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Thermal protection strategies for hypersonic space vehicles: aerothermodynamics, TPS configurations, and performance effects

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Abstract

The Thermal Protection System (TPS) is one of the essential parts for visualizing the aerothermodynamic effect for a hypersonic moving body, i.e., M > 5. This detailed review paper deals with discussing the importance of aerothermodynamic effects, presents an overview of TPS, and highlights the key points on the influence of aerodynamic performance. The incorporation of TPS materials alters surface roughness, vehicle contour, mass distribution, and structural stiffness, thereby affecting drag, lift-to-drag ratio, boundary layer transition, and overall flight efficiency. The review aims to provide a cohesive understanding of the interdependence between aerothermodynamics, TPS material behavior, and aerodynamic performance, thereby supporting advanced design strategies for next-generation hypersonic space transportation systems.

Keywords: Aerodynamic Performance, Aerothermodynamics, Hypersonic, TPS

1. Introduction

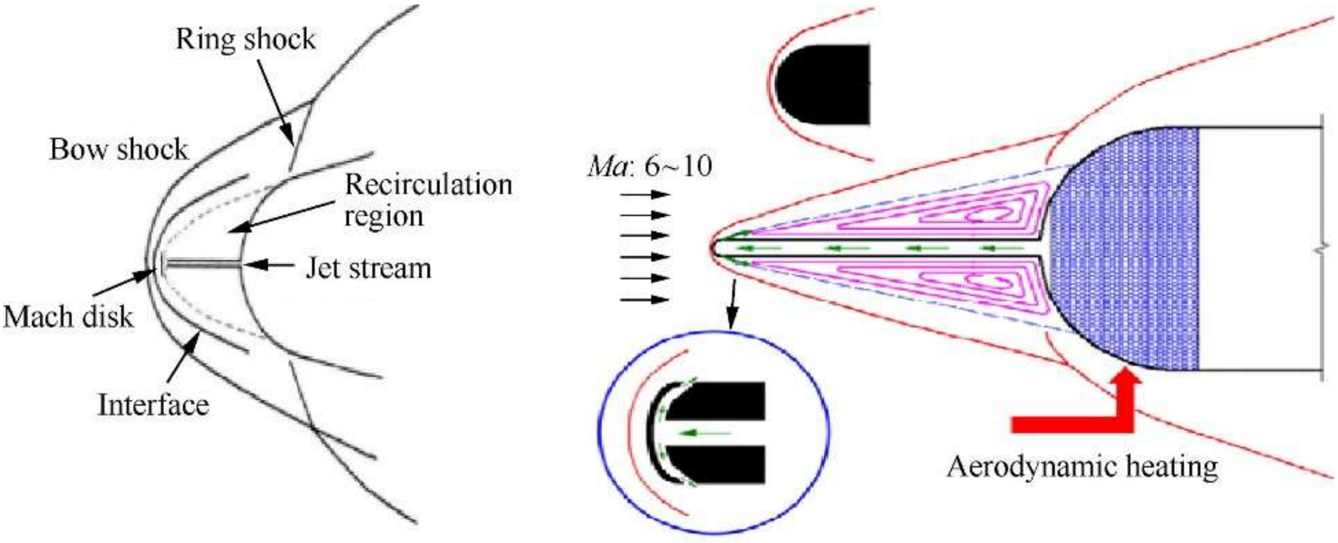
Thermal Protection System (TPS) is a widely used system to incorporate the shielding effect and aerodynamic heating over the specified supersonic as well as hypersonic space reentry vehicles. The major use of TPS is to be considered for the space vehicles traveling at higher Mach numbers, i.e., M > 5, which in turn responds to the strong effect of aerodynamic friction and shock generation, leading to exceeding the temperature at 2000-3000 ℃. TPS is considered to be one of the potential features, especially for understanding the structural integrity of the vehicles moving at supersonic and hypersonic speeds that could lead to several failures, cracks in growth, and formation of thermal stresses [1], [2], [3]. The general TPS consists of three layers, where the first layer represents the outer layer where the effect of incident heat flux is to be accumulated and further emitted in the form of radiation. The second and third layers are used as an insulation material layer. The classification of TPS-based materials includes- carbon-phenolic, reinforced carbon-carbon composites that lie under the category of ablative coatings, low thermal conductive materials that include silica as well as ceramic tiles in the category of insulative coatings, metallic as well as ceramic coatings that lie in the category of reflective coatings, nickel-based superalloys and ultra-high temperature ceramics, respectively [4] [5]. The major factors that affect the TPS are- flight profile and its speed, atmospheric conditions, exposure to aerodynamic heating, several material properties such as thermal conductivity, specific heat ratio, expansion coefficient, dissipation rate, etc., that are suitable for determining the perfect combination of TPS materials. Along with these other factors, structural integrity and reusability are included as per the mission requirements.

