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PASSIVE THERMAL PROTECTION MATERIALS FOR HYPERSONIC AIRBREATHING FLIGHT VEHICLES

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Abstract. *Several research centers are designing aerospace vehicles for flight, in the Earth's atmosphere, at hypersonic speed, i.e., greater than five times the local speed of sound ($M > 5$), using airbreathing propulsion systems, based on supersonic combustion (scramjet technology). Aerospace hypersonic vehicles equipped with hypersonic airbreathing propulsion systems face extremely severe environments during the hypersonic flight in terms of thermal and aerodynamic loads. Thermal protection systems (TPS) and structural materials are the key techniques in hypersonic vehicle design. Hypersonic scramjet vehicles represent the future trends of access to space, passengers and merchandise transportations, and military (aircraft and/or weapons) applications, playing an important role in future aerospace hypersonic flight. From ballistic missiles and ballistic re-entry vehicles to hypersonic cruise and transatmospheric vehicles, flying within the Earth's atmosphere, it requires thermal protection systems and specific structures technologies. In those cases, leading edges can reach temperatures even higher than 2000°C (2273.15 K), thus special materials are necessary for their thermal protection. In general, ceramic matrix composites (CMC), ultra-high temperature ceramics (UHTC), and superalloys are applied in hypersonic vehicle designs. In the present article, an overview of TPS and thermal management techniques were briefly discussed, with focus on rocket and airbreathing vehicles, which are needed to stand the aerodynamic heating, consequently, support the aerodynamic loads. Additionally, a brief review of the carbon-carbon composites (C/C), and carbon-silicon carbide composites (C/SiC) applied as passive thermal protection were presented. The advantages and limitations of these CMCs for hypersonic vehicle structures were also discussed, which may be applied to leading-to-trailing edges for hypersonic scramjet vehicles.*

Keywords: *hypersonic vehicle, high-temperature, thermal protection, hot structure*

1. INTRODUCTION

Reentry Spacecrafts have been traveling hypersonically through the Earth's upper atmosphere as they decelerate from orbit, since the 1950s, including unmanned and manned vehicles from different countries. Those spacecrafts are designed to have blunt geometries with high drag shapes, minimizing the aerodynamic heating during the atmospheric reentry (Allen, 1958). On the other hand, sharp high-speed leading edges can be applied to a wide range of missions, including maneuvering hypersonic (cruise, trans-atmospheric) aircraft and ballistic missiles.

Sharp leading edges induce minimum drag, requiring lower thrust during ascent flight, achieving a higher cross-range during reentry, leading to larger reentry windows, but supporting severe aerothermodynamic loads (Böhrk et al., 2014). Both geometries – blunted bodies with high drag and sharp shapes with low drag—are used to design aerospace vehicles, whose flight velocity exceeds five times the sound speed, i.e., corresponding to $M > 5$.

The TPS is required to protect the internal structural materials and payloads of aerospace vehicles flying in hypersonic velocities. However, hypersonic vehicle design is an extremely challenging process involving not only high complexity geometries but also several strong coupled disciplines, such as aerodynamics, aerothermodynamics, control, avionics, navigation systems, propulsion, and structure.

Today, several research centers, including aerospace enterprises, are pursuing to design and construct an airbreathing atmospheric vehicle capable of sustaining hypersonic speeds more than five times the speed of sound. A hypersonic airbreathing cruiser flying at 3000 m/s (10800 km/h, Mach number $\cong 10$) would be able to reach halfway around the globe in about four hours or accelerate a rocket up to about 60 km of altitude, in about 15 secs, at $M \cong 10$.

Hypersonic airbreathing propulsion system using supersonic combustion (scramjet technology) is the one with the greatest potential, meeting the basic requirements of extremely high speed ($M \cong 5$), reliability, safety, and with relatively low cost (Heiser et al., 1994). Consequently, scramjets are the ones that have received the most attention in research by the scientific community and financial investment from development agencies in several countries, interested in mastering

new propulsion techniques applied to aerospace vehicles (Curran, 2001). Since the 1960s, several research centers have been creating programs to develop a hypersonic vehicle that includes a scramjet engine to demonstrate the supersonic combustion concept (Hallion, 1987).

In the mid-1980s, the U.S.A. National Aero-Space Plane (NASP) program was the first ambitious hypersonic aircraft project Single-Stage-To-Orbit (SSTO). It was a reusable multi-cycle propulsion system vehicle envisioned to take off from a conventional runway, using airbreathing propulsion to accelerate to hypersonic speeds, fly into space to achieve low Earth orbit, and return for a runway landing. NASP fuselage's lower front portion should operate as a shock wave compression ramp for air entering the scramjet engines. Its fuselage after portion was a single expansion ramp nozzle used to expand the exhaust flow for maximum engine thrust (Barthelemy, 1989; Chase, 1995).

