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Research Paper

Assessment of thermal-mechanical performance with structural efficiency concept on design of lattice-core thermal protection system

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HIGHLIGHTS

- LTPS with both thermal insulation and load bearing capacities is exhibited.
- Structural efficiency is defined to assess thermal-mechanical performance of LTPS.
- 30° inclination angle is the best choice for LTPS.

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ABSTRACT

A lattice-core thermal protection system (LTPS) integrated thermal insulation and load-bearing capacities was regarded as a promising candidate for future hypersonic vehicles. However, it was found that the concept of thermal insulation efficiency (TIE) is no longer suitable to assess not only the thermal insulation effect of LTPS, but also the load-bearing capacity. Therefore, an innovative concept of structural efficiency is proposed in this paper. The effect of lattice-core inclination angle on the structural efficiency was investigated by numerical simulation approach. Numerical results show that there exists a competition on enhancing the structural efficiency and utilization of bearing material. The inclination angle of 30° is the best choice to obtain the greatest structural efficiency. The maximum stress of C/SiC LTPS is 139 MPa, smaller than the strength of C/SiC composite and locates at the connection between rods and lattice-core sheets. The thickness of C/SiC LTPS is 67.9–69.7 mm, reducing the thickness of multilayer thermal protection system (MTPS) up to 29.3%. The density of the LTPS is 0.15–0.2 g/cm^3, linearly increasing with the inclination angle. Structural efficiency provides an evolution index to assess the thermal-mechanical performance of the LTPS.

Abbreviations

TPS	thermal protection system
LTPS	lattice-core thermal protection system
MTPS	multilayer thermal protection system
TFS	top face sheet
BFS	bottom face sheet
BTIB	bottom of thermal insulation blanket

Symbols

$\bar{\rho}$	the relative density of the C/SiC lattice core
β	the inclination angle of the lattice core truss (°)
h_{lc}	the thickness of lattice core (mm)
h_{TIB}	the thickness of thermal insulation blanket (mm)
k_{eq}	the equivalent thermal conductivity W/(m °C)
T_{TFS}\;	the temperature on the top face sheet (°C)
T_{BTIB}	the temperature on the bottom thermal insulation blanket (°C)
T_{in}\;	the temperature inside the inner structure (°C)
T_{out}	the temperature outward ambient sink environment (°C)
q_l	heat flux of the LTPS (W/m^2)
q_r	the heat flux of surface radiation of the TFS (W/m^2)
q_c	the heat flux of convection heat transfer (W/m^2)
q	the incident heat flux of on the TFS (W/m^2)

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h_c the convection heat transfer coefficient under the BTIB W/(m °C)
k_{lc} the equivalent thermal conductivity of the lattice core filled with the aerogel W/(m °C)
ρ_m the average density of the MTPS(kg/m^3)
H_M whole thickness of the MTPS(mm)
ρ_L the average density of the LTPS(kg/m^3)
H_L whole thickness of the LTPS(mm)
TIE thermal insulating efficiency(m^2/kg)
SE structural efficiency
ε the emissivity of the surface
σ the Stefan-Boltzmann constant(W/(m^2 K^4))

1. Introduction

A thermal protection system (TPS) covering the outside surface of hypersonic spacecraft is mainly used to protect the inner system from excessive aerodynamic heating during ascent and reentry stages [1–3]. Recently, lightweight corrugated- and lattice-core sandwich structures with high specific stiffness and strength have been applied to TPS's design to integrate the thermal insulation and mechanical load bearing capacities [4–7]. However, since the structure and the service loadings of the lattice-core thermal protection system (LTPS) are very complex, there has little study on structural efficiency evaluation and optimization of the LTPS so far. Actually, it is the key for the potential applications of the LTPS.

Traditionally, TPSs are designed for the thermal insulation purpose while they have very poor mechanical properties. This type of TPS could be easily destroyed by outside impact and thus exists serious potential safety hazard. In 2006, Bapanapalli et al. [8] firstly applied the corrugated-core sandwich panel in TPS design and proposed an LTPS concept integrating corrugated-core sandwich panel with inner thermal insulation material. Metallic LTPS used refractory alloys were designed and studied in some articles [8,9], whereas there still has some problems for the metallic LTPS, such as the service temperature limitation and the thermal short effect. To mitigate the thermal short effect, a tailorable structural core was designed by the NASA Langley Research Center [10]. This improvement not only decreased the mass of the LTPS but also improved its in-plane shear strength. However, overly complicated hollow structure limited the fabrication and brought complicated problems, such as the connecting problem among cores.

