Challenges of Hypersonic Travel

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Abstract

Hypersonic travel has the potential to revolutionize aviation as it can drastically reduce travel time for long distances, making global and interstellar travel more efficient. When reaching hypersonic speeds without proper thermal protection systems (TPS), the aircraft's interior could reach 3000 to 5000 degrees Fahrenheit, frying both any electrical systems and passengers on board. This paper will review essential design elements such as materials, heat management systems, and drag profiles, which will help manage the extreme heat within hypersonic vehicles. Materials are vital in reducing weight, increasing fuel efficiency, and resisting external heat, all of which are factors in improving TPS. Heat management systems are also crucial as aircrafts need to cool down the internal heat their engines produce. Making an aircraft design with as little drag as possible is essential for TPS as it reduces heat caused by friction. This paper will identify challenges and future steps for TPS designs.

Introduction

In the evolving landscape of transportation, speed and efficiency have always been a driving factor in development. Despite the continued advancements in traveling technology, the concept of hypersonic travel is still an obstacle waiting to be conquered. Hypersonic travel, defined as achieving speeds greater than five times the speed of sound (Mach 5) or 6,174 kilometers per hour (3,836 miles per hour), holds the promise of revolutionizing how we travel the globe. Hypersonic speed's potential for rapid intercontinental travel presents many opportunities through shortening travel times by flights worldwide. For instance, a flight from New York to London in a Boeing 737 would take 7 hours, while a flight in a hypersonic vehicle would only take 2 hours [6].

As air travel continues to be the backbone of international connectivity and trade, reducing flight durations can bring transformative benefits. According to the International Air Transport Association (IATA), the global aviation industry is projected to double by 2037, with passenger numbers expected to reach 8.2 billion annually [4].

Fig. 1. All the flights on Thanksgiving day November, 2018. (Medium, ImageSource). The number of planes in the sky can cause air traffic to soar. The imperative to innovate becomes increasingly urgent as the skies become congested. Quicker flights allow more planes to take off and land on time, reducing the number of planes in the air.

Despite its need, there are struggles in achieving hypersonic speed, including aerodynamics, identifying best-suited materials, and thermal protection systems (TPS). Reaching hypersonic speeds generates massive amounts of heat, which must be offset to protect the pilot and any computer systems on board. With aerodynamic design considerations, planes can limit the amount of heat produced. The most effective materials will reduce stress on engines and withstand the harsh conditions of hypersonic flight. TPS cools planes, actively getting rid of any heat that is being produced. There are three primary considerations for designing TPS in hypersonic vehicles: aerothermodynamics and passive thermal protection, active thermal protection, and materials and designs.

Aerothermodynamics and Passive Thermal Protection

The aerothermodynamics of hypersonic vehicles pose significant challenges; when the vehicle's speed increases, the temperature does as well [3]. At Mach 5, the temperature on the outside of the vehicle can range from approximately 1,200–1,500°C; at Mach 10, these temperatures are approximately 2,000–3,000°C; and at Mach 15, these temperatures are approximately

3,500–4,500°C. Incredibly high temperatures put pilots and the technology within the vehicle at risk. Simultaneously, computational fluid dynamics (CFD) simulations utilize advanced modeling techniques to analyze complex aerothermal interactions. This two-step approach significantly allows for a comprehensive understanding of the aerodynamic heating associated with hypersonic flight as Mach numbers, the ratio of the aircraft's speed to the speed of sound, rapidly increase.

The paper by Tung Le et al. [5] investigates the role of thermal protection systems (TPS) in hypersonic vehicles, aligning with the challenges highlighted in aerothermodynamics research. The study covers structural and material design, thermomechanical performance, and manufacturing methods for TPS, aiming to meet the demands for low-cost reusable launch vehicles. It emphasizes the significance of effective TPS in managing aerodynamic heating during hypersonic flight, stressing the necessity for lightweight and efficient solutions. The review by Glass discusses various types of TPS and their required materials, offering insights into temperature gradients, deformation limits, and mechanical strengths. He highlights eight forms of TPS [1].