In 2002, The University of Queensland (UQ), Australia, demonstrated the feasibility of the supersonic combustion concept in the HyShot 2 flight (Paull et al., 2005). In 2004, the two flights of X-43— burning hydrogen in about 10s at $M = 7$ and 10 (Marshall et al., 2005a; 2005b), and from 2010 to 2013, the flights of X-51 – burning hydrocarbon in about 140s (Rondeau and Jorris, 2013), provided by the new U.S. hypersonic strategy (after the NASP program), served to successfully demonstrate the supersonic combustion and gave a fresh renaissance in hypersonic technology. After the lessons learned with the test, The UQ and its partners are looking for the same goal as X-43 and X-51 aerospace vehicles programs, through the HIFiRE (Dolvin, 2008) and SCRAMSPACE (Tirtey et al., 2011) projects.

The efficient aero-thermal-structural design of a hypersonic vehicle may ensure good performance, increasing confidence in a successful flight, thereby mitigating risks during the flight testing. Engineering (analytical), numerical (CFD) and experimental (hypersonic devices) methodologies may be applied to the scramjet aerodynamic design, considering fuel (hydrogen)-air combustion, and promoting dynamic analysis of efficient use of hydrogen as a fuel, as well as refrigerant to actively cool the fuselage. Airbreathing hypersonic vehicles are designed with slender sharp leading edges, which promote high thermal loads and consequently high thermally induced stresses. Thus, thermal-structural analysis is one of the most important design parameters in the design of hypersonic vehicles.

Rocket-powered space vehicles minimize their trajectories through the atmosphere. However, scramjet flies through the Earth dense atmosphere (up to 60 km altitude) from subsonic to orbital speeds, in the dynamic pressure trajectory suitable to minimize structural loads and take advantage of the use of air as an oxidizer. Basically, scramjet is a fully integrated airbreathing aeronautical engine, with no moving parts, that uses the oblique/conical shock waves generated during the hypersonic flight, to provide compression and deceleration of freestream atmospheric air at the inlet of the scramjet, which are pushed to combustion chamber. 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 (combustor). Right after, both oxygen (from the atmospheric air) and onboard hydrogen fuel are mixed. The combination of the high energies of the fuel and of the oncoming supersonic airflow starts the combustion at supersonic speed. Finally, the divergent exhaust nozzle at the afterbody vehicle accelerates the combustion products, providing thrust. Due to the long time in the atmosphere in hypersonic flight, the structural materials are submitted to high temperatures, because the kinetic energy is a function of squared speed. Therefore, refractory composites, metal matrix composites, and super alloys resistant to extremely high temperatures are the materials used for the successful flight of hypersonic vehicles.

Passive, semi-passive and active thermal management are, commonly used to deal with those severe thermal environments, and to cool down hypersonic vehicles. Passive thermal management, such as thermal radiation (insulated for relatively short times, and heat sink structures for moderate short times) and phase change materials, is an efficient thermal management system that can be used effectively on ballistic flight trajectories such as the fundamental science scramjet flight experiment. For longer times and high heat fluxes, a semi-passive approach may need to be utilized. For high heat fluxes and for long times, heat pipe is used to transfer by a working fluid to another heat pipe region where the heat is radiated away, and for a single use for extremely high heat fluxes, and for relatively short times, ablation is used to keep the structure cool. For higher heat fluxes and for long times, active convective cooling is required, in general at the propulsion systems. Film cooling (operates as a thin, cool, insulating blanket and is injected into the flow, usually at an upstream location and at a single, discrete location), and transpiration cooling (the coolant is injected into the hot gas flow through a porous structure continuously over large areas). In both film and transpiration cooling the structure will reach high temperatures and operate hot (Glass, 2008; Dong, 2019).

Following the general aspects of scramjets previously reviewed, important demonstrators built worldwide are presented. The main materials applied in their structure and their thermal management systems are emphasized and aerodynamical and thermal fluxes are analyzed. Finally, considering the aspects revised, the properties of materials applied for passive thermal protection on scramjets are discussed.

2. SUPERSONIC COMBUSTION DEMONSTRATORS

Upon comprehension of the working conditions, such as flight velocity, thermal loads, atmosphere, and gas ionization, it is possible to design adequate equipment for hypersonic flights, thus the selection of adequate materials is made. Several demonstrators' projects of different organizations, along with their flight conditions and main materials applied are presented.

The HyShot Flight Program, from The UQ was designed to demonstrate the supersonic combustion in flight and to validate pressure measurements made in the T4 UQ Shock Tunnel. The flight was undertaken in 2001, and supersonic combustion was achieved in flight for approximately five seconds during the descendent trajectory.

