THERMAL-MECHANICAL COUPLING ANALYSIS AND OPTIMIZATION DESIGN ON TPS WITH GAP

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Abstract

The connection area of the thermal protection system (TPS) of hypersonic vehicle is prone to be weak area due to the aerodynamic heat, structural matching and assembly technology, etc. However, the analysis of thermal protection structure always ignores the gap leading to error. In order to design TPS structure more accurately, it is needed to consider the local heat effect of the gap to get more accurate temperature distribution. The influence of the gap heating on structure temperature field with gap and without gap was studied under a typical reentry condition. Then, the thermal-mechanical coupled optimization model was developed using FEM software Abaqus Python script file based on the optimization Isigh platform to fulfill both thermal and mechanical functions for minimal areal density. The dimensions of thermal protection component were optimized based on gradient optimization algorithm, taking insulation tile height, gap width and strain isolation pad thickness as the design parameters, considering temperature, stress, expansion and deformation as design constraints, using the minimal mass per unit area as the objective function. After 170 times of iterative calculation, the minimum mass per unit area of the TPS was obtained. The results show that the TPS structure thickness and the mass per sectional unit area decreased by over 50%, and the performances of materials were fully utilized. Compared to the optimization result of ignoring the local heat gap heating, the gap width decreased and the heat insulation tile height and the SIP thickness increased.

1 Introduction

Once hypersonic air flows over the aircraft, the aircraft surface temperature increases rapidly by the violent friction and energy exchange leading to a large temperature gradient in the TPS. For example, the temperature range of the different positions on the TPS of aircraft is from 650K to 1700K during the launch and reentry [1]. To ensure the efficiency of structure, it is necessary to use different materials in different regions [2]. Even if the same material is used in one area, considering the manufacturing process and replacement, modular assembly design is needed [3]. Therefore, connections inevitably occur in the TPS components, and gaps are the main forms. For example, gaps are widely used in the TPS of the space shuttle for releasing the stress caused by thermal expansion and aerodynamic load between the reusable insulation tiles as shown in Fig.1. However, gaps may potentially result in the local heating, where hot plasma leaks into the structure.

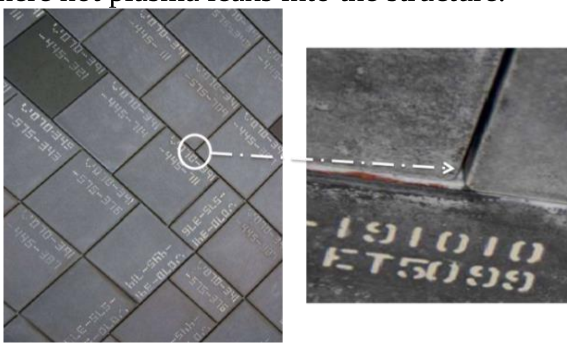


Fig.1 RSI on Space Shuttle

For the TPS with gaps, the researchers have studied by the means of theoretical analysis, the numerical simulation and experiments. The theoretical study of gaps heat flux for supersonic and hypersonic flows was started by Chapman [4] in 1956. Then Denison [5] developed the theoretical model of Chapman, which was proved by Larson and Nicoll [6,7] in experiments. However, the theories could not predict the local heat flow distribution along the wall inside the gap until Burggraf [8] presented a revised theory which put forward the local heat flux along the wall in the gap. The theory was proved to be in good agreement with the experimental and numerical results in various flow conditions [9,10]. To better understand the thermal performance of the TPS, a tile gap heating experiment was developed and the research showed that the peak heat flux of the gap heat flux on upper side of the windward wall may be several times of the condition without gap [11]. Besides, Blosser [12] found that radiation heating became particularly important when the temperature of insulation tiles is relative high, which may be a vital factor of the gap heating.

It can be seen that the heat transfer mechanism in the gap of TPS is extremely complex, involving convection, radiation and conduction, as shown in Fig.2. In fact, the gap heating in the TPS structure depends on the thermal state and width of the gap in a severe transient thermal environment.