Category	Types and definition	Temperatures Ranges	Energy Consumption
Passive TPS	**Insulated Structures**: Insulates vehicle against heat using materials with high-temperature durability. They can manage moderate temperature gradients with low deformation and have moderate mechanical strength.	Up to 1,500°C	Negligible energy consumption because it relies on materials with high-temperature resistance for insulation.
	Heat Sink Structures: Absorbs and dissipates heat within the vehicle, effectively handling high-temperature gradients. They face low deformation and have high mechanical strength.	Up to 1,500°C	Low energy consumption because of the initial heating and cooling cycle.
	Hot Structures: Can withstand extreme temperatures using high-temperature alloys on the outside of the vehicle and are directly exposed to high gradients. They face minimal deformation and have very high mechanical strength.	1,500°C to 2,500°C	Negligible energy consumption because it depends on alloys with high-temperature resistance.
Semi-passive TPS	**Heat Pipes**: Transfer heat through a phase change. They efficiently manage	Up to 1,200°C	Moderate energy consumption

	temperature gradients with minimal deformation and high mechanical strength.		because of the usage of the phase changed material.
	Ablation: Absorbs heat through material consumption, handling high gradients with designed erosion. They face high deformation due to the temperatures they face and have sufficient mechanical strength for single use.	Up to 3,000°C	No active use of energy but energy is consumed in the material's degradation process.
Active TPS	**Convective Cooling**: Removes heat using fluid flow and is highly effective at managing temperature gradients. It faces minimal deformation, and its mechanical strength is dependent on the integrity of the coolant used.	1,500°C to 2,500°C	High energy consumption to circulate coolant fluids.
	Film Cooling: Applies a thin coolant film on surfaces, providing localized cooling with moderate gradient management. It faces minimal deformation and has moderate mechanical strength.	1,500°C to 2,500°C	High energy consumption to pump and distribute the coolant.
	Transpiration Cooling: Pumps coolant through a porous material to form a protective film on the surface. It minimizes deformation and relies on the integrity of the coolant and porous material for mechanical strength.	1,500°C to 2,500°C	High energy consumption to pump coolant onto the surface. [1]

These different models of TPS provide for a range of uses in hypersonic vehicles. For example, ablation can function effectively even at extremely high temperatures, so it is used on the bottom of reentry vehicles that come from space. As the vehicle re-enters Earth's atmosphere, the friction causes the bottom of the vehicle to reach up to 1477°C, offset by the bottom's disintegration [9]. Film Cooling is also widely used in aerospace. Rocket engines and gas turbines can reach lethal temperatures if not adequately cooled. By applying a thin coolant film, engines and turbines can prevent extreme temperatures [1].

Additionally, it outlines future research directions and challenges in advancing TPS technology for space exploration. Vehicles that utilize TPS effectively are able to better retain their longevity and safety. An efficient TPS refers to a system that removes as much heat as possible while using as little energy as possible. The energy produced by TPS is partially transformed into heat, so an efficient TPS must use as little energy and heat as possible while maximizing heat removal.

There is a limit to the effectiveness of passive thermal protection systems, such as tiles, as shown by Huang and Yao [3]. The amount of heat that can be resisted is limited. However, passive cooling's ability to resist heat provides a cheaper option up to a temperature and heat flux limit without being destroyed, as shown in Figure 2. Figure 2 shows various TPS options and the effect of heat on them. Passive cooling methods can only be used after a specific temperature has passed. In systems using both active and passive thermal protection, the more heat resisted, the less strain was put on the active thermal protection since there is less heat to dissipate. These systems face challenges adapting to the extreme thermal environments encountered during hypersonic flight. Issues like thickness and temperature resistance limitations underscore the necessity for innovative and adaptive solutions in thermal protection. If the metal on the aircraft's outer surface is too thick, it protects the insides but reduces its ability to fly quickly and stresses the engine due to the added weight. If the metal on the aircraft's outer surface is too thin, it fails to protect the insides, making them burn up far too fast. There is a need for continued research and development efforts in the field, aiming to overcome the shortcomings of current systems and enhance the overall thermal protection efficiency.

