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ABLATIVE THERMAL PROTECTION STRUCTURE DESIGN OF BALLISTIC REENTRY SPACECRAFT

by

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ABLATIVE THERMAL PROTECTION STRUCTURE DESIGN OF BALLISTIC REENTRY SPACECRAFT

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Abstract

The paper presents the ablative thermal protection structure design of a ballistic reentry spacecraft. The concepts, material selection, design approach, analytical computation and evaluation are described.

Key words: Thermal protection structure, ablative material, ballistic reentry spacecraft and design.

I. Foreword

The reentry module of a ballistic reentry spacecraft can adopt three types of thermal protection structures: ablative, radiation and heat-absorption type thermal protection structures. The decision on adopting a particular thermal protection structure should be based on the peak thermal flux density and the total heat quantity at the reentry stage.

The ablative thermal production structure should be adopted for a thermal flux density between 4.2×10^5 and 4.2×10^7 W/m^2, and the total heat quantity added between 4.2×10^5 and 4.2×10^8 J/m^2. The ablative thermal protection structure is also a type of thermal protection structure [1, 2] with relatively extensive applications in successful spacecraft flights.

The reentry module should pass through three stages of heating environment: heating environment in the ascent stage, heating environment in the orbiting stage, and heating environment at the reentry stage. The thermal performance design of the thermal protection structure should be based on the heating environment of the reentry stage; when designing the structural coordination performance one should take into account the heating environment of the orbital stage.

II. Selection of Concepts and Materials of Ablative Thermal Protection Structure

1. Ways of designing the ablative thermal protection structure

There are two ways of designing the ablative thermal protection structure: whole-depth ablation and partial-depth ablation as shown in Fig. 1 [3].

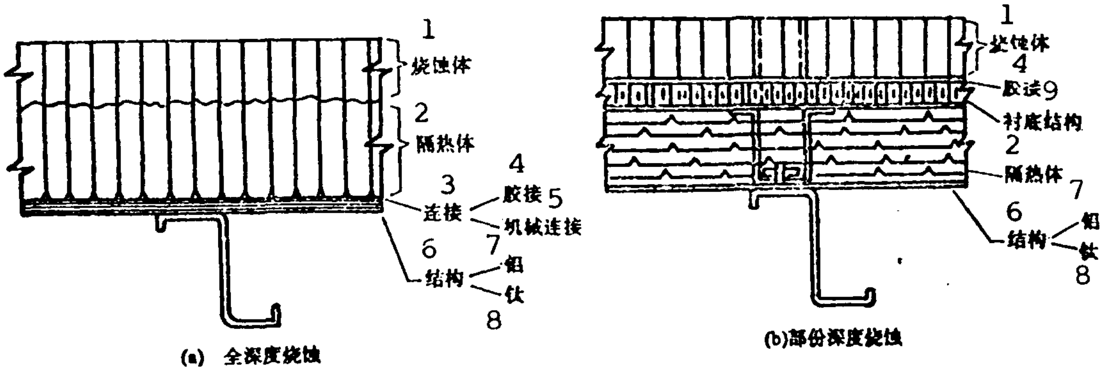

Fig. 1. Design approaches of ablation thermal protection structures
LEGEND: a - whole-depth ablation b - partial-depth ablation
KEY: (1) ablation body (2) insulation body (3) connection (4) adhesion (5) mechanical connection (6) structure (7) aluminum (8) titanium (9) structure at base of layer

For partial-depth ablation: in designing the thermal protection structure system, adiabatic materials with insulation properties superior to the ablative materials are used to replace the ablative materials for the insulated portion; thus, the thermal efficiency of the entire thermal protection structure is increased significantly. In comparing these two design schemes, in the latter case the structure is seen to be more complex with more factors to be considered in the material selection; the technical execution is more difficult. A high-temperature adhesive should be used as adhering material between the ablative material layer and the heat insulation layer. In making the structural design and material selection, adequate consideration should be given to the problem of structural coordination among the three layers of ablation, insulation material and load-acting structure during the orbital flight.

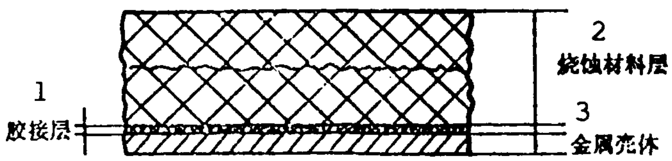

Fig. 2. Ablation thermal protection structure of reentry module
KEY: 1 - adhesive layer 2 - ablation-material layer 3 - metal casing

As shown in Fig. 2, the whole-depth ablation thermal protection structure should be used for the reentry module. The temperatures at the adhering layer are relatively low so the adhesive operates at lower temperatures; thus, conventional adhesive can be used. Since the ablative layer directly adheres onto the load-bearing structure, the integrality between the ablative layer and the load-bearing structure is enhanced; thus, the system structure is simple; reliability is high; and actual execution is easier.

