Study on the performance of inflatable decelerator under hypersonic aerodynamic load

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Abstract. In order to understand the influence of hypersonic aerodynamic force and aerodynamic heat on the performance of flexible structure of inflatable decelerator, a unidirectional thermal-fluid-structure three field coupling model under the extreme conditions of reentry trajectory is established in this paper. The temperature distribution of thermal protection structure (TPS) and structure response are obtained. The numerical results show that the TPS has a good insulation effect, and the cooling contribution of insulation layer in TPS is up to 80.90%. The stress is concentrated at the contact position between the flexible structure and the blunt head. The stress of TPS layer fluctuates greatly.

1. Introduction

The inflatable membrane has a large deformation due to the influence of hypersonic aerodynamic force and aerodynamic thermal load in the reentry process of inflatable decelerator, which leads to the shape change of inflatable decelerator, and then changes the aerodynamic loads. It is a typical thermal-fluid-structure three field coupling problem.

Since the 1980s, a lot of researches on hypersonic thermal-fluid-structure coupling have been carried out. A hypersonic thermal-structure coupling simulation of stainless steel plates was conducted by Thornton and Dechaumphai [1]. Besides, Allan et al. [2, 3] carried out a thermal-fluid-structure coupling study on a cylindrical shell, and compared the numerical results with wind tunnel test results [4]. In 2010, Culler and Adam [5] developed a prediction model to determine the strong and weak coupling relationship in thermal-fluid-structure coupling. Wu et al. [6] proposed a hierarchy solution for the hypersonic airfoil in thermal-fluid-structure coupling [7].

Traditional thermal-fluid-structure coupling problems are mainly about rigid structures such as airfoils, control surfaces and turbine blades [8-10]. Andrew et al. [11] obtained the surface deformation of hypersonic IAD by fluid-structure coupling method. The thermal-fluid-structure coupling problems about flexible structures are more complicated. They involve nonlinear structural dynamics and fully coupled interaction between the compressible fluid flow, with heat flux, and the membrane structure undergoing large deformations. Therefore, some simplification and hypothesis are necessary in the simulation of the thermal-fluid-structure coupling problems about flexible structures. Xia et al. [12] compared the loose coupling and tight coupling results of the heating problem of a hypersonic tube. It showed that the loose coupling method was more efficient and had similar accuracy as the tight coupling method when the characteristic time of the flow field was much smaller than the heat transfer.
In this paper, the characteristic time of the flow field is much smaller than the heat transfer, so a loose coupling method is used in the simulation. The thermal-fluid-structure coupling of the inflatable decelerator is calculated. The temperature distribution of the TPS layers and structural results are studied.

2. Coupling method

Coupling computation is realized based on Workbench software in this paper. The process of coupling calculation is shown in figure 1.

![Figure 1. Coupling calculation process.](image)

In this paper, S-A model is used as turbulence model to solve the hypersonic viscous flow. The wall of inflatable re-entry and descent technology (IRDT) is simulated as no-slip wall. The far field boundary is simulated as pressure far field. In heat transfer calculation, the radiation and convective boundary conditions are adopted at the outer and inner walls, respectively. The finite element method is used for structural calculation. Its boundary is inertia relief in static analysis. The physical quantities such as stress, displacement, heat flow and temperature on the coupling surface satisfy the following equation:

\[
\begin{align*}
  n \cdot \tau_f &= n \cdot \tau_s; \\
  u_f &= u_s; \\
  q_f &= q_s; \\
  T_f &= T_s
\end{align*}
\]

(1)

The fluid mesh is inconsistent with structure mesh on coupled surface because the solvers have different calculation velocities. The data transfer between different physical fields on the coupled surface is mapped by the mapping algorithm of grid interface [13].

3. Method verification

The accuracy of coupling method is verified by a round tube in the hypersonic flow [3]. The comparison of numerical results in this paper and literature [3] are shown in figure 2 and figure 3. The distribution of surface pressure and tube temperature are consistent with the literature results. The average errors of pressure and stagnation temperature are 1.3% and 15%, respectively. The maximum stress appears at the tube stagnation point. Its error is 5.1%. The above results show that the coupling...
method used in this paper can accurately predict aerodynamic forces, aero-thermal loads and their effects on the structure.