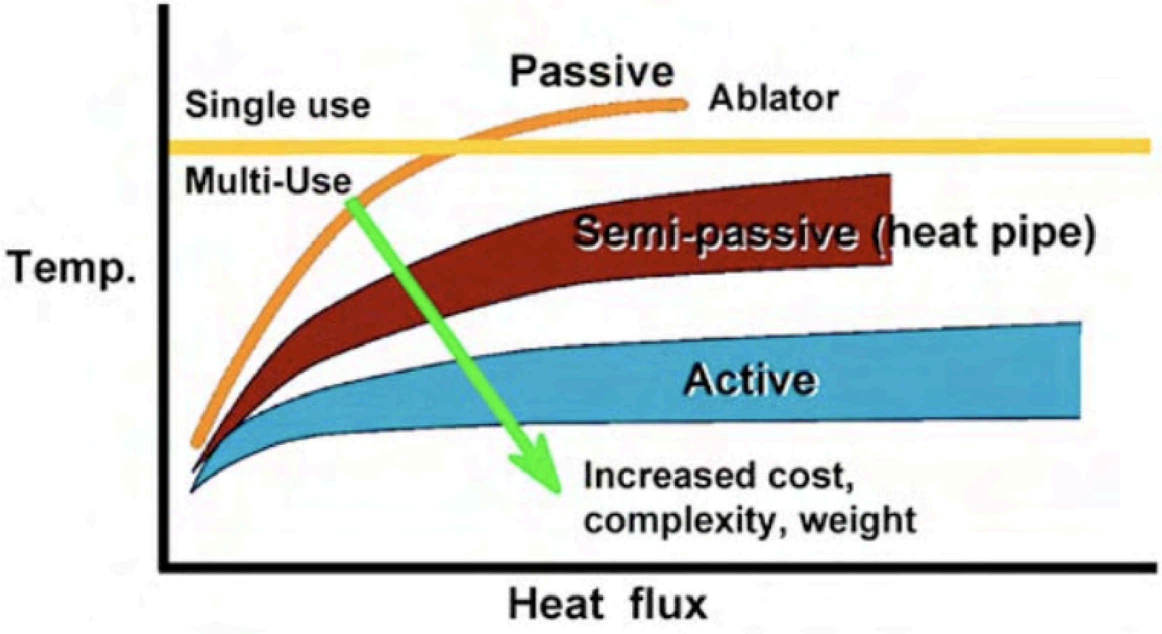

Fig. 2. A graph comparing different thermal protection methods using temperature and heat flux [1].

Challenges Faced in the Martian Atmosphere

The Martian atmosphere presents unique aerodynamic heating challenges for hypersonic vehicles. The research done by Yang et al. combines experimental methods and computational fluid dynamics (CFD) with a finite-rate thermochemistry model to analyze the impact of surface thermochemistry on aerodynamic heating during Mars entry [11]. The research highlights the need for tailored thermal protection mechanisms when designing hypersonic vehicles for extraterrestrial missions. Earth has a far denser atmosphere than Mars, so vehicles on Earth must have robust heat shields and thermal protection systems due to the greater drag produced. On Mars, however, far less drag is produced, reducing the aerodynamic heating. Earth also has a much greater gravity than Mars, so hypersonic vehicles on Earth will need powerful propulsion systems and robust structural integrity to handle high gravitational forces, which will not be as necessary on Mars. The median surface temperature on Mars is -65°C, while Earth has a median surface temperature of 15°C. Mars's lower temperatures result in vehicles on Mars having to handle less thermal loads from the environment than vehicles on Earth. However, Mars's extremely low oxygen content makes air-breathing vehicles useless since air-breathing engines need to take in air to function. Further research must be completed on solutions allowing air-breathing vehicles to function on Mars without massive drawbacks.