2. Selection principle of ablative materials

There are relatively more types of ablative materials. The features of the thermal environment during the reentry of the reentry module are as follows: high enthalpy, low pressure, low peak value of thermal flux density, long reentry time, and high thermal load. Thus, it is required that the ablative materials should have good ablative properties; moreover, these materials should have good insulation properties. By analyzing the ablative mechanism of the various types of ablative materials, and through much experimental research, it was found that the most effective ablative material for a reentry module is carbonization ablative material with low-temperature decomposition. This type of ablative material has the following properties.

(1) This type of ablative material has good evaporation and cooling effects. During heating, low-temperature carbonization ablative material absorbs heat; and decomposition of materials releases large quantities of gas to form a carbon layer at the surface. Through the carbon layer, the decomposed gas is injected into and enters the adhesive layer to exercise a thermal blocking effect. The greater the quantities of injected gas, the greater is the pneumatic *heating quantity* for a weakening of the blocking effect. The low-temperature decomposed carbonization ablative material leads to larger gasification fractions. The gasification fraction of phenolaldehyde--nylon composite material, a typical low-temperature carbonization ablative material, can be as high as 70 percent.

(2) Found after ablation of low-temperature carbonization ablative materials, the carbonization layer is basically composed of carbon. The radiation coefficient of carbon is high, therefore large quantities of heat can be re-radiated at high tempratures. Fig. 3 shows the distribution diagram of heat of this type of ablative material using ablation [4].

3. Method of selecting thermal properties of ablative materials

During the reentry stage of a reentry module, the thermal flux density in the unit area is low; however, the total heating quantity is high. This situation requires that the ablative material not only has good ablative properties, but also good heat insulation. In indicating the heat insulation of a material, the overall parameter is the $\rho \cdot \kappa / c_p$ ratio. The smaller the ratio, the better the heat insulation. For low values of material density ρ, and heat conduction coefficient κ, but high c_p value of specific heat with respect to volume, the lower is the value of $\rho \cdot \kappa / c_p$. From the above analysis, the most ideal ablative material for a reentry module is a low-density, low-temperature carbonization ablative material.

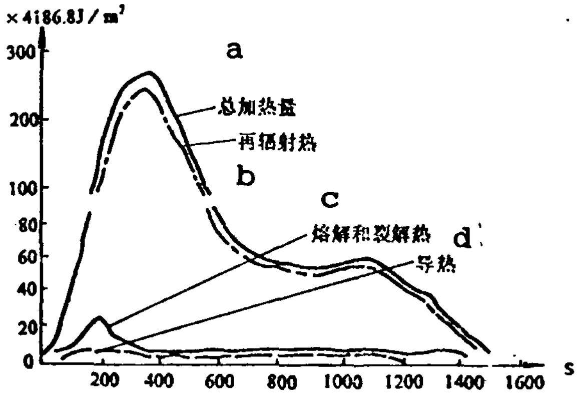

Fig. 3. Distribution of quantity of heat during ablation of low-temperature carbonization ablative material
KEY: a - total quantity of heat added
b - heat of re-radiation c - fusion and cracking decomposition heat
d - thermal conduction

III. Structural Coordination Property of Ablative Thermal Prevention Structure

Since the reentry module should operate in orbital space for a relatively long time, in addition to good ablative and insulation properties for the material, the properties of the material in space resisting vacuum radiation, coordination between the material and the load-bearing structure, and the formability of the material should also be considered.

In selecting a thermal prevention material for a reentry module, the structural coordination property of the material is a relatively unique problem. Although some materials have very good thermal properties, yet these materials have a relatively greater difference between the coefficient of linear expansion of the material, and the coefficient of linear expansion for the load-bearing structure, therefore mismatching occurs during heating and cooling.

1. Damage caused by structural incompatibility

Because of the structural incompatibility of the ablative thermal-protection structure, the thermal-protection structure may be damaged.

(1) In a cool environment, these damages include elongation damage of the ablative layer, and compressive damage of the ablative layer.

(2) the compression damage of the ablative layer during the reentry process; and

(3) in a cool environment, elongation damage of the adhesive layer, or shearing damage along the margins.

In the general situation, strength of the resin composite material is lower than the strength of metal materials. In particular, the tensile strength of plastics is relatively low. When the reentry module is in the low-temperature environment during the orbital stage, since the linear expansion of the ablative layer and of the structure layer are not compatible (generally, the coefficient of linear expansion is greater than that of metals), the ablative layer is in the elongation state as the layer is compressed along the structure; therefore, the elongation damage of the ablative layer at low temperatures is relatively significant.

2. Measures to solve the problem of structural incompatibility

There are three technical approaches in solving the problem of compatibility between the ablative material layer and the structure.

(1) Select an ablative material such that its linear expansion coefficient is close to the coefficient of the structure; or, select such an ablative material with better elasticity, thus reducing the stresses caused by expansion incompatiblity.

(2) Improve the connection mode between the ablative thermal protection layer and the structure layer, or modify the structural form of the thermal protection system.