Sengupta et al. performed numerical simulations based on thermal control of transonic shock-boundary layer interaction over a natural laminar flow airfoil. The study results in a detailed discussion about vortical and entropy contour plots that indicate flow features, such as creation and interactions with the shock wave [6]. Zhang et al. reviewed the thermal protection and drag reduction induced by flow control devices in supersonic/hypersonic flows. This study also highlights the two different active control flow methods, i.e., counter-flowing jet and energy deposition. It also provides an in-depth study of the challenges and opportunities leading to future advancements in control flow methods [7]. Huang et al. demonstrated a novel study on the role of TPS for hypersonic wings, which further enhances the structural integrity as well as thermal protection efficiency. This study also employs numerical modelling to investigate the thermal protection mechanism and thermal performance [8]. Liu et al. performed numerical simulation on the thermal–hydraulic performance of multiple parallel cooling channels to realize active thermal protection for hypersonic aircraft. It also highlights different arrangements of cooling channels, such as triangular, rectangular, and diamond, respectively. From the experimental data and numerical validation, it was confirmed that diamond-based channels are highly effective for protection and efficiency as compared to others [9]. Wan et al. reviewed the aero thermoelastic problem for hypersonic vehicles. This work highlights the wind tunnel experiments and numerical results that were conducted over a time span of five years. It also discusses the major challenges and upcoming future trends that lie at the bottom of the aerodynamic heating effect [10]. Another review study conducted by Hu et al [11] describes the recent research development for thermal protection structures to be implemented for hypersonic-based vehicles. The study also summarizes the performance, suitable material selection, and technical as well as structural challenges. Savino et al. performed CFD analysis to understand the aerothermodynamic on ultra-high temperature ceramics (UTHs) to investigate the thermal response characteristics for reusable launch vehicles. This study offers a deep insight into the numerical modelling performed based on coupled mechanism flow behavior in laminar-turbulent transition, as well as the effect of surface recombination, which highly impacts the thermal field for heat flow [12]. Arnold et al. describe the development and design of the thermal protection for a cover panel system meant to insulate an inflatable decelerator from aerodynamic heating during entry into the Martian atmosphere [13]. Sziroczak et al. reviewed design issues specific to hypersonic flight vehicles. Operational issues such as mission profiles, environmental effects, and human factors are described. Also, the technical challenges in terms of vehicle aerothermodynamics, propulsion system, and structural aspects are covered [14].

The reviewed literature was obtained systematically using the popular scientific databases, which are the NASA Technical Reports Server (NTRS), IEEE Xplore, Elsevier ScienceDirect, Springer Link, Wiley Online Library, and MDPI journals, and all of which provide a vast amount of peer-reviewed academic sources in the subject area of aerospace engineering and thermal sciences. The chosen corpus covers the years between 1995 and 2025, hence, allowing us to consider the discoveries made in the field of thermal protection systems (TPS) applied to supersonic and hypersonic aircraft since then. Relevant keywords used in the search strategy included thermal protection system, hypersonic aerothermodynamics, aerodynamic heating, ablative TPS, reusable insulation, ultra-high temperature ceramics (UHTC), active cooling, aerothermoelasticity, shock-boundary layer interaction, and hypersonic vehicle thermal management. Inclusion criteria were set to encompass peer-reviewed journal articles, conference proceedings, monographs, and technical reports that address TPS materials, aerothermal loading, heat-transfer mechanisms, and thermal management strategies for high-speed aerospace platforms. The preference was given to the recent studies (2019-2025), but at the same time, incorporating the classical sources necessary to provide the theoretical basis and to formulate the models. Publications that were not considered to be technically relevant to TPS or aerothermodynamics, those that were found in more than one database, and non-peer-reviewed papers that lacked substantive experimental or computational validation were excluded. This filtering provided 56 very relevant publications and thus a good coverage in material technologies, aerothermodynamic mechanisms, and the protection strategies in the next generation of supersonic and hypersonic aerospace vehicles.

2. Aerothermodynamics effect on hypersonic vehicles

The role of aerothermodynamics is suitable for analysing the flow behavior at high Mach speeds. An emerging concept about the supersonic channel airfoil (SCA) applies to the leading edges of wings, tails, fins, struts, and other components of aircraft, atmospheric entry vehicles, and missiles in supersonic flight for the occurrence of drag reduction. This concept is highly proficient in which the leading edge is significantly blunted, and the Mach number lies in the normal range, indicating that the leading edge is supersonic. The concept is found to result in significantly reduced wave drag and total drag (including skin friction drag) and significantly increased lift-to-drag ratio [15]. Furthermore, a sufficiently small channel is responsible for the existence of a normal shock in front of the leading edge, thus creating a choked entrance condition. The normal shock decelerates the channel entrance flow and reduces gradients around the channel lip relative to a started condition geometry [16].



(a) Axial jet (b) Lateral jet

Figure 1. Typical combinational concepts of aerospike and counterflowing jet on the nose tip [17]

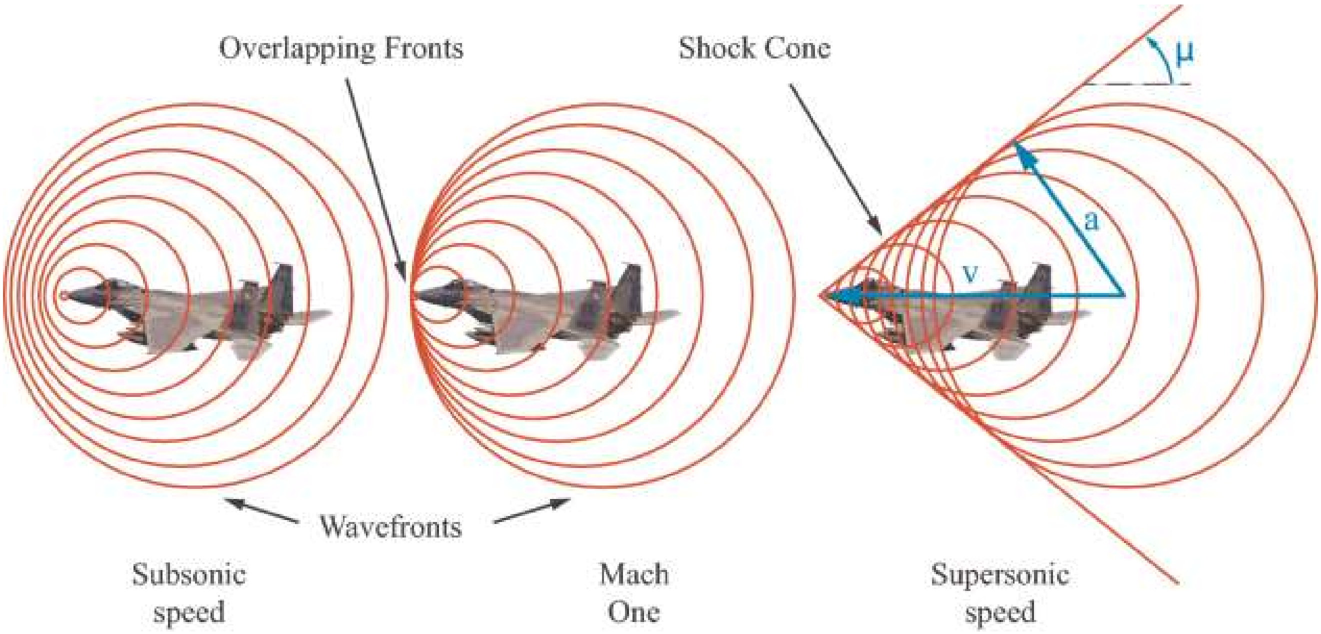


Figure 2. Wavefront behavior at subsonic, sonic, and supersonic flow regimes [36]