The paper by L. Zhu et al. proposes a novel drag and heat reduction strategy for hypersonic vehicles, combining a spike and multi-jet approach. The study uses numerical simulations with a high-resolution upwind scheme and models, such as the SST k-ε turbulence model, to consider fluid-thermal interactions through the conjugate heat transfer approach. Analysis of parameters like spike length-to-diameter ratio, jet pressure ratio, and lateral jet location reveals significant improvements in drag and heat reduction efficiency. The paper emphasizes the importance of this multi-jet strategy in enhancing hypersonic vehicle design, addressing aerodynamic drag, and tackling severe aeroheating challenges [13].

Active Thermal Protection Methods

The heat generated at the lowest speeds necessary for hypersonic speeds can reach approximately 1,5000°C as a result of aerodynamic heating and friction with the air. Primarily affecting the vehicle's leading edges, nose, and other aerodynamic surfaces. Passive cooling alone cannot dissipate all the heat hypersonic speeds create. As a result, effective active thermal protection methods are needed. Dissipating intense heat while contending with limited cooling sources requires innovative solutions. The constraints imposed by the high relative heat load demand careful consideration of the thermal dynamics involved in the active cooling process.

Ongoing advancements in active cooling aim to optimize fuel utilization by making it a cooling agent. Transcritical fuel flow, a phenomenon that occurs when the fuel undergoes both liquid and gaseous phases simultaneously, poses many significant challenges. The research done by Zhang et al. emphasizes the importance of understanding and mitigating this challenge to enhance the efficiency of regenerative cooling systems. This work underscores the intricate balance required to harness the fuel's cooling potential while navigating the complexities of its phase transitions [12]. Film cooling introduces a protective layer of coolant film over the vehicle's surface. This method is crucial for reducing the direct exposure of the vehicle's structure to the harsh aerothermal environment. Researchers are actively exploring novel film cooling strategies to enhance coverage and effectiveness, recognizing the importance of optimizing the distribution and thickness of the coolant film for maximum thermal protection.

Transpiration cooling involves releasing a coolant through the porous structure of the vehicle. This approach creates a cooling layer that helps dissipate heat efficiently. Ongoing research aims to refine transpiration cooling techniques, addressing challenges related to the selection of porous materials, flow rates, and the overall effectiveness of the cooling layer.

An emerging trend in active thermal protection involves integrating multiple cooling techniques to form a comprehensive and synergistic approach. Sziroczak and Smith introduce a novel drag and heat reduction strategy combining a spike and multi-jet approach. The spike and multi-jet approach refers to a combined strategy using a physical spike in the front of the aircraft to disrupt the airflow in front of the vehicle and multiple jets to manage airflow, significantly reducing aerodynamic drag and heat on high-speed vehicles. This innovative method, analyzed through numerical simulations, demonstrates the potential for substantial drag and heat reduction efficiency improvements, showcasing the promising future of hypersonic vehicle design. The design and optimization of active thermal protection methods heavily rely on computational fluid dynamics (CFD) simulations. Research done by S. Zhang et al. explores the challenges and advancements in active thermal protection methods for air-breathing hypersonic vehicles, particularly those equipped with scramjet engines. Figure 3 shows the change that will occur in hypersonics as air-breathing technology is further developed. The study emphasizes the limited cooling resources available for these vehicles, presenting a complete review of active thermal protection techniques, including regenerative cooling, film cooling, and transpiration cooling. Highlighting the significant issue of a "relative heat load," the paper addresses the constraints posed by the scarcity of coolant in hypersonic conditions.