The HyShot was assembled as a payload of the second stage Orion rocket engine. A nose cone was used to cover the frontal section, to protect the payload and to provide a well-defined aerodynamic shape during the ascent flight. The two-stage rocket engine was used to boost the payload (HyShot) to an apogee of approximately 315km. However, after the second stage burned out and, at approximately 100km altitude, the nose cone was ejected. The HyShot with the second stage attached fell back to Earth, gathered speed, and between 37km and 23km, they were travelling at $M \cong 7.6$, thus measurements of supersonic combustion were made. The gradient temperature across 12 mm copper plate combustion chamber walls, used to dissipate the unsteady aerodynamic heating, provided a difference of 80 °C between the inner and outer surfaces, towards the end of the flight. No active cooling was used (Paull et al., 2005).

In 2004, NASA promoted two X-43 flights with supersonic combustion technology as airbreathing propulsion system. The X-43 reached $7 < M < 10$. Basically, the X-43 structure was made of steel, titanium, and aluminum longerons and bulkheads with steel and aluminum skins (Fig. 1). Steel material was selected based on vehicle stiffness requirements, and titanium aft bulkhead, in thermal requirements. The frontal section was a massive solid wedge of tungsten, necessary for vehicle balance, where the leading-edges of the fuselage was thermally protected by a carbon-carbon composite, which wrapped around the sides of the tungsten to form chines (Fig. 1).



Figure 1. X-43 structural and thermal protection materials (Harsha et al., 2005).

The upper and lower surfaces used alumina-enhanced thermal barrier ceramic tiles. The horizontal and vertical tails were hot structures (Haynes nickel-steel alloy) and were thermally protected only along their leading edges. For the $M = 7$ vehicle, the horizontal surfaces only were protected by C/C inserts, whereas for the $M = 10$ vehicle, the C/C protected both the horizontal and vertical surfaces. The engine was made of heat-sink copper alloy (Glidcop) and incorporated active water cooling of its cowl and sidewall leading edges (Harsha et al., 2005). Thus, high-temperature materials were employed in the fabrication of the hot structural components (with no thermal protection system), like the X-43 nose, horizontal tail, and vertical tail, to withstand the high temperatures and high thermal stresses (Fig. 2). Thermocouple instrumentation in these hot structures recorded the flight thermal responses (Leonard et al., 2005). The X-43 project is considered a legacy from the early project X-30 airbreathing hypersonic vehicle, from NASP USA, that was made of advanced heat-resistant materials. Its nose cone (leading edge), wings and trailing edges, and combustor chamber internal walls were actively cooled. Titanium-based alloys and metal matrix composites were developed and integrated into new structural components of the vehicle and were extremely lightweight and of high strength at high temperatures (Gao, 1998).

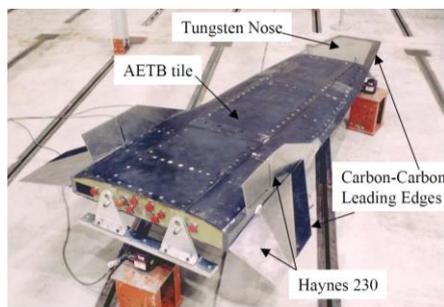


Figure 2. Hot structures components (Leonard et al., 2005).

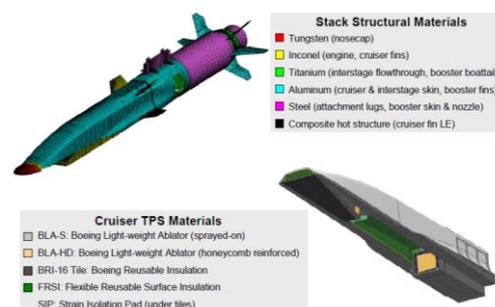


Figure 3. X-51 structural and thermal protection materials for the stack and cruiser vehicles (Hank et al., 2008).

The X-51A Scramjet Engine Demonstrator-waverider vehicle was the flight demonstration of JP-7 hydrocarbon fuel-cooled supersonic combustion, and the vehicle was expected to reach from $M = 6$ to 6.5, in a series of four flight tests beginning in August 2009. Conventional metals for the basic structure covered with lightweight thermal protection systems (BLA-S sprayed on upper surface) foam and (BRI-16) tiles (like used on portions of the space shuttle underside) were used in areas like the chine, where a sharp leading edge was desired, and for the inlet ramp (Fig. 3).

The internal airframe and bulkheads were made from machined aluminum. A tungsten nose cap, covered with silicon dioxide thermal barrier coating was used for the high heat loads at the nosetip and as ballast for longitudinal stability. The skin of the cruiser and interstage were made of aluminum, as the four movable off-the-shelf fins on the booster. Inconel nose cap adapter was used to prevent thermal conduction to the rest of the vehicle. The scramjet engine was constructed of thin-walled Inconel panels, which were fuel-cooled, and the four moveable cruiser fins were also Inconel with carbon-carbon composite hot structure leading edges. On the interior of the X-51 nozzle, a honeycomb-reinforced, BLA-HD, was used to protect the hot combustion products from the combustion chamber (Hank et al., 2008).

