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A Review of Advances in Thermal Protection Systems and Insulation Materials for Hypersonic Vehicles

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Abstract. Hypersonic vehicles experience intense aerodynamic heating during re-entry and high-speed flight, imposing stringent demands on thermal protection systems (TPS) and insulation materials. Accordingly, this paper reviews the classification and design principles of TPS, along with the structural properties and performance of typical insulation materials. In this context, passive, semi-active, and active TPS offer protection across varying thermal environments, with active systems delivering superior performance in extreme conditions, yet they entail higher complexity and cost. In terms of insulation materials, foam ceramics hinder heat conduction through porous structures, fibrous materials suppress conduction and convection through multi-level pores, whereas aerogels offer ultralow thermal conductivity and lightweight features. The results reveal that while considerable strides have been made in TPS and insulation materials, challenges persist in attaining thermal stability at extreme conditions, integrating multiple functionalities, and accelerating development, highlighting the need for innovative, adaptive TPS solutions for future hypersonic missions."

Keywords: Hypersonic aircraft, Thermal protection system, Insulation material performance, Heat transfer mechanism

1. Introduction

The rapid development of hypersonic flight technologies has posed unprecedented challenges to structural safety. As speed increases and flight duration extends, vehicles are inevitably exposed to severe aerodynamic heating, thus requiring highly efficient thermal protection systems (TPS) and advanced insulation materials to ensure safety and extend service life. To meet these demands, TPS are generally divided into passive, semi-active, and active types. Moreover, each type differs in its underlying mechanism, applicable environments, and structural complexity. In addition, insulation materials demonstrate distinct thermal resistance mechanisms based on conduction, convection, and radiation heat-transfer modes, with their performance largely determined by accurate measurements of thermal conductivity and related parameters. This paper reviews TPS classifications and design characteristics, emphasizes representative mechanisms, and summarizes recent advances in foam ceramics, fibrous insulation, and aerogels. Furthermore, it highlights key challenges, such as limited thermal stability, insufficient multifunctional integration, and extended development timelines, and proposes potential strategies for developing multifunctional and adaptive TPS materials to enable future hypersonic missions.

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2. The classification and design characteristics of thermal protection systems

2.1. Mechanisms of passive thermal protection systems

According to different thermal protection mechanisms, TPS can be divided into passive and active types [1]. Passive TPS protects the structure by isolating the vehicle from external high-temperature gases through thermal insulation layers. As illustrated in Figure 1, the passive leading-edge design incorporates passive thermal management, with its mechanisms mainly reflected in two aspects. On the one hand, thermal protection materials can absorb and store incoming heat, thereby reducing the heat flux reaching the structural components, which represents a typical thermal sink mechanism. On the other hand, the outermost layer of the TPS is usually coated with a high-emissivity material with an emissivity greater than 0.8, allowing the absorbed heat to be radiated into the atmosphere and lowering the wall temperature. The radiative heat flux at the wall can be determined using the Stefan-Boltzmann law.

$$Q = \mu\sigma(T_w^4 - T_r^4) \tag{1}$$

where Q_r represents radiative heat flux, μ is the wall surface emissivity, T_w denotes the wall temperature, T_e is the ambient temperature, and σ is the Stefan-Boltzmann constant, with a value of $5.67 \times 10^{-8} W/(m^2 \cdot K^4)$. This illustrates that the primary characteristic of passive TPS lies in its ability to effectively protect the vehicle through both heat absorption and thermal radiation [2].

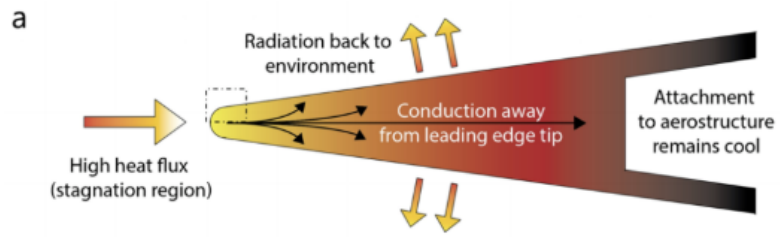

Figure 1. Illustration of passive thermal protection at the leading edge

2.2. Mechanisms of semi-active thermal protection systems

The semi-active TPS is an advanced heat-shielding system derived from passive TPS, designed for hypersonic vehicles experiencing severe aerodynamic heating during re-entry. In comparison with passive TPS, semi-active systems deliver enhanced thermal protection, though they exhibit greater structural complexity and higher overall weight and lifecycle costs.