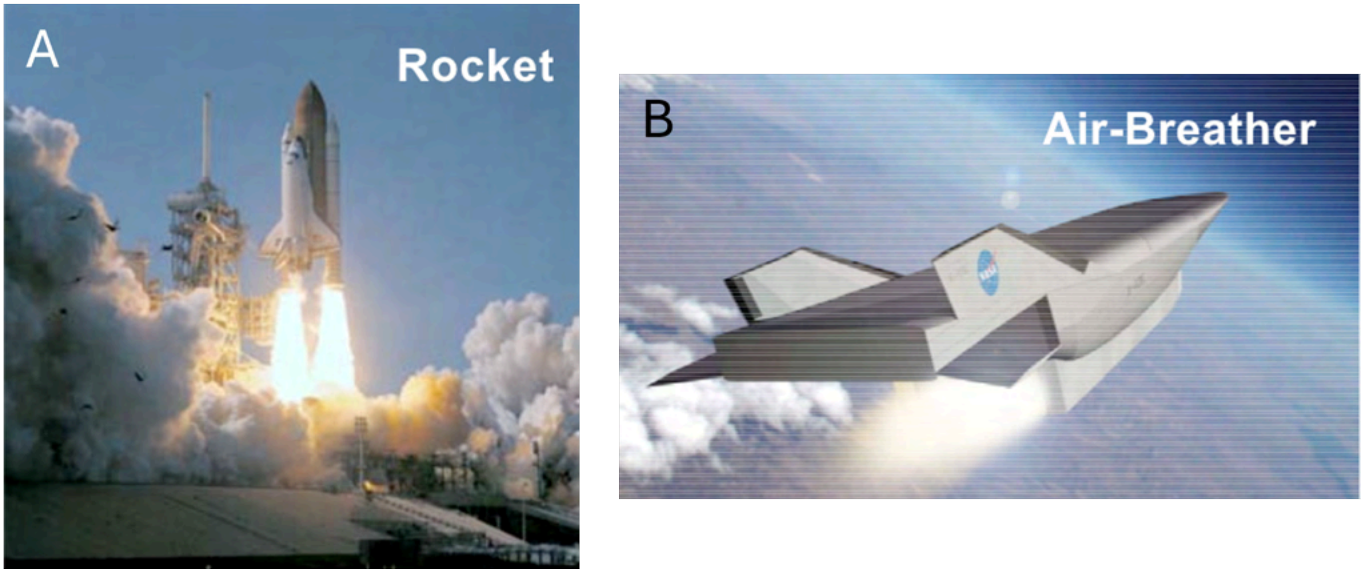

Fig. 3. Model A shows an example of an older hypersonic vehicle, with boosters attached to the space shuttle so it can reach significant speeds (Flickr, ImageSource). Model B shows a model of the future in hypersonic vehicles with air breathing mechanics, which do not use boosters (NASA. *Development X-43*.Blogspot, ImageSource).

Material and Design Considerations

Developing hypersonic vehicles requires carefully considering materials and design elements to protect them from aerodynamic heating. Finding the best efficiency, safety, and sustainability solutions is pivotal to achieving hypersonic travel.

Scramjet

A scramjet, short for Supersonic Combustion Ramjet, is an airbreathing jet engine designed to operate efficiently at high speeds, including hypersonic speeds. A simplified model of a scramjet is shown in Figure 4. Scramjet engines enable aircraft to fly above Mach 8, even above altitudes of 100,000 feet. Unlike traditional jet engines, scramjets rely on the vehicle's high speed to compress incoming air, facilitating efficient combustion without mechanical compressors. This streamlined design makes scramjets ideal for hypersonic vehicles, offering high speed, simplicity, efficiency, and versatility. They generate thrust by compressing and combusting air, propelling the vehicle forward. However, their need for air limits their use to only inside the atmosphere of Earth.

Regarding Thermal Protection Systems (TPS), scramjets pose unique challenges due to the intense heat generated during hypersonic flight. The heat produced by scramjets during hypersonic flight can exceed 1,000°C and sometimes reach 2,000°C. TPS must be designed to withstand and dissipate this heat effectively, with scramjets influencing TPS design by providing parameters for heat generation and airflow patterns. Ultimately, scramjets and TPS work together to ensure hypersonic vehicles' safe and efficient operation.