(3) Select such an adhesive with better flexibility between the ablative layer and the structure layer; thus, the adhesive layer has sufficient elasticity and strength over a wider temperature range. The strains caused by different thermal expansion between the structure and the ablative thermal protection layer can be adjusted. This compression flexible adhesion system can absorb large amounts of energy due to shearing, compression and tension deformations, thus harmonizing the incompatibility between thermal expansion of the ablative thermal protection layer and the structure layer.

IV. Thermal Analysis of Ablative Thermal Protection Structure [3,7,8]

When selecting the thermal protection scheme and design of thermal protection structure, a thermal analysis of the ablative thermal protection structure should be conducted based on the thermal environment, thus determining the thickness of the ablative material, ablative layer and the heat insulation layer; thickness of the heat insulation layer; the working temperatures of the adhesive layer and the load-bearing structure; and the temperature distribution of various sites along the depth direction of the various layers.

1. Thermal design criterion of ablative thermal protection layer

The thickness of the ablative thermal protection layer is determined by the following factors.

(1) Design conditions should be selected for the ballistic external heat flow during heating with the maximum total heating that may occur in the reentry corridor.

(2) The allowable working temperature at the adhesive layer between the ablative thermal protection layer and the thermal insulation layer or the layer of load-bearing structure is an important factor.

(3) the allowable working temperature of materials for the load-bearing structure;

(4) If the equal-thickness design in the module is applied, it is required to select the site with the largest thermal load as the cross section for thermal analysis. If the variable thickness design is adopted in the entire module, various sites with typical representation should be selected for the thermal analysis.

2. Comparative selection of ablative computation model

With external thermal flux heating, three regions are formed in the low-temperature carbonization ablative material: carbonization region, reaction region (decomposition region) and the original material layer, referring to Fig. 4 (a).

The thermal conductivity and material transport equations are derived, based on the properties of these three regions. The thermal analysis computations can be conducted with known boundary conditions and known initial conditions. To simplify the computation, the compression in the reaction region can be compressed into a plane; this is shown in Fig. 4 (b) as the ablation model.

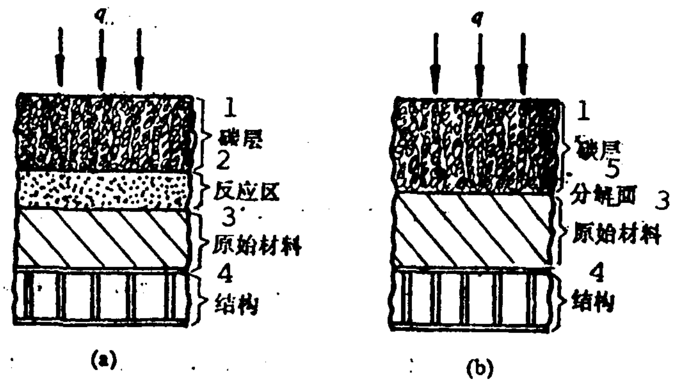

Fig. 4. Models for two types of ablation computation
KEY: 1 - carbon layer 2 - reaction region 3 - original material 4 - structure 5 - decomposition surface

The thermal analysis is conducted on two ablation models for the thermal prevention structure of the reentry module. Moreover, the computation results are compared with the results from ground experiments and flight experiments. Between the computation results and the experimental results for two types of ablation models, these results are basically consistent. The computation results and the experimental results by using the ablative model in Fig. 4 (a) are relatively consistent with the temperature distribution of the carbon layer thickness, and along the depth direction of the ablation thermal prevention structure. By applying the ablation model in Fig. 4 (b), the computed thickness of carbon layer is on the thicker side as compared with the experimental value; the computed surface temperature is on the lower side; and the computed temperature at the back wall is on the higher side.

The computation model in Fig. 4 (a) should be employed in the thermal analysis and design computation of the ablative thermal protection structure of the reentry module. If the computation in Fig. 4 (b) is applied in the design, the computation will allow the design to be on the conservative side; however, the model can be used for reaching a general estimate.

V. Results

The ablative thermal protection structure is the kind of thermal protection structure that is employed fairly broadly in the thermal protection of reentry vehicles. This structure is most often applied in reentry modules and reentry vehicles of reentry-type satellites. The structure can be used only once.

The ablative thermal protection structure has higher adaptation capability for variations in external thermal flux. This is because the ablative material is insensitive to variations of thermal flux density; damage to the thermal prevention structure will not caused due to variation of local or instantaneous thermal flux density. Conversely, the thermal efficiency of the thermal protection structure will increase with increasing density of thermal flux (within certain range). Therefore, this is a thermal protection structure with relatively high reliability.

When designing the ablative thermal protection structure, adequate consideration should be given to thermal compatibility between the thermal protection layer and the structural layer under the alternating environments of high and low temperatures in the operating orbit.

When selecting materials, further adequate consideration should be given to capabilities of resisting vacuum, radiation and low-temperature soaking of the ablative material. Finally, the realistic feasibility in the technical process is the determining factor in deciding on the thermal protection structure.

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