Typical mechanisms of semi-active TPS include ablation-based protection and integrated heat pipes. Through material phase changes, ablation protection dissipates substantial heat: endothermic vaporization or surface ablation occurs in high-temperature regions, which effectively reduces the heat flux to the vehicle structure. Integrated heat pipes rapidly transfer heat through conduction and phase-change cycles, where vapor generated in high-temperature regions carries heat to cooler areas, condenses, and returns to the hot end via capillary action, providing cyclic thermal protection. The combination of these two mechanisms enables semi-active TPS to maintain high thermal protection efficiency under extreme conditions. As illustrated in Figure 2, the semi-active lithium heat pipe leading-edge structure provides efficient thermal management at 1500 K [2].

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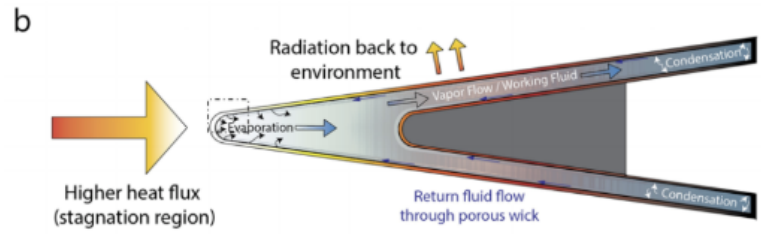

Figure 2. Illustration of a semi-active lithium heat pipe leading edge at 1500 K

2.3. Mechanisms of active thermal protection systems

For long-duration hypersonic re-entry, active TPS offer the most effective defense against extreme aerodynamic heating. In comparison with passive and semi-active TPS, active systems can actively regulate heat flow and greatly reduce the thermal load on the vehicle through external or internal cooling [2]. However, they are the most complex in structure, the heaviest in weight, and incur the highest lifecycle cost. The main methods by which active TPS mitigate heat are convective cooling, transpiration cooling, and film cooling. In convective cooling, heat is removed by coolant flow. Transpiration cooling injects liquid coolant into hot regions via micropores, where it vaporizes and circulates to lower the wall temperature. Film cooling forms an insulating gas layer on the surface, blocking direct heat transfer to the structure. These mechanisms allow active TPS to ensure reliable heat shielding under extreme conditions. As shown in Figure 3, the active leading-edge structure greatly reduces incident heat flux through transpiration, protecting the internal components.

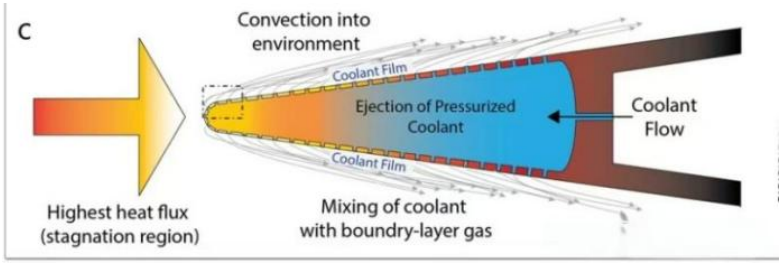

Figure 3. Illustration of an active leading-edge structure mitigating heat flux through transpiration

3. Mechanisms and properties of thermal insulation materials

3.1. Heat transfer mechanisms and principles

Heat transfer between or within objects is generally induced by temperature difference and occurs mainly via three mechanisms, namely conduction, convection and radiation [3]. Thermal insulation materials are designed to attenuate the three modes of heat transfer, and their working principles under each mechanism are summarized in Table 1. Due to structural differences, various thermal insulation materials exhibit distinct insulating mechanisms and heat transfer behaviors. Accordingly, the effect of thermal conduction can be reduced by decreasing both the thermal conductivity and the effective conduction area of the material, thermal convection can be limited by minimizing porosity and pore interlinkage, while thermal radiation can be weakened by enhancing the material's capacity for infrared shielding. For more efficient thermal insulation performance, the practical application environment and specific heat transfer modes must also be comprehensively considered [4].