On May 1st, 2013, the fourth and final X-51A flight traveled more than 426 km, during 210 s, burning hydrocarbon fuel, reaching $M = 5$, demonstrating the feasibility of an airbreathing scramjet-powered vehicle boosted to required conditions and could sustain supersonic combustion during autonomous flight operations. Standard aerospace materials such as aluminum, steel, Inconel, and titanium were used as expected. The leading edges contained C/C composites and silica-based TPS, were used like Boeing reusable insulation tiles (Rondeau and Jorris, 2013).

The Hypersonic International Flight Research and Experimentation (HIFiRE) is a joint program developed by the US Air Force Research Laboratory (AFRL) and the Australian Defense Science and Technology Organization (DSTO). Started in 2006, the program was created to perform experimental tests and gather data about the propulsion phenomena and technologies deemed critical to practical and efficient hypersonic flight. One of the investigated areas, aerodynamic heating is the main challenge for the airbreathing hypersonic vehicles, and for the HIFiRE 8 the use of ablative materials was appropriate. For the scramjet combustor, there are several composite contenders. Carbon-carbon leading edge design was developed (Bowcutt et al., 2012).

Most of the HIFiRE flights were planned to use a ballistic sounding rocket trajectory approach, conducting the supersonic combustion experiment during the reentry to the atmosphere at extremely high flight path angles, with the scramjet remained attached to the second stage booster, similarly to the HyShot flight. On the other hand, the HIFiRE 8 vehicle (Fig. 4) was intended to fly at $M = 7$, powered for 30 s at approximately zero flight path angle. Generally, the scramjet combustion chamber has actively cooled metallic structures. However, due to the high-temperature capabilities, the CMCs have the potential to provide an option for at least a portion of the flowpath. Due to the relatively short flight test time (~ 30 s) and the single use of the HIFiRE 8, a scramjet combustor constructed using a passive CMC material was considered. Thus, flat panels of the DLR carbon/carbon-silicon carbide (C/C-SiC) were tested in the NASA Langley Direct Connect Supersonic Combustion Test Facility (DCSCTF) using the durable combustor rig (DCR). In addition to the C/C-SiC, the DLR C/C material was also tested (Glass et al., 2014).



Figure 4. HIFiRE 8 flight vehicle (Glass et al., 2014).

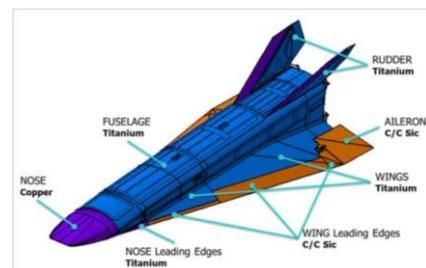


Figure 5. Material composition for Hexafly Experimental Flight Test Vehicle (Steebant et al., 2018).

The High-Speed Experimental Fly Vehicles International (HEXAFLY-INT) is the first international civil high-speed transportation vehicle project. It gathers partners from Europe Community (ESA, CIRA, DLR, ONERA, AIRBUS, TET, TSD, GDL, Marotta, University of Stuttgart, Von Karman Institute), from the Russian Federation (TsAGI, CIAM, LII and MIPT), and from Australia (The University of Sydney, University of New South Wales/UNSW, The University of Queensland). Both a glider (Europe Community) and a hydrogen-propelled variant of the high-speed vehicle (Russian Federation) are being considered. The overall objective is to flight-test an experimental waverider-based vehicle concept to verify the high cruise efficiency of a potential civil passenger hydrogen fueled high-speed vehicle ($M > 7$) during a free-flight. In parallel, the concept will be a flight at low speed to prove that the waverider concept is able to take-off, accelerate to subsonic speed, and land in an efficient and robust way (Carandente, 2016). A sounding rocket will be applied as flight platform to test out breakthrough technologies. One of the most critical challenge is to identify and test high-temperature materials and hot structures under realistic conditions, such as high temperature lightweight materials, cooling concepts, and reusability aspects. The metallic structure of the glider vehicle (fuselage, wing, and vertical tail) will be composed of titanium alloy, apart from the copper nose section. Wing leading edges and ailerons are in C/C-SiC

(Fig. 5). The metallic exposed surface parts are thermally protected by high emissivity or ZrO_2 coatings (Steelant et al., 2018).