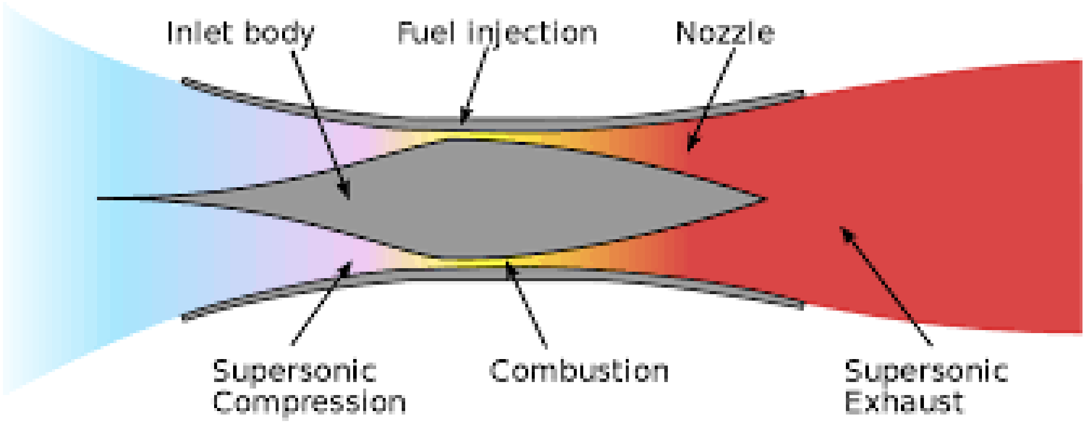

Fig. 4. An image of the components to a scramjet engine.

Sandwich Structures

Sandwich structures comprise lightweight materials arranged in layers, providing strength and thermal resistance. A model of how they are made is shown below in Figure 5. Thermal protection systems, utilizing sandwich structures, play a critical role in mitigating aerodynamic heating during hypersonic flight. Another benefit of sandwich structures is their ability to produce lighter frames, which maximizes efficiency. Lightweight structures contribute to fuel efficiency and the vehicle's ability to withstand rapid thermal cycles without compromising structural integrity. The study goes into the thermomechanical performance of these materials, highlighting the need for a delicate balance between weight reduction and maintaining mechanical strength under the extreme conditions of hypersonic flight.

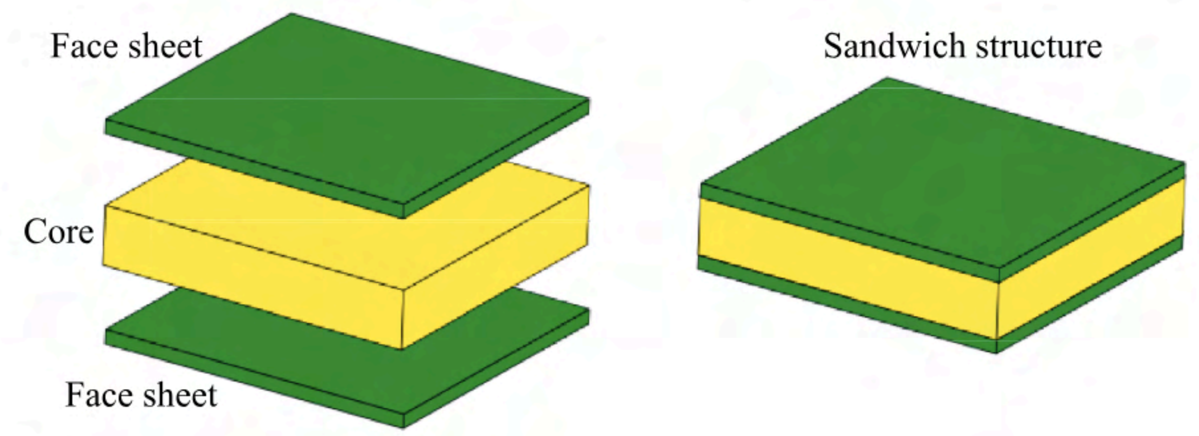

Fig. 5. Shows a model of how sandwich structures are created.