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Table 1. Insulation mechanisms of materials under different heat transfer modes

Mode of Heat Transfer	Fundamental Mechanism	Thermal Insulation Mechanism
Conduction	Thermal motion and interactions of microscopic particles (molecules, atoms, phonons)	Reduce intrinsic thermal conductivity and minimize heat transfer paths; aerogels achieve this via ultralow solid content and nanoscale pores
Convection	Gas movement within pores	Smaller pore size and lower connectivity suppress gas convection; fibrous materials restrict airflow through complex pore structures
Radiation	Transfer of energy by electromagnetic waves (mainly infrared)	Enhance infrared shielding; high-temperature ceramic foams incorporate opacifying particles to reduce radiative heat transfer

3.2. Thermal insulation properties of ceramic foam materials

Foam ceramic thermal insulation materials are multifunctional composites composed of a solid insulating phase and irregularly distributed pores. Their microstructure is typically characterized by millimeter-scale pores, high porosity, and low bulk density, effectively suppressing heat conduction in thermal protection applications [5]. For example, the addition of vermiculite to porous insulation reduced the thermal conductivity to 0.065 W/(m·K), thus illustrating that early strategies to enhance insulation performance largely relied on increasing porosity [6]. Porous mullite-corundum ceramics prepared with alumina as the matrix also exhibit excellent thermal properties, featuring a porosity of 73.7%, a compressive strength of 3.05 MPa, and a thermal conductivity of only 0.287 W/(m·K) at 1000 °C, highlighting their potential for aerospace thermal protection applications [7]. In addition, zirconia ceramics prepared by water-based gel casting and vacuum freeze-drying exhibited 74.44% porosity and 3.19 MPa compressive strength [8]. Recently, high-porosity rare-earth silicates have attracted attention. For example, Y_2SiO_5 porous ceramics prepared using a gelatin gel system with gel casting, freeze-drying, and pressureless sintering exhibited thermal conductivities ranging from 0.036 to 0.062 W/(m·K), showing promise for high-temperature insulation [9]. Despite effective heat-conduction blocking, the large pores of ceramic foams permit convection, reducing insulation efficiency. Thus, pore size and porosity are key factors governing their thermal behavior.

3.3. Structural features of fibrous thermal insulation materials

Fibrous insulation materials consist of a solid fiber matrix and a continuous gas phase, and are classified as fiber membranes or fiber felts, with fiber membranes being more common. Leveraging fine-diameter, high-porosity fiber membranes markedly boosts high-temperature thermal insulation. For example, the mesoporous SiO_2 network derived from a nanomembrane skeleton strengthens mechanical properties while keeping a room-temperature thermal conductivity of 0.021 W/(m·K) [10]. To strengthen the usually weak mechanical properties of nanofiber membranes, reinforcement fibers may be added or fiber alignment modified. Accordingly, in multiphase Si-Zr-O-C nanofiber membranes, the Si-O-C phase and multiphase interfaces effectively suppress radiative and solid conduction heat transfer, resulting in a thermal conductivity of only 0.139 W/(m·K) at 1000 °C [11]. In comparison, fiber felts are gaining attention for ultra-high-temperature applications. Flexibility is preserved and thermal conductivity reduced when silica aerogel is added to glass fiber felts [12]. In addition, ZrO_2-TiO_2 composite fiber sponges exhibit a room-temperature thermal conductivity of

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only 0.027 W/(m·K) at a typical density of 9.5 mg/cm^3, much lower than that of single-component materials [13]. Similarly, sandwich insulation samples of quartz fiber cloth and core-type felts reach a thermal conductivity of 0.0518 W/(m·K) at 30 mm thickness, exhibiting excellent insulation [14]. Previous studies have shown that the thermal conductivity of fiber felts increases significantly with temperature, reaching around 4.9 times the room-temperature value at 1000 °C, showing thermal insulation behavior completely different from that at low temperatures [15].