3. THERMAL STRUCTURAL MATERIALS FOR THE UFRN HYPERSONIC AIRBREATHING VEHICLES

The aerospace vehicles from deep space mission (Moon, Mars) or from Earth orbit (ISS) travel through the Earth's atmosphere at escape velocity or at orbital velocity, respectively, obeying the constant dynamic pressure trajectories. The lessons learned from the space shuttle reentry, to prevent the excessive structural forces and drag, or too large wing area for sustained hypersonic atmosphere flight emphasize that the dynamic pressure cannot be too large or too small. Also, to generate adequate thrust to reach and sustain high speed flight, the hypersonic airbreathing (scramjet) vehicles must fly at Earth's dense atmosphere to capture and process the surrounding air (Araújo et al., 2020). Therefore, Heiser and Pratt (1994) presented the ideal trajectories of the scramjet flight into Earth's dense atmosphere, based on the constant dynamic pressure trajectory and the freestream mass airflow per unit area (Fig. 6).

A two-dimensional generic hydrogen-powered scramjet was designed at the Universidade Federal do Rio Grande do Norte (UFRN), using an engineering approach, to demonstrate the supersonic combustion during atmospheric flight, from the flow of atmospheric air (at supersonic speed) with hydrogen, when the scramjet vehicle is at 2050 m/s (Mach number 6.8) at an altitude of 30 km (Fig. 7) (Toro et al., 2018a; 2018b).

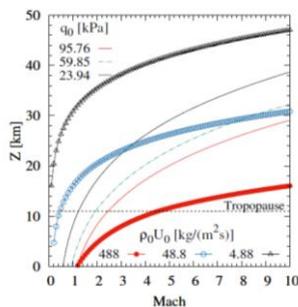


Figure 6. Constant dynamic pressure and freestream mass airflow per unit area (Araújo et al., 2020).

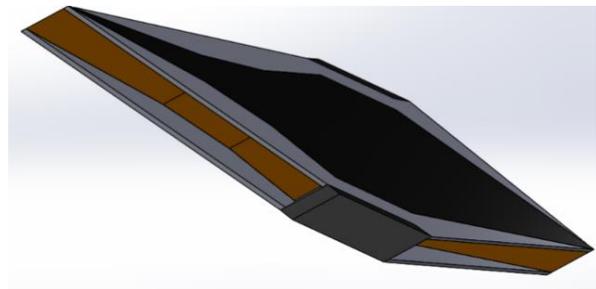


Figure 7. Generic supersonic combustion (scramjet) demonstrator (Carneiro, 2020).

The exchange of energy between any solid structural material and the environment atmosphere happens due to a temperature gradient and involves the three basic forms of heat transfer: conduction, convection, and radiation. The temperature distribution influences appreciably the material properties such as modulus of elasticity and the coefficient of thermal expansion. Therefore, thermo-structural analysis must be developed to support both thermal and aerodynamic loads.

Considering the UFRN generic scramjet (Fig. 7) flight conditions, 30 km of altitude at 2050 m/s ($M = 6.8$), the aerodynamic heating was estimated. The scramjet inlet leading edge was blunted with a 1 mm radius, establishing a normal shock wave considering the hypersonic velocity of 2050 m/s ($M = 6.8$). A cold-wall heat flux was determined by assuming that the wall temperature remained constant at 300 K. Fay and Riddell (1958), assuming a Lewis number of one, and Lees (1956) theories were applied to the stagnation point and the cylinder section of the blunt body geometry, respectively. The aerodynamic heating at the stagnation point was about 4.4 MW/m^2 , and at the cylinder section the aerodynamic heating presented a senoidal behavior and at the intersection of the cylinder section and the first ramp deflection the aerodynamic heating was about 197 kW/m^2 (Toro et al., 2018c).

The thermal analysis was developed considering isotropic material thermal properties (Inconel 718, tungsten, titanium alloy and copper alloy) (Tab. 1), used in some supersonic combustion demonstrators (HyShot, X-43, X-51).

Inconel and Copper Alloy presented temperatures at the external surfaces higher than the (lower) temperature of, the respective, material melting point of 1533 K and of 1356 K. On the other hand, Titanium Alloy presented a good thermal response, since the distribution was always lower than the Titanium Alloy melting point (Tab. 1).

Considering that the wedge was composed of Tungsten and Inconel 718, the maximum temperature is 1398.4 K and the minimum temperature is 860.7 K. Note that, in this case, the maximum temperature of 1338.4 K on the Inconel 718 was lower than the material melting point (1533 K) (Fig. 8). Finally, applying 0.5 mm of thermal barrier coating based on alumina, at titanium and Inconel 718 materials (Fig. 9), the maximum temperature was about 1399 K (on Titanium) and at Inconel 718 the external temperature decreased with the minimum temperature of about 858 K (Toro et al., 2018c).

Table 1. Thermal properties of isotropic materials (Toro et al., 2018c).