The design of a future supersonic aircraft is still very challenging due to the complexity of several problems, such as static stability performance during the acceleration phase from subsonic speeds to supersonic speeds. Several flight conditions, ranging from subsonic to supersonic speeds, were investigated in detail by using Computational Fluid Dynamics. Figure 1. shows the combinational concept of aerospike and counterflowing jet on the nose tip. The aerodynamic force and moment coefficients are computed with fully three-dimensional and steady state Reynolds Average Navier-Stokes simulations, carried out in turbulent flow conditions [18], [19]. The effect of shock wave formation is considered to be one of the most prominent factors to study the aerothermodynamic effects for supersonic flows. Several researchers have attempted experiments to study the shock waves caused by aerodynamic heating over several shapes, such as plates, airfoils, and cylindrical bodies [20]. The four major targeted areas to explore the study on shock wave interaction lie in understanding low frequency unsteadiness, heat transfer prediction capability, phenomena in complex (multi-shock boundary layer) interactions, and flow control technique, respectively [21]. The effect of drag highly affects the vehicle moving at hypersonic speed. The novel technique introduced to reduce the effect of drag and aerodynamic heating by using an aerospike. Aerodynamic heating is another critical consequence of supersonic flow over airfoils. The conversion of kinetic energy into internal energy through viscous dissipation and shock compression leads to elevated wall temperatures, particularly near the leading edge, where stagnation effects are strongest. Although convective heating rates at supersonic speeds are lower than those encountered in hypersonic regimes, sustained exposure can still impose stringent thermal constraints on structural materials and coatings. Consequently, aerothermodynamic design must account for heat transfer characteristics alongside aerodynamic optimization [22], [23]. Several studies conducted worldwide showed effective results by considering parameters such as Mach number, length-to-diameter ratio, and angle of attack, respectively. These studies were performed based on computational analysis in ANSYS Fluent. Along with the computational analysis, a numerical approach has also been taken into account to understand the flow behavior that is assigned for a large number of moving independent particles. It also generates the outcomes of motion of molecules and surface interactions based on a deterministic approach [24], [25], [26]. Figure 2. shows the wavefront behavior at subsonic, sonic, and supersonic flow regimes. The interplay between aerodynamic forces and thermal effects necessitates integrated analysis approaches for supersonic airfoil design. Traditional inviscid theories, such as linearized supersonic flow theory, provide initial insight into pressure distributions but fail to capture viscous heating and shock-induced thermal loads [27].

3. Overview of Thermal Protection System

The thermal protection system (TPS) is a critical component of the engineering sub-system that was created to ensure that aerospace aircraft are protected against the intense heating forces of hypersonic flow and atmospheric re-entry. When a spacecraft re-enters Earth’s atmosphere, kinetic energy is converted into thermal energy via shock-wave compression and viscous dissipation, producing temperatures that exceed 1500–3000 °C at stagnation points. TPS materials are utilized as thermal-resistant materials that slow down excessive heat transfer into the vehicle structure, thus maintaining structural integrity, protecting the payloads, and making missions successful. The concept of TPS has been used in modern designs to combine aerothermodynamics, materials science, and structural mechanics to address extreme thermal loads at minimum mass and maximum reliability. Aerospace re-entry systems Reviews identify TPS as one of the most crucial enabling technologies to reusable missions and planetary exploration missions [28], [29]. Figure 3. shows the schematics of TPS for heat sink, hot structure and insulated surface respectively. When moving at hypersonic velocity, a bow shock is developed in front of the vehicle, which significantly increases the temperature and heat flux of the gases. Heat transfer is mainly achieved by convection, radiation, and catalytic reactions at the surface. Molecules of the high-energy gas are passing the energy on to the surface of the vehicle, and chemical dissociation and recombination contribute to the intensity of heating even more. Thermal loads are spatially varying, with the highest heat loads at nose cones and leading edges. Advanced TPS thus has to withstand high temperature gradients, oxidation, and thermo-mechanical stresses simultaneously. Research shows that TPS should still be able to function over large temperature scales, such as cryogenic in the space environment, as well as extreme heat in re-entry, and thus material choice is extremely complicated [29], [30].