The paper provides a comprehensive review of diverse TPS materials applied in sandwich structures, including laminated composite, ceramic matrix composite, and metals, emphasizing the importance of understanding temperature gradients, deformation limits, and mechanical strengths. These considerations are fundamental for selecting materials that can withstand the thermal conditions experienced during hypersonic flight. The study explores material properties and advancements in TPS manufacturing methods. Novel manufacturing techniques contribute to the production of TPS components that meet the stringent requirements of hypersonic vehicles, including those related to weight, thermal resistance, and durability.

Tung Le and his partners outline future research directions in advancing TPS technology for space exploration. The paper written by Uyanna and Najafi provides a comprehensive overview of Thermal Protection Systems (TPS) in space vehicles, discussing their evolution and applications from the mid-twentieth century to the present. It covers various TPS types—passive, semi-passive, and active—used in reusable launch vehicles (RLVs) and interplanetary manned missions. The paper also goes over current challenges identified by NASA, including mass-efficient materials, modeling tools, and sensors. This work reinforces the challenges of reaching hypersonic speed as a result of obtaining experimental data at these conditions. The study also discusses historical contexts, such as the development of TPS during World War II, emphasizing the necessity for effective thermal barriers due to hypersonic flight challenges. The paper concludes with insights into future TPS advancements. It emphasizes the ongoing need for technological advancements to address challenges in material science, thermal protection, and manufacturing processes [10]. As discussed by Zhang et al., integrating active thermal protection methods, such as regenerative cooling and multi-jet strategies, requires careful consideration of material compatibility and structural design. Future research should focus on optimizing the integration of active and passive thermal protection systems for enhanced performance [12].

Material and structural solutions for hypersonic vehicles are needed, highlighting the need for higher operating temperatures, especially for vehicles powered by air-breathing engines. The paper explores operating conditions for different components of hypersonic vehicles, such as stagnation regions, inlet ramp conditions, upper surface conditions, and internal engine components. Calculations for stagnation point wall temperatures, inlet ramp conditions, surface properties, internal engine pressures, temperatures, and species mass fractions provide insights into the design challenges and considerations for developing hypersonic vehicles with air-breathing propulsion systems, aiming for higher speeds and improved performance.

The challenges and opportunities in materials science for hypersonic vehicles show great potential, focusing on various aspects of materials performance in extreme conditions. The paper shows the importance of material selection, characterization, and testing methodologies in ensuring the reliability and durability of hypersonic vehicle components. Research efforts aim to address the unique material challenges associated with hypersonic flight, paving the way for the development of robust and efficient hypersonic vehicles.

Sziroczak and Smith give a review of the technical issues and challenges of designing hypersonic vehicles. The paper focuses on Hypersonic Transports and Space Launchers. It adopts a multifaceted approach, examining historical backgrounds, considerations regarding operations, and technological challenges. The paper emphasizes the need for a systems perspective in developing successful hypersonic vehicles, addressing aspects like safety, security, maintainability, operational flexibility, reliability, and sustainability. It discusses mission profiles, markets, and environmental concerns, presenting a detailed analysis of the unique operational characteristics of Space Launchers and Hypersonic Transports. The study also reviews historical hypersonic flight developments, highlighting essential vehicles such as the X-15, Space Shuttle, Buran, SpaceShipOne, and X-37 [7].

Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) plays a crucial role in hypersonic travel, where the extreme conditions of flight subject vehicle structures to immense stresses. Early detection is paramount in SHM systems, providing a proactive approach to maintenance by identifying structural degradation, fatigue, or damage before they escalate into catastrophic failures [8]. Sensor technologies such as strain gauges, accelerometers, and fiber optic sensors are strategically positioned throughout the vehicle's structure to capture pertinent data on structural responses, vibrations, and loads.