Material	Coefficient of thermal expansion ($\mu\text{m} / \text{m}\cdot^\circ\text{C}$)	Specific Heat ($\text{J}/\text{g}\cdot^\circ\text{C}$)	Thermal Conductivity ($\text{W}/\text{m}\cdot\text{K}$)	Melting Point (K)	Emissivity	Temperature(K)	
						Maximum	Minimum
Inconel 718	13.0	0.435	11.4	1533-1609	0.85	1587	887
Copper Alloy	24.8	0.385	400	1356	0.66	1459	1242
Titanium Alloy	8.90	0.528	17.0	1923-1933	0.63	1546	965
Tungsten	4.40	0.134	117	3643	0.15	-	-

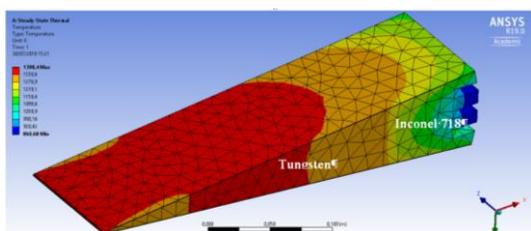


Figure 8. Temperature field over scramjet configuration at the blunted region using Tungsten and Inconel 718 (Toro et al., 2018c).

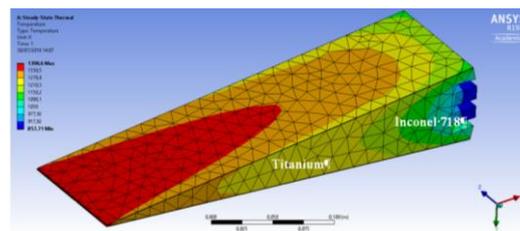


Figure 9. Temperature at external surface material using Titanium and Inconel 718, both with 0.5 mm Alumina (Thermal Barrier Coating) (Toro et al., 2018c).

Due to fuel (hydrogen)-air combustion, the maximum surface temperature occurs in the combustion chamber. Considering viscous effects, the static temperature and the airflow velocity (Mach number) at the entrance of the combustion chamber is 1210 K and 1494 m/s ($M = 2.14$), respectively, and one-dimensional (Rayleigh) flow with heat addition, the velocity, after the combustion, is supersonic ($M = 1.2$), the hydrogen-air spontaneous combustion temperature was about 2300 K, the scramjet trailing-edge velocity was about 2350 m/s, higher than the flight velocity of 2050 m/s, generating a positive uninstalled thrust of 319,22 N (Carneiro, 2020). For the combustion chamber section, hot materials should be applied.

4. THERMAL FLUX ON HYPERSONIC AIRBREATHING VEHICLES

For a hypersonic airbreathing vehicle, the aerodynamics, propulsion system, and airframe (structures), including much of the TPS and hot structures, are highly integrated (Fig. 10), where the entire under side of the vehicle is part of the propulsion system. In general, the realistic hypersonic airbreathing vehicles (HIFiRE 8 and Hexafly) are being designed, for low drag slender bodies with low thickness to chord ratio, to take-off horizontally, from the conventional airport, fly at high dynamic pressure (Fig. 6), accelerate and cruise (with high heat loads) in the dense atmosphere, to capture the air for the combustion chamber (engine). Due to different materials attached at various components (tank, insulation, structure, TPS) and operating at a wide range of temperatures (large thermal gradients), the thermal structure for a hypersonic airbreathing vehicle is challenging.

Typical ascent leading-edge heat flux for a SSTO vehicle shows the thermal levels encountered during a hypersonic flight (Fig. 10). Aerodynamic heating (heat flux) is inversely proportional to the squared root of the radius. The nose (small radius) leading-edge flux is about 5000 Btu/ft²-sec (56732.1 kW/m²), while the wing (larger radius, with 1-inch, 25.4mm, radius) leading edge heat flux is ~500 Btu/ft²-sec (5673.2 kW/m²), and the cowl (due to a Type IV shock-shock interaction) leading edge maximum heat flux is ~50,000 Btu/ft²-sec (567321.4 kW/m²). For comparison, for the Space Shuttle Orbiter the maximum heat flux at the wing leading edge was approximately 70 Btu/ft²-sec (794.4 kW/m²) and for the re-entry capsules Apollo/Crew Exploration Vehicle (Orion) heat shield maximum heat flux was expected to be ~700 Btu/ft²-sec (7944 kW/m²). Also, the passive nose leading-edge for the X-43 $M = 10$ scramjet vehicle was designed to reach nearly 4000°F (2478 K) during the short 130s flight (Fig. 11) (Glass, 2008).