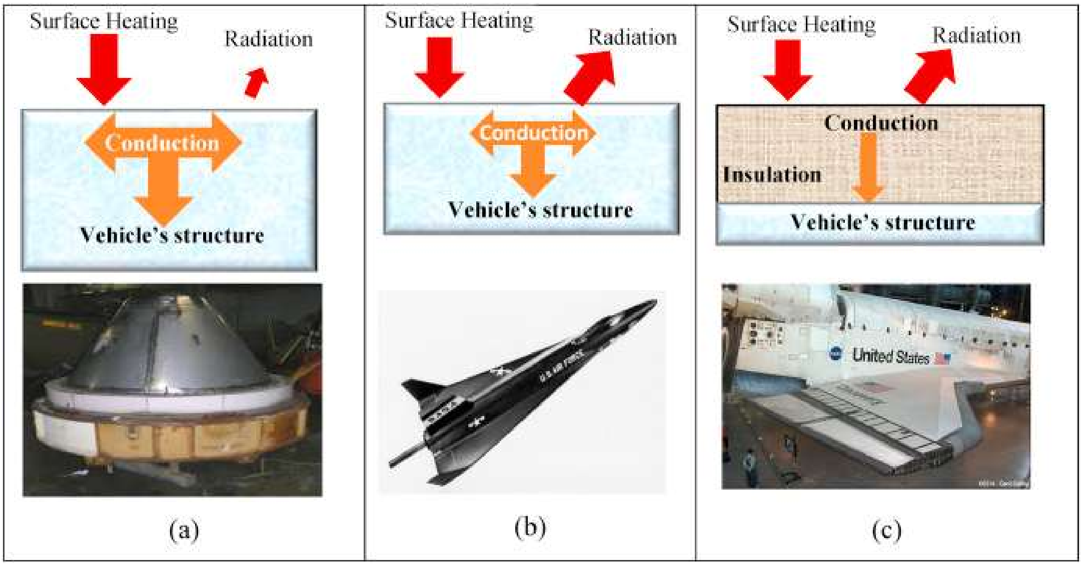


Figure 3. Schematics of TPS for (a) Heat sink, (b) Hot structure, (c) Insulated Surface [2]

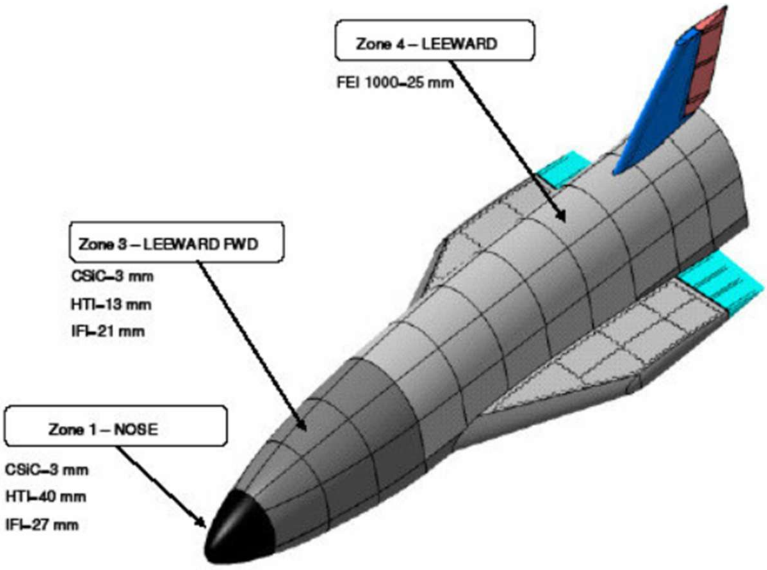


Figure 4. Thermal protection system layout [35]

The latest hypersonic aircraft are open to using hot-structure technology, whereby structural elements are subjected to high temperatures in themselves. Ceramic matrix composites (CMCs) and ultra-high-temperature ceramics (UHTCs) enable operation above 2000 °C and are thus suitable for leading edges and propulsion-integrated structures. The NASA studies argue that the next generation hypersonic aircraft will require a shift in the use of insulated structures into load-bearing high-temperature materials [30], [31]. Figure 4. shows the layout of Thermal Protection System based on different components. TPS materials are validated through arc-jet testing, plasma wind tunnels, and high-enthalpy facilities that replicate re-entry heating conditions. It has been experimentally proven that reusable TPS ceramics can survive intense thermal cycling and heat flux testing with oxygen-fuel torch testing techniques [32]. TPS design demands precise prediction of aerothermal loads, material degradation, and internal temperature limits. Traditional experimental testing is not sufficient since, on Earth, it is impossible to completely simulate flight conditions. As a result, the use of physics-informed neural networks and reduced-order models to model the TPS thermal behaviour in a cost-effective manner, which includes uncertainties, is introduced by contemporary research [33], [34].

3.1 Types of Thermal Protection Systems

3.1.1 Overview of Thermal Protection System

There are several types of thermal protection systems which are discussed below.

3.1.1 Ablative Thermal Protection System. The ablative thermal protection system protects structural components that lie below it through moderate sacrificial wear of the outermost material when subjected to high levels of heat flux. When subjected to extreme aerodynamic heating attendant to atmospheric re-entry, the exterior surface undergoes pyrolysis, charring, melting, and controlled recession of material. The gases produced in the pyrolysis process create a protective coating layer, which reduces thermal conduction, and the endothermic reactions take in a lot of thermal energy. Ablative TPS is commonly used in non-reusable vehicles that enter space, e.g., in the Apollo Program, and in modern capsule vehicles. Figure 5. represents the schematic of an ablative heat shield. Examples of representative materials are phenolic impregnated carbon ablators (PICA) and carbon-phenolic composites.

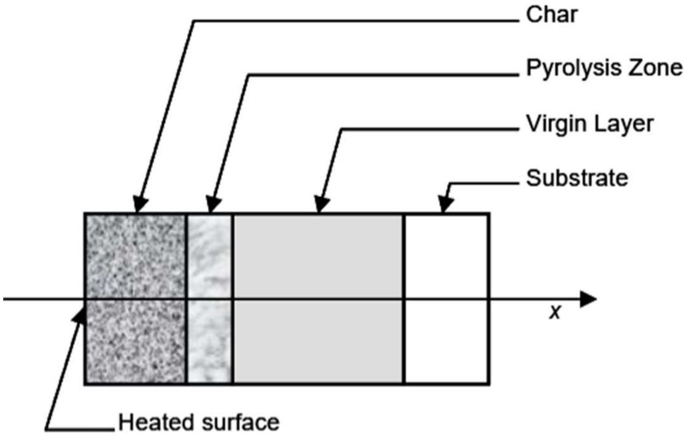


Figure 5. Schematic of an ablative heat shield [37]

3.1.2 Reusable Insulating Thermal Protection System. Reusable insulating TPS has been based mostly on constituents with very low thermal conductivity to delay heat transfer to the structural subsystem. These systems do not lose materials as much as the ablators and are created to undergo repeated thermal cycles. One canonical example is the silica ceramic tile system that was used on the Space Shuttle Orbiter and consists of LI 900 silica tiles and carbon fiber-reinforced carbon (RCC) panels on leading edges. The tiles have a relative porosity of about 90 per cent by volume, which greatly reduces the conductive heat transfer. Figure 6. shows the tile assembly for shuttle thermal protection system. On re-entry, the outer tile surface can reach temperatures of over 1200 °C as the internal aluminum framework does not reach operational temperatures.