To overcome the temperature limit of metallic LTPS, ceramic matrix composites were applied in the design of TPS [11,12]. Compared with metallic materials, ceramic matrix composites can withstand higher temperature. Wei et al. fabricated a ZrB_2-SiC-graphite ultra-high temperature ceramic (UHTC) corrugated panel and tested its compressive modulus and strength [13]. However, the brittleness of ceramic materials limited the widespread use of this kind of TPS. Another structurally integrated TPS was designed by NASA Langley Research Center [14]. The unique feature of the TPS is that rigid insulation bars were wrapped with impregnated ceramic-fiber cloth and stacked in a 0°/90° configuration. The TPS possessed both thermal insulation and load bearing capacities, in particular, it mitigated the thermal short effect compared with ceramic corrugated core TPS. But it still faced the separation and bonding problems between ceramic-fiber cloth and rigid bars [15]. Higher temperature limit, slightly performance degradation at ultra-high temperature, good oxidation resistance, and ductility are primary requirements for selecting TPS materials. Carbon fiber reinforced silicon carbide matrix (C/SiC) composite is one of the high-temperature materials and has been adopted in the design of TPS in recent reports. Wei et al. had fabricated C/SiC composite lattice to balance the performance of the LTPS between thermal insulation and high-temperature stiffness and strength [16]. Ma et al. studied the C/SiC LTPS under aerodynamic heating loadings and they reported that although the insulation ability was improved by an attached insulation blanket, the temperature of the cold surface of the sandwich panel would converge to a stable value in a certain time range [17]. Yang studied a C/SiC LTPS and reported that high-temperature oxidation had great effects on the mechanical properties of the LTPS [18]. Chen et al. studied the compressive properties and failure behaviors of C/SiC lattice sandwich panel using numerical simulation approach [19].

Although some research works had been conducted to study the thermal response or mechanical properties of the C/SiC LTPS, still few reports focus on how to assess and optimize the structural efficiency of the LTPS. Parametric study of thermal-mechanical characterization focused on the geometric shapes of lattice-core rods other than its inclination angle [20,21]. Yan et al proposed a concept of thermal insulation efficiency to assess the thermal insulation effect of multilayer thermal protection system (MTPS, Fig. 1a), but not suitable for LTPS [22]. Typical MTPS is consisted of a ceramic matrix composite (CMC) panel and N-layers thermal insulation materials. CMC panel and thermal insulation materials play the roles of bearing mechanical loads and thermal insulation, respectively. To realize the integration of load-bearing and thermal insulation capacities, CMC panel is replaced with a lattice C/SiC lattice-core sandwich panel and thermal aerogel is filled between in lattice core, as shown in Fig. 1b. This type of LTPS which enhances the load-bearing capacities and saves the space is proposed as the thermal structure for future hypersonic spacecraft. The effect of inclination angle sensitivity on the structural efficiency is studied in this paper.

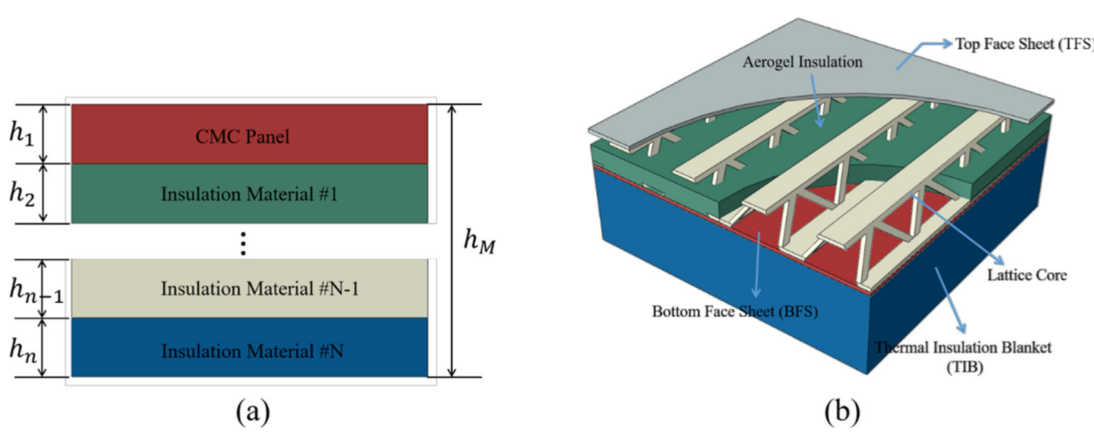

Fig. 1. (a) The sketch of MTPS; (b) the mesostructure of the LTPS. Top face sheet (TFS), the gray sheet covers the outside of the whole LTPS; aerogel insulation, the aquamarine filler material filled in the lattice structure, is an important layer of heat insulation; lattice core, the beige hollow structure, is the main load bearing part; bottom face sheet (BFS), the red sheet, locates in the middle position of the LTPS; thermal insulation blanket (TIB), the blue block at the bottom of the LTPS, prevents heat passing from BFS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)