3.4. Performance and thermal behavior of aerogel insulation materials

With bulk densities as low as 3 mg/cm^3, porosities above 99%, and specific surface areas exceeding 1000 m^2/g, aerogels, which are porous materials composed of a nanostructured particle skeleton and gas, exhibit extremely low thermal conductivity and excellent insulation performance [16]. Based on differences in their constituent materials, aerogel insulation materials can be classified into types such as inorganic oxides, organic polymers, carbon-based materials, and carbide aerogels [17]. The continuous nanoscale network and excellent thermal stability of inorganic oxide aerogels, such as SiO_2, Al_2O_3, and ZrO_2, classify them as Class A non-combustible materials. Once hydrophobically modified, they are widely used for insulation for insulation in construction and industry. In contrast, organic aerogels, including phenolic and polyimide variants, provide excellent flexibility and water repellency but possess limited heat resistance, thus making them ideal for applications in flexible thermal and sound insulation. Due to their strong electrical conductivity and ultra-high-temperature resistance, carbon aerogels are well suited for electrodes and thermal insulation in inert atmospheres, yet they readily fail under oxidative conditions. Carbide aerogels, such as SiC and ZrC, demonstrate outstanding oxidation resistance and mechanical properties, maintaining structural stability under extreme high temperatures. However, due to complex preparation processes and high costs, they are currently mainly used for thermal protection in aerospace applications.

4. Existing challenges and future prospects

Existing thermal protection materials have made significant progress in high-temperature insulation and mechanical load-bearing, hence laying a strong foundation for hypersonic vehicle development. However, these materials still face bottlenecks like insufficient high-temperature stability, limited functional integration, and long research and development cycles, which restrict their widespread application in extreme flight environments.

From the perspective of current challenges, the high-temperature tolerance of materials remains limited, making it hard to endure the extreme heat faced by hypersonic vehicles on long missions. Their multifunctional synergy is insufficient, hindering the simultaneous achievement of thermal insulation, structural load-bearing, and stealth capabilities. In addition, conventional approaches are inefficient, with long cycles required for material screening and optimization, which also constrains the rapid deployment of new thermal protection systems.

Future development directions can be highlighted in several aspects. In terms of material design, the development of multifunctional composites can boost thermal insulation, structural strength, and stealth via integrated functions. Besides, biomimetic concepts and multi-scale structural designs can be introduced to improve overall thermal protection efficiency and enhance structural reliability. In addition, the integration of materials genome engineering and artificial intelligence can expedite the screening and optimization of high-performance materials, thereby shortening development cycles.

Moreover, advancement of flexible and adaptive thermal protection systems can enable intelligent responses and dynamic regulation under complex and variable thermal environments,

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thus meeting the demands of next-generation hypersonic vehicles for long-duration and multi-mission operations.

5. Conclusion

This paper has summarized the classification, design characteristics, and recent advances in TPS and insulating materials for hypersonic vehicles. The results demonstrate that passive, semi-active, and active TPS are suited to different thermal environments, with semi-active and active systems markedly enhancing thermal protection efficiency via mechanisms like phase-change cooling and forced convection. In terms of insulating materials, ceramic foams, fibrous materials, and aerogels exhibit distinct heat transfer mechanisms and performance characteristics owing to structural differences, showing significant potential in ultra-high temperature tolerance, lightweight design, and multifunctional composites. However, it depends largely on literature and theoretical analysis, without experimental verification. As such, the practical applicability of the conclusions is yet to be confirmed. Future studies should blend experiments and simulations to reveal material performance in actual flight, and create smarter TPS materials for long hypersonic flights.

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