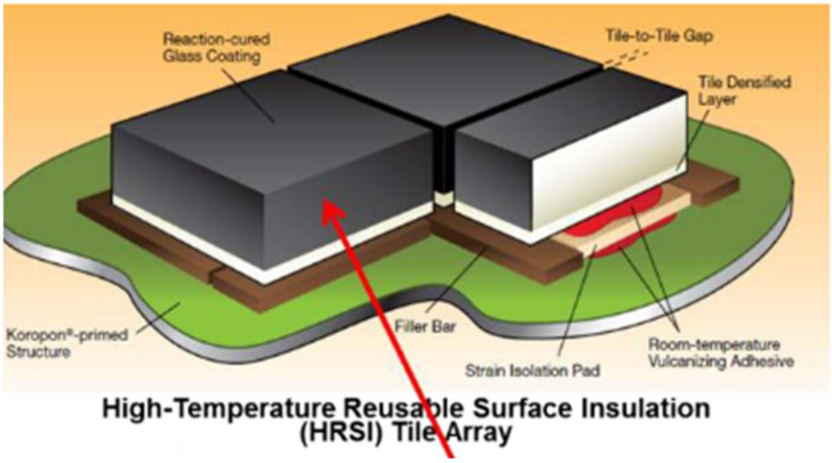


Figure 6. Space Shuttle thermal protection system (TPS) tile assemblage [38]

3.1.3 Radiative Thermal Protection System- Radiative TPS is designed in such a way that it can cool down mainly by heat loss and not by eliminating material or by large amounts of insulation. These systems use materials with high emissivity and high temperature strength, like ultra-high temperature ceramics (UHTCs) like zirconium diboride (ZrB_2) and hafnium carbide (HfC). Figure 7. shows the generic layout structure of radiative thermal protection system. Under exposure to hypersonic flow, the heated surface reradiates a considerable fraction of absorbed energy back into the environment in accordance with the Stefan–Boltzmann law. Radiative TPS are especially beneficial on sharp leading edges on hypersonic vehicles where aerodynamic efficiency is of the greatest importance.

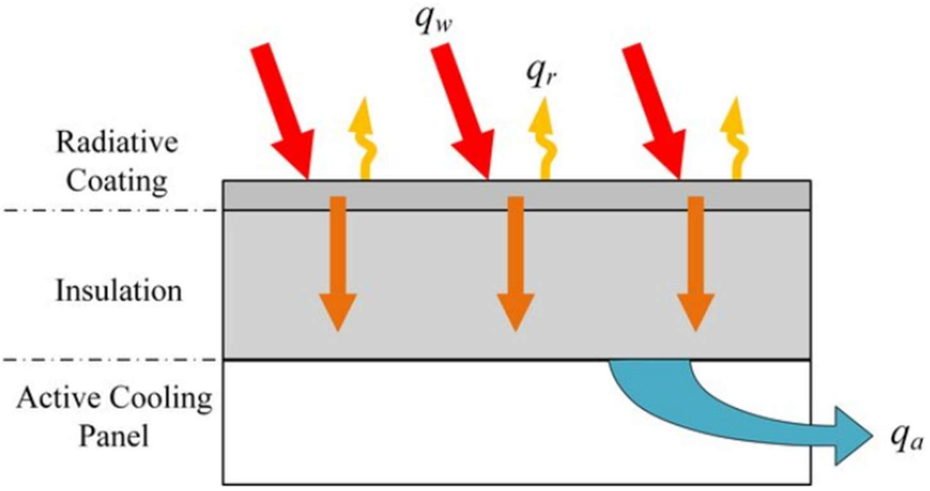


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Figure 7. Generic structure of radiative thermal protection system [39]

3.1.4 Active Thermal Protection System. Active TPS integrates mechanical or fluid-based cooling mechanisms to remove heat continuously. In transpiration cooling, a coolant - gas or liquid - is injected through a porous wall, thereby generating a protective boundary layer that reduces convective heat flux. Regenerative cooling entails the circulation of fuel or coolant through internal channels beneath the heated surface before combustion or discharge. Figure 8. represents the schematic diagram of a transpiration cooling thermal protection system. They have the ability to operate in highly high heat flux regimes like scramjet engines or sharp hypersonic leading edges. Although markedly efficient, active systems introduce additional structural complexity and mass.