The data gathered from SHM sensors undergoes meticulous analysis to extract actionable insights about the vehicle's structural condition. Advanced signal processing algorithms and predictive analytics enable the identification of patterns, anomalies, and potential damage indicators, facilitating accurate diagnosis and severity assessment.

Among SHM's key advantages are its real-time monitoring and decision-support capabilities. Once active, SHM systems continuously transmit information to ground control stations, empowering operators to make informed decisions regarding the vehicle's health and operational status. This real-time feedback loop enables proactive adjustments to flight parameters, routing, or mission objectives based on evolving structural conditions.

SHM significantly bolsters the resilience and reliability of hypersonic vehicle structures. By facilitating proactive maintenance and condition-based monitoring, SHM allows for timely repairs, component replacements, or structural reinforcements, thereby prolonging the vehicle's operational lifespan and minimizing downtime.

The practical implementation of SHM necessitates close integration with hypersonic vehicles' design and manufacturing processes. Incorporating structures with integrated sensor nodes, embedding adapting materials, and introducing redundancy in critical components enhance the efficacy of SHM systems. Furthermore, leveraging digital twins and virtual testing environments facilitates predictive maintenance strategies and enables iterative enhancements in vehicle design for improved structural performance.

Collecting this data in hypersonic vehicles is possible but challenging, as shown in the report by the German Aerospace Center [2]. The instruments must withstand the thermomechanical stresses experienced during flight to efficiently provide reliable data for analysis. The success of previous hypersonic flight experiments, such as SHEFEX-I and SHEFEX-II conducted by the German Aerospace Center (DLR), has demonstrated the feasibility of gaining valuable data for future high-speed flight vehicles and validating design tools. DLR will work with RWTH Aachen University in future steps to leverage new-generation HM sensors like Fiber Optic Sensing (FOS) and high-speed data acquisition systems with sampling rates up to 2 MHz. These advanced sensors and data acquisition systems will further enhance the capability to monitor the health state of spacecraft structures during hypersonic flight, contributing to the development of safer and more efficient high-speed flight vehicles [2].

In conclusion, SHM serves as a cornerstone technology for ensuring hypersonic vehicles' structural integrity and operational readiness. By utilizing advanced sensor technologies, data analytics, and real-time monitoring capabilities, SHM enables proactive maintenance, early damage detection, and informed decision-making throughout the vehicle's lifecycle, which is essential for safe and reliable hypersonic travel.

Conclusion

The potential benefits of reducing flight durations in the aviation industry are significant. As the number of planes in the sky increases, innovative solutions become essential to manage air traffic congestion and ensure timely takeoffs and landings. However, achieving hypersonic speeds poses substantial challenges in aerodynamics, materials selection, and thermal protection systems (TPS).

Addressing these challenges involves a deep understanding of aerothermodynamics and the development of efficient TPS. The extreme temperatures encountered during hypersonic flight and the necessity of effective thermal protection to safeguard pilots and onboard systems require advances in both passive and active thermal protection methods. Passive systems provide cost-effective solutions, while active systems offer enhanced cooling capabilities through techniques like regenerative cooling and transpiration cooling.

Integrating Structural Health Monitoring (SHM) systems further ensures hypersonic vehicles' structural integrity and operational readiness. SHM enables early damage detection and effective maintenance, enhancing their safety and reliability. Additionally, material and design considerations, such as the use of scramjet engines and sandwich structures, play a pivotal role in optimizing their performance and efficiency.

As research progresses, innovative strategies like the multi-jet approach for drag and heat reduction, as well as advanced CFD simulations, contribute to the development of more efficient hypersonic vehicles. Solving challenges faced by hypersonic vehicles on Earth extends to extraterrestrial use, including on Mars.

The journey towards achieving practical hypersonic travel is marked by significant technological and engineering challenges. Overcoming these hurdles requires continued research and development in aerodynamics, materials science, and thermal protection systems. By leveraging advancements in these areas, the aviation industry can move closer to the benefits of reduced flight durations and global connectivity.

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