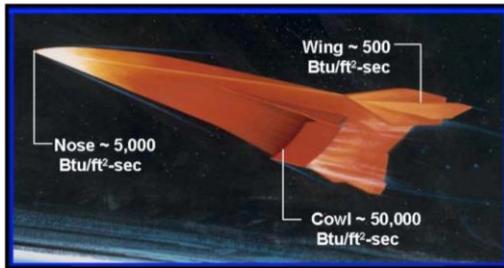


Figure 10. Typical ascent leading-edge heat flux for a SSTO vehicle (Glass, 2008).



Figure 11. C/C leading edge architecture for X-43 (Glass, 2008).

The hypersonic airbreathing vehicles require high temperature materials, with capability (2000 to 4000 °F, 1366 to 2478 K), high specific strength at elevated temperature, high toughness, light weight, and environmental durability. Metallic Matrix Composites (MMC), super alloys, and titanium have good specific strength, but it drops off by the 2000°F (1366 K) range. CMCs, such as C/SiC material, Advanced Carbon/Carbon (ACC), and SiC/SiC provide high strength at elevated temperatures which are key for hypersonic airbreathing vehicles.

5. THERMAL-STRUCTURAL MATERIALS FOR THE UFRN HYPERSONIC AIRBREATHING VEHICLES LEADING EDGES

As discussed, the surface of hypersonic airbreathing vehicles is subjected to high aerodynamic heating due to the friction of the atmospheric air when operating (Glass, 2008; Zhu et al., 2018). Thus, the material mechanical properties must withstand high dynamic loads at high temperatures. In addition, with the high thermal shock, that is, a sudden increase in temperature and pressure, many materials break and fracture, so the property of resistance to thermal shock is also desired (Mouritz, 2012). The regions exposed to these effects are the leading edges of the hypersonic airbreathing vehicle. Their volumetric stability at high temperatures is desired, maintaining the vehicle aerodynamics stable (Glass, 2008). Thus, the low coefficient of thermal expansion is an important property to be considered. Also, in hypersonic vehicles, materials must allow their manufacture in sharp leading edges, inducing minimum drag and decreasing aerothermodynamic loads (Böhrk et al., 2014). However, many ceramic materials that withstand high temperatures also have high fragility, which does not allow certain geometries to be carried out. Although the volume and geometry are important characteristics, the density of the materials applied in crafting a hypersonic vehicle is another essential property. Thus, low-density materials are preferable. Finally, oxidation resistance under high temperatures is required, allowing the material's longer life. It should be noted that under hypersonic speeds and high temperatures the dissociated atmospheric gas species are highly reactive. (Van Wie et al., 2004; Fahrenheitz and Hilmas, 2017).

For most of the described properties required for scramjets structural materials, the ultra-high temperature ceramics (UHTCs) and CMCs are presented as adequate options for crafting leading edges. They act as passive thermal protection systems, that undertake temperatures higher than 1900K (Glass, 2008; Dong, 2019). Special attention is given to the C/C composite, and the necessity for the C/SiC is explained.

UHTCs are defined as compounds with melting points higher than 3273K. Usually belonging to the group of borides, carbides e nitrides, these ceramics also present higher hardness compared to other ceramics and good geometric stability at high temperatures. Some examples of UHTCs are TaC, HfC, NbC, TaN, and HfB₂ (Fahrenheitz and Hilmas, 2017). Besides the high melting points, the UHTCs present challenges when applied to hypersonic vehicles. The main disadvantages on their application are the high density of these materials (resulting in weight limitations), low thermal shock resistance (fracturing under high thermal shock loads), and low fracture toughness (Glass, 2011).

Alternatively, CMCs present high fracture toughness, low thermal expansion, and high strength at high temperatures and pressures. CMCs are defined as materials containing distinct phases: a continuous ceramic matrix and a dispersed phase of reinforcements shaped as fibers, whiskers, or particles (Alves et al., 2016).

The C/C are lightweight composites that can withstand temperatures above 3273K, in non-oxidative atmospheres, while maintaining great mechanical properties. For example, according to Bansal and Lamon (2015) and Alves et al. (2016), when produced with alternated layers of unidirectional fibers and carbon blankets, C/C can have a specific strength of 160 MPa/g.cm³ at 2273K, greater than conventional ceramics. Besides, a fiber C/C presents higher mechanical properties along the fiber axis, due to its anisotropic characteristics, depending also on the way it was produced and on the fiber density and its arrangement inside the carbon matrix. The C/C also has excellent thermal shock resistance, ideal for hypersonic vehicles in extreme conditions, and low thermal expansion (Mouritz, 2012).