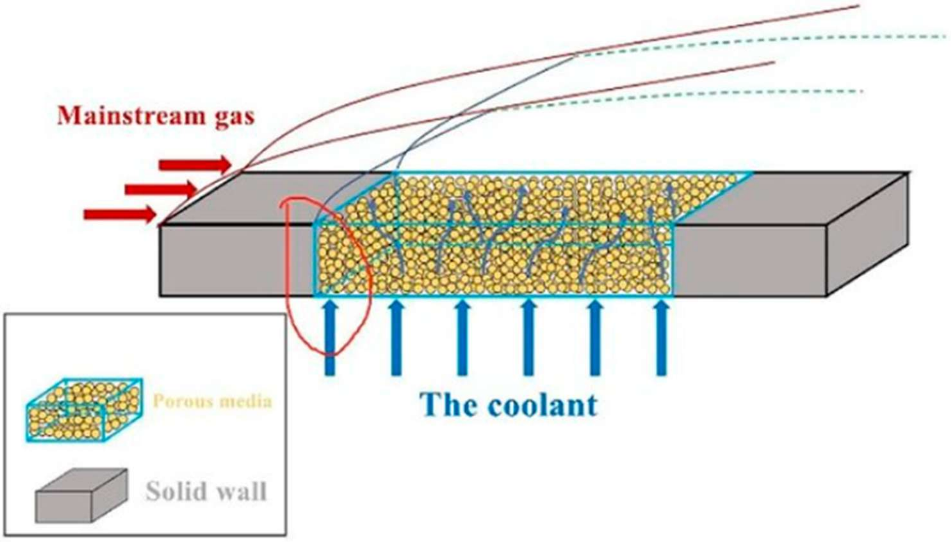

Figure 8. Schematic diagram of transpiration cooling thermal protection system [40]

3.1.5 Multi-Layer Insulation Thermal Protection System- Multi-layer insulation (MLI) is commonly used in the thermal control of spacecraft in a vacuum as opposed to atmospheric re-entry. It consists of multiple thin reflective foils separated by low-conductivity spacers, thereby drastically diminishing radiative heat transfer between surfaces. Figure 9. shows the typical structure of conventional multilayer insulation (MLI) and its installation. MLI works through the reflection of infrared radiation over sequential interfaces, thereby reducing the net heat exchange. The technology is also greatly used in satellites and cryogenic vessels.

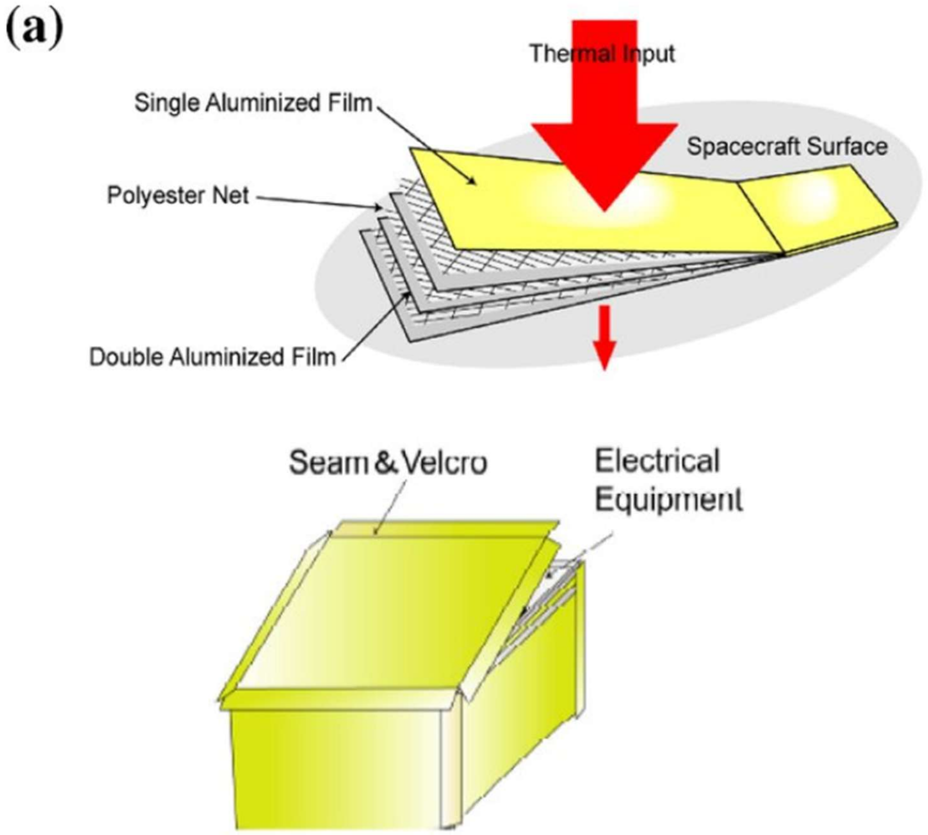

Figure 9. Typical structure of conventional multilayer insulation (MLI) and its installation [41]

For moderate heating environments, exemplified by low supersonic flight or reusable spacecraft surfaces, reusable insulating TPS constructed from ceramic tiles or fibrous insulation are prevalently deployed, owing to their low mass and capacity to withstand repeated thermal cycling, as evidenced by the Space Shuttle Orbiter program. Radiative TPS based on carbon-carbon or ultra-high temperature ceramics is often the choice because of its capability of withstanding temperatures in excess of 2000 up to 2000000 K, and because of its capability to cool components using radiation. Similarly, there are active TPS systems (e.g., regenerative cooling or transpiration cooling) believed to be a good idea in long-duration hypersonic flights, where constant thermal loads exceed the capacity of passive materials. The principal trade-offs across these systems encompass reusability, structural complexity, mass, and reliability: ablative systems furnish robust protection yet are single-use; reusable insulations offer lightness but are constrained by temperature limits; radiative TPS tolerates extreme temperatures but is costly and brittle; and active systems grant superior thermal control at the expense of significant mechanical complexity and weight increases.

The literature comes to the conclusion that there is no single TPS technology that fits all mission requirements, and there has been increasing interest in hybrid types of TPS architecture, which combines passive and active modalities and special materials like ceramic matrix composites. However, conclusive statements are still not available about the lifecycle of ultra-high temperature ceramics at repeated hypersonic cycles and the feasibility of active cooling systems in working vehicles, hence, requiring additional experimental experiences and combined aerothermo-structural research.

A comparison Table 1. has been shown below to represent the performance metrics for all types of TPS based on parameters such as materials, temperature capability, reusability, thermal protection efficiency, etc.