![Figure 2. Surface pressure of the tube.](image)

![Figure 3. Temperature distribution in the tube.](image)

4. Model

The IRDT simulated in this paper is a cone with six rings stacked inside (figure 4). The blunt head part is rigid and the cone part is flexible. The elastic modules of the blunt head part and cone part are 2e+11pa and 9e+10pa, respectively. The Poisson's ratios are 0.3 and 0.35, respectively. The thermal expansion coefficients are 1.2e-5/k and -2.5e-6/k, respectively. The TPS layers consist of a heat-shield layer, an insulation layer and a load layer. The calculation parameters are shown in table 1, the rings and load layer have same material parameters. This paper calculates two cases, one altitude, Mach number and attach angle are 82km, 24.6Ma and 0 degree, respectively. This case has the largest thermal load at the deceleration trajectory. Another altitude, Mach number and attach angle are 71km, 14.3Ma and 0 degree, respectively. This case has the largest force load at the deceleration trajectory.

![Figure 4. IRDT structure.](image)

| TPS layers     | Thickness (mm) | Density (kg/m³) | Thermal conductivity (w/(m.k)) |
|----------------|----------------|-----------------|-------------------------------|
| Heat-shield layer | 0.508          | 1362            | 0.146                         |
| Insulation layer    | 6              | 128             | 0.12                          |
| Load layer          | 0.3            | 1468            | 0.04                          |

5. Results

5.1. Temperature distribution of TPS layers

Since IRDT is centrosymmetric, the temperature distribution of TPS layers is also centrosymmetric. The distribution curves along the meridian are shown in figure 5. It can be seen that the temperature of TPS layers are higher under the condition of 24.6Ma. The heat-shield layer can resist high temperature. The heat insulation effect of the insulation layer is obvious because its thickness is large. The load layer is used for absorbing load with low heat insulation effect. The contribution of each TPS layer for
heat insulation is 6.87%, 80.90%, 12.23%, respectively. The heat insulation effect can be improved by changing the thickness or thermal conductivity of the TPS layers.

![Temperature distribution curves of TPS layers along the meridian](image)

**Figure 5.** Temperature distribution curves of TPS layers along the meridian (up:24.6Ma down: 14.3Ma).

5.2 Structure response

![IRDT deformation contours](image)

**Figure 6.** IRDT deformation contours.

Figure 6 are IRDT deformation contours. It can be seen that the deformation of IRDT is small under an internal pressure of 150kPa. The deformation of IRDT is higher under the condition of 24.6Ma. The blunt head part has larger deformation because it has large thermal expansion coefficient and high temperature. The maximum deformation of rings is located at the outermost ring. The maximum deformation of TPS layer is located at gap which is connected with the rings.
Figure 7. Stress distribution curves of TPS layers along the meridian (up: 24.6 Ma down: 14.3 Ma).

Figure 7 shows the stress distribution curves of TPS layers along the meridian. The stress distribution law is consistent in two cases, while the values are larger under the condition of 24.6 Ma. Stress concentrations are occurred at the contact position between the flexible structure and the blunt head. The change of the stress distribution curves of TPS layers are basically the same. The flexible structure between two rings would collapse when subjected to external aerodynamic loads (figure 8), leading to a wavy distribution of the stress. Under an internal pressure of 150 kPa, the upwind pressure and internal pressure are almost equal. The outer layer and the inner layer both exert a force to the middle layer (figure 9 (a)), so the middle layer has the minimum stress at the windward side. At the leeward side, the internal pressure is greater than the external pressure (figure 9 (b)), so the stress increases from the inside to the outside.

Figure 8. Force diagram of the TPS and ring.

Figure 9. Force diagram of the TPS layers.

6. Conclusion
This paper establishes a unidirectional thermal-fluid-structure model to analysis the performance of IRDT under the maximum aerodynamic thermal load condition (Ma=24.6) and the maximum aerodynamic force load condition (Ma=14.3). The conclusions are as follows:

1) The TPS layers have a good insulation effect, and the cooling contribution of insulation layer is the most significant as its cooling contribution is up to 80.90%.
2) IRDT can still maintain a good aerodynamic shape under high inflated internal pressure.
3) The TPS layers have higher temperature and stress under the condition of 24.6Ma.
4) The maximum stress appears at the contact position between the flexible structure and the blunt head. Due to the interaction between TPS layer and rings, the TPS layer has a wavy distribution of stress. The insulation layer has the minimum stress at the windward side, while the load layer has the minimum stress at the leeward side.

Acknowledgments
Supported by the National Natural Science Foundation of China (11602018). A Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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