Even though C/C presents high-temperature sublimation (~ 4000K) in an oxidizing environment, its oxidation happens at 723 K. Thus, the protection systems, such as external layers, are necessary to reduce the deterioration of the material, increasing its lifetime (Glass, 2008; Krenkel, 2005). Examples of protective coatings are SiC, HfC, and ZrC (Van Wie et al., 2004). For instance, layers of the UHTC HfC (melting point of 3900K), oxidize at 773K, producing a refractory oxide (non-passive), the HfO₂, with a melting point of 3083K (Verdon et al., 2014). Differently, the SiC coating (melting point

of 3100K) is usually desired when the oxygen present in the high-temperature atmosphere is abundant, allowing the production of SiO_2 , a protective and passive layer, that maintains its effectiveness up to 2573K. However, at high temperatures with a low oxygen ratio, the volatile SiO gas is developed (Roy et al., 2014). Moreover, to amplify the stability of the layers, multilayers of different protective coatings are also produced. In this sense, the favorable properties of the carbon fibers are often applied in a SiC matrix instead of a carbon matrix, obtaining a C/SiC ceramic composite, that can operate at higher temperatures in oxidative environments (Alves et al., 2016; Krenkel, 2005).

Lastly, the general properties of the composite ACC were compared to other materials commonly applied in aerospace engineering. Those materials are metals and metallic alloys (Ti, TC4 or Ti-6Al-4V, Inconel 718 and W, usually applied in scramjets body parts), UHTCs (TiC, HfB_2 , TaC, and HfC), and the silicon carbide (SiC). The following graph (Fig. 12) shows the properties of melting point, oxidation temperature, density, and coefficient of expansion. The materials are organized according to their density.

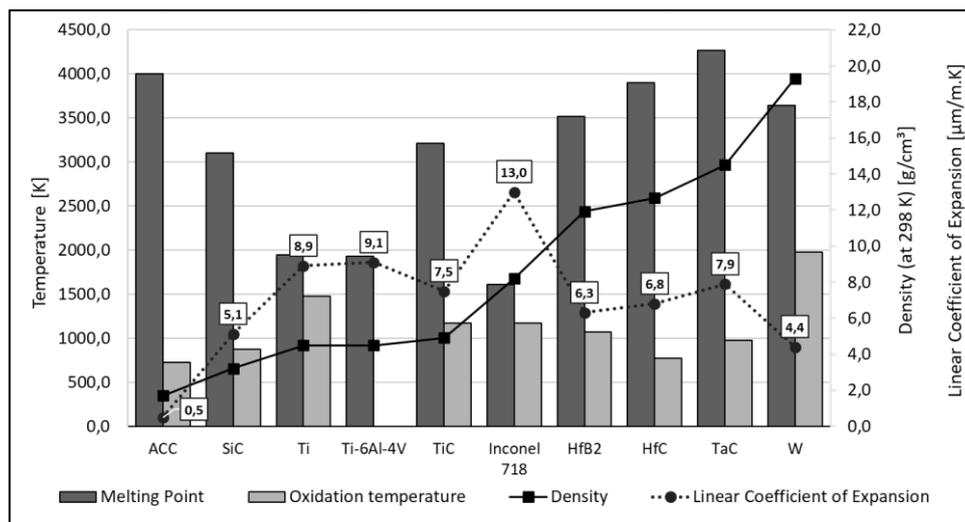


Figure 12. Materials properties graph – melting point, oxidation temperature, density, and linear coefficient of expansion (Parmar et al., 2019; Dey and Mehta, 2020; Greene and Finfrock, 2000; Lassner and Schubert, 1999; Alves et al., 2016; Tolias, 2017; Roy et al., 2014; Toro et al., 2018c; Van Wie et al., 2004; Verdon et al., 2014; Weimer, 1997).

6. CONCLUSION

The ability to build and fly the hypersonic airbreathing vehicles successfully depends on the ability to use passive, semi-passive, and active thermal management techniques. These techniques are commonly used to deal with the severe thermal environments, and to cool down and to protect the internal structural materials and payloads of hypersonic airbreathing vehicles flying at high dynamic pressure trajectories in hypersonic velocities, with high aerodynamic heating loads (at $M > 5$ velocities), into the dense Earth atmosphere, to capture the airflow needed to burn the fuel (hydrogen).

The lessons learned from the thermal protection systems and hot structure materials has been used in the modern supersonic combustion demonstrators: HyShot (designed by Undergraduate, Graduate and Professors from The University of Queensland), X-43 (developed by NASA), X-51 (a missile designed by the US Air Force) and HIFiRE 8 (a joint program in development by the US Air Force Research Laboratory/AFRL and the Australian Defense Science and Technology Organization /DSTO). These new hypersonic airbreathing vehicles based on the hydrogen fueled high-speed technology are being designed for civil passenger purposes.

In the Graduate Program in Material Science and Engineering, at UFRN (Natal/RN, Brazil), researchers are studying the carbon-carbon composite and carbon-silicon carbide composite for aerospace applications, specifically the leading-to-trailing edges of hypersonic airbreathing vehicle components, such as nose cone and nozzle.

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