Table 1. Comparison of Thermal Protection Systems (TPS) for Hypersonic Space Vehicles

Parameter	**Ablative TPS**	**Reusable Insulative TPS**	**Radiative TPS**	**Active TPS**	**Multi-Layer Insulation (MLI) TPS**	**References**
Working principle	Heat absorbed by material decomposition and surface recession (ablation)	Low thermal conductivity materials reduce heat transfer to the structure	High-temperature materials radiate heat to the surroundings	Coolant flow removes heat through convection	Multiple reflective layers reduce radiative heat transfer	[28], [47]
Typical materials	Carbon-phenolic, PICA, AVCOAT	Silica tiles, ceramic blankets, TUFROC	Refractory metals, ultra-high-temperature ceramics	Transpiration cooling, liquid hydrogen, or water channels	Aluminized Mylar, Kapton multilayer foils	[28], [48]
Maximum temperature capability	Very high (>3000 °C)	Moderate to high (1200–1600 °C)	High (1500–2500 °C)	Extremely high (depends on coolant)	Low (<500 °C)	[28], [47], [49]
Reusability	No (single use)	Yes (multiple missions possible)	Yes	Yes, but complex maintenance	Yes	[28], [48]
Thermal protection efficiency	Excellent for extreme heat flux	Good for moderate heating	Good for sustained high temperature environments	Excellent due to continuous heat removal	Very good for radiation insulation in a vacuum	[28], [47]
Mass efficiency	Moderate (material loss during operation)	Lightweight	Moderate	Heavy due to the pumps and the coolant system	Extremely lightweight	[47], [49]
Structural complexity	Simple passive system	Moderate (tile integration)	Moderate	Very complex (cooling channels and pumps)	Simple layered structure	[28], [47]
Maintenance requirement	Replacement required after each mission	Inspection and occasional repair	Low maintenance	High maintenance due to fluid systems	Minimal maintenance	[28], [48]
Cost implications	Lower development but high operational replacement cost	High development but reusable	Moderate	Very high due to complex systems	Low	[28], [47]
Heat flux tolerance	Very high heat flux (>1000 kW/m²)	Moderate heat flux	Moderate to high heat flux	Extremely high heat flux	Low heat flux	[47], [49]
Typical applications	Re-entry capsules (Apollo, Orion)	Space Shuttle, reusable launch vehicles	Hypersonic leading edges	Rocket engines, hypersonic vehicles	Satellites and cryogenic spacecraft insulation	[28], [48], [49]
Advantages	Proven technology, handles extreme re-entry heating	Reusable and lightweight	Passive cooling with durable materials	Highest heat removal capability	Excellent radiation shielding in space	[28], [47]
Limitations	Single-use, erosion, and shape change	Fragile tiles and inspection needed	Limited heat rejection under extreme flux	Complex and heavy system	Not suitable for atmospheric re-entry heating	[28], [48], [49]

4. Influence of Thermal Protection System on Aerodynamic Performance

Design and development of a TPS on aerospace high-speed vehicles has a significant effect on aerodynamic characteristics such as drag, heat-flux distribution, lift-to-drag ratio, and stability [2] [7]. At hypersonic flight conditions, the interaction of the TPS and the flow field also changes the structure of shock waves and the behavior of the boundary layer, which in turn has a direct impact on the aerodynamic forces and moments acting on the vehicle [31]. As an example, blunt TPS geometries (usually utilized to support high heat fluxes) excite strong detached shock waves that enhance drag and reduce peak surface heat transfer [43]. Conversely, TPS configurations that are sharp or spike-based remodel the shock system into a weaker oblique shock, thereby reducing both the heat load and aerodynamic drag while preserving lift characteristics. Active TPS types that can alter the flow field further to reduce stagnation heating and decrease surface pressure include opposing jet designs or spikes that can be used to achieve a reduction in the drag as compared to passive, insulating shields [44].

The aerothermoelastic behaviour of structural panels is also affected by the thickness and existence of TPS layers, as it affects both the local distributions of aerodynamic heating and pressure, and hence the onset of flutter and other aeroelastic instabilities- constituents in aerodynamic performance. Additionally, aerodynamic performance is affected by the thermal properties of the TPS, since surface-temperature gradients modify gas viscosity and density within the boundary layer, which in turn influences skin friction and shock-layer characteristics. This means that both aerodynamic performance and TPS integration require a combined aerothermal/fluid structure optimization in order to remain stable, reduce drag, and provide structural safety in all flight regimes [45]. Contemporary computational studies demonstrate that integrating TPS shape and material design with aerodynamic optimization yields superior lift-to-drag ratios, improved heat-flux control, and greater operational flexibility across a range of Mach numbers and attitudes, thereby underscoring that the TPS serves not merely as a heat shield but as a pivotal aerodynamic control element in hypersonic vehicle design.

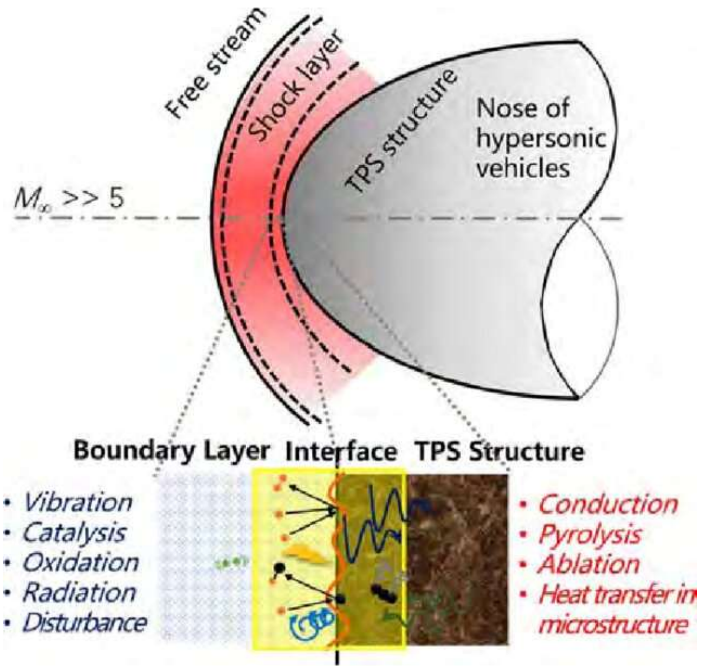

Figure 10. Schematic overview of physics of heat transfer phenomena with interface effects in high-enthalpy and high-speed flow [42]

