing for that coating. The scramjet engine due to its high thermal load was selected to contain a ceramic coating, both for thermal protection and for protection against oxidation. The type of coating will be the TBC (Thermal Barrier Coatings) using Zirconia (ZrO2). The processing will be by the process of thermal spray to plasma with laser treatment, as this process proved to be more efficient than without the laser treatment.

Studies have been done on the addictive air and heat transfer generators with the objective of designing a cooling system for the 14-X S vehicle, as the continuity of the work will depend on this information.

The next step of the work is to study the variables that are related to the vehicle's cooling system (thermal management system and thermal protection coating), with the objective of making a complete thermal protection system design for the Technological Demonstrator "scramjet"14-X S. Will be used numerical simulation to design the Thermal Protection System and Cooling system.

Therefore, with the success of the selection of structural materials and thermal protection and cooling systems of the "scramjet" 14-X S Technological Demonstrator, it will be possible to predict the atmospheric flight, placing Brazil also with a reference in the Research and Development of Hypersonic Aerospace Vehicles.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Assunção, T. L. de. Determinação Analítica do Aquecimento Aerodinâmico do Veículo Hipersônico Aeroespacial 14-X S.2014. 157f. Dissertação de mestrado em Propulsão Espacial e Hipersônica – Instituto Tecnológico de Aeronáutica, São José dos Campos.

Costa, F. J. Projeto Dimensional para Manufatura do Veículo Hipersônico Aeroespacial 14-X. 2011. 79f. Trabalho de Graduação - FATEC de São José dos Campos: Professor Jessen Vidal, 2011.

Costa, G. J.; Costa, F. J.; Coelho, B. L.; Laiton, S. N. P.; 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 Motor Scramjet do Demonstrador Tecnológico 14-X S.4to Congreso Argentino de Ingeniería Aeronáutica. Cordoba, Argentina, 2016.

Galvão, V. A. B. Análise Teórico-Analítica da Aerodinâmica do Demonstrador Tecnológico scramjet VHA 14-X B a 30km de Altitude em número de Mach 7. 2013. 52f. Trabalho de Conclusão de Curso – UNIVAP de São José dos Campos, 2013.

Glass, D. E. Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles. NASA Langley Research Center, Hampton, VA 23681, 2008.

Harsha, P. T., Keel, L. C., Castrogiovanni, E. A. e Sherrill, R. T. X-43AVehicle Design and Manufacture. In: AIAA/CIRA 13th International Space Planes and Hypersonic Systems and Technologies Conference, 2005 (AIAA 2005-3334), Capua, Italia. Anais… 2005. 9f.

Leite, S. F. O., Valéria. Caracterização do Escoamento de uma Bancada de Testes de Combustores Supersônicos Alimentada por Ar Viciado. 2006. 203f. Tese de doutorado – Instituto Tecnológico de Aeronáutica, São José dos Campos.

Limar, C. R. C. Revestimentos Para Barreira Térmica: Evolução e Perspectivas. 2014. Soldag. Insp. São Paulo, Vol. 19, Nº. 04, p.353-363.

Silva Junior, J. E.; Pinto, J. A. C. C. ; Rego, I. S. ; Toro, P. G. P. ; Minucci, M. A. S. ; Costa, F. J. .Seleção Preliminar de Materiais Estruturais e de Proteção Térmica para o Demonstrador Tecnológico "Scramjet" 14-X S para voo Atmosférico a 30 Km de Altitude e Velocidade Correspondente a Número de Mach 7. ABCM Newsletter, 2016.

Teleginski, V.; Chagas, D. C.; Vasconcelos, G. Modificação por Laser de Revestimentos para Palhetas de Turbinas Aeronáuticas Obtidos por Plasma Spray. In: V Simpósio de Ciência e Tecnologia do Instituto de Estudos Avançados, 2014, São José dos Campos. Anais do Simpósio de Ciência e Tecnologia do Instituto de Estudos Avançados, São José dos Campos: IEAv, 2014.

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