The thermal protection system (TPS) plays an important role in aerodynamic performance (it exclusively changes the external geometry, surface roughness, thermal boundary conditions, and structural stiffness of high-speed vehicles). Even a small geometric change induced by TPS thickness or tile gaps, at supersonic speeds and hypersonic speeds, can change the distribution of the local pressures and the position of shock-waves, which influence the lift, drag, and pitching-moment properties. Blunted TPS configurations also enhance stand-off shock distance, which lowers convective heat transfer, and at the same time, this raises wave drag. Figure 10. shows the overview of physics of heat transfer phenomena with interface effects in high-enthalpy and high-speed flows. Conversely, slender or sharp TPS geometries improve aerodynamic efficiency yet expose the surface to higher stagnation heating, necessitating advanced materials such as ultra-high-temperature ceramics. Surface roughness caused by the misalignment of tiles or recession caused by ablation can cause the transition of the surface boundary layer to turbulent flow prematurely, which significantly increases the rates of skin-friction drag and heating. Furthermore, the mass loss experienced during re-entry in an ablative way dynamically changes the shape of the vehicle and may change the aerodynamic-centre positions and alter the stability margins. Structural deformation is also influenced by thermal gradients in TPS layers, resulting in aero-thermalelastic coupling in which aerodynamic shape is changed under load due to thermal expansion.

Active cooling system - transpiration or regenerative cooling systems add surface-blowing effects to alter the thickness of the boundary-layer, but can also have impacts on the properties of pressure recovery and the flow-separation. Also, TPS material emissivity and surface temperature affect the viscosity and density of near-wall gases, having a subtle effect on shear-stress distribution and aerodynamic-heating profiles [46]. Therefore, when integrating TPS with control surfaces, there should be little aerodynamic interference, but thermal integrity should be maintained. In modern hypersonic vehicle design, multidisciplinary optimization methods are becoming popular, whereby TPS material selection, distribution of thickness, and shape of the outer-mold-line are optimized together to keep the lift-to-drag ratio constant, and minimize heating loads.

A comparison Table 2. has been shown below to represent the comparison of TPS types based on their influence on aerodynamic performance.

Table 2. Comparison of TPS types based on their influence on aerodynamic performance

TPS Type	**Surface Roughness / Drag Effect**	**Boundary Layer Transition**	**Shape Stability**	**Aerodynamic Heating Control**	**Suitability for Hypersonic Flight**	**Ref.**
Ablative TPS	Surface recession increases roughness and drag	Early transition due to ablation products	Moderate (material erosion changes geometry)	Very high heat absorption through ablation	Excellent for short-duration re-entry	[50], [53]
Reusable Insulative TPS	Smooth surface, but tile gaps may cause minor drag	Local disturbances near tile joints	High geometric stability	Insulates the structure from heat flux	Suitable for reusable hypersonic vehicles	[52], [55]
Radiative TPS	Smooth coatings minimize drag	Minimal effect if the surface is uniform	High stability with refractory materials	Radiates heat to the environment	Suitable for sustained high-temperature flight	[53], [55]
Active TPS	Smooth aerodynamic surface	Surface temperature control may delay transition	Very high due to cooling	Excellent heat removal via coolant flow	Ideal for advanced hypersonic vehicles	[54], [56]
Multi-Layer Insulation (MLI)	Negligible aerodynamic role	Not applicable	Not designed for aerodynamic loads	Prevents radiative heat transfer in a vacuum	Not suitable for atmospheric hypersonic flight	[51], [55]

5. Conclusions and Future Scope

Thermal Protection Systems (TPS) are an essential part of the protection of the structural integrity and mission success of hypersonic vehicles that work under severe aerothermodynamic conditions. The significant aerodynamic heating of the shock-wave interaction, compression of the boundary-layer, and the viscous dissipation require the implementation of effective thermal shielding solutions. There are numerous TPS strategies, such as ablative, reusable insulative strategies, radiative strategies, and active cooling strategies, which have been designed to meet different mission needs and expected thermal loads.

However, TPS use has a strong impact on such aerodynamic parameters as drag, lift-to-drag ratio, surface pressure distribution, and the overall stability of the vehicle. Blunt configurations mitigate peak heating but incur higher wave drag, whereas slender geometries enhance aerodynamic efficiency at the expense of elevated thermal stress. Also, the aero-thermo-structural coupling highlights the importance of considering thermal expansion and material behavior in the process of assessing the performance of aerodynamics. It has been shown that the nature of TPS geometry, material properties, and flow physics are interdependent, and as such, TPS is not just a passive heat shield but an active participant in the overall vehicle performance. It follows that syntactic design processes that are based on aerodynamics, heat transfer, and structural mechanics are essential to the design of next-generation vehicles.

Future studies in the area of TPS in supersonic and hypersonic systems must focus on the creation of new high-performance materials, including ultra-high-temperature ceramics, ceramic matrix composites, and functionally-graded composites, which can withstand high thermal and mechanical loads. Production of lightweight, reusable, and self-healing TPS parts will be important towards improving mission re-usability and reducing operational costs. The active cooling paradigms, such as the transpiration and regenerative strategies, should be further validated and optimized in experiments to enhance aerodynamic efficiency and achieve control of the heat flux simultaneously. The incorporation of artificial intelligence and data-driven optimization approaches may further refine the synergy between TPS and aerodynamic systems.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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