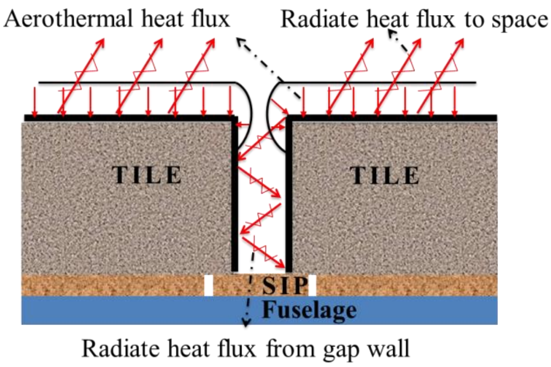


Fig.2 Mechanism in TPS gap heating

In this paper, the influence of the gap heating with local aerodynamic heating and radiation on the temperature field inside the TPS component was studied and the dynamic responses of the structure under a reentry flight condition were analyzed. On this basis, a thermal-mechanical coupling optimization model of TPS component was established, and the influence of the gap heating on thermal protection structure design was studied.

2 Thermal-mechanical Coupling Analysis

From the perspective of heat protection, vehicle surface discontinuities should be avoided to preventing high-temperature air sneaking into the gap, leading to the local heat effect. From the perspective of heat matching, gaps can release the thermal stress and expansion, avoiding excessive local stresses. Therefore, there is a contradiction between thermal protection and heat matching in the design of TPS structure. The effect of the geometric change of the gap caused by the expansion and deformation of the TPS structure by the local heat effect of the gap must be considered in the design.

2.1 Model Description

The thermal protection system of the shuttle orbiter is mainly made up of reusable surface insulation (RSI) tiles with coating, which are bonded to the aluminum skin of the vehicle through a strain isolation pad (SIP).

Considering the thickness of RSI tiles is about 0.5~4.0 in (12.7~101.6mm), and the width of the gaps is 0.01 in~0.13in (0.254~3.3mm) depending on their locations on the vehicle in the different temperature range (900K~1500K) in reference [13], an initial TPS component (400×400×66mm) is designed, as shown in Fig.3. The height of tile is 60 mm, the width of gaps is 0.8 mm and the thickness of SIP and metal skin is both 3mm.

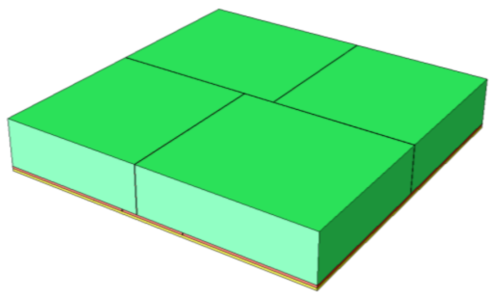


Fig.3 Initial TPS components

Table.1 shows the properties of materials used in this model and some of the properties depending on temperature are listed as average values. To be specific, the material of SIP used between the metal skin and the insulation tiles to release thermal stress is a nonlinear superelastic material and the relationship between stress and strain is taken from the reference [14].

Table.1 Material properties

Parameters	Tile	Al	SIP
ρ (Kg/m^3)	200	2770	150
E (MPa)	30	70	-
μ	0.2	0.3	-
C_p (kJ/kg·K)	1.0	0.9	1.0
k (W/m·K)	0.05	155	0.06
α (10^{-6}/K)	1.15	24.5	30
ε	0.85	0.12	0.85

2.2 Load and Boundary Conditions

In order to prevent the turbulent transition of hypersonic flow and alleviate the pressure difference between tiles, TPS tiles are arrayed with 45 degree diagonal orientation of the main flow direction. As shown in Fig.4, the "A tile" has two leeward sides while the "C tile" has two windward sides, and the "B tile" has a leeward side and a windward side, the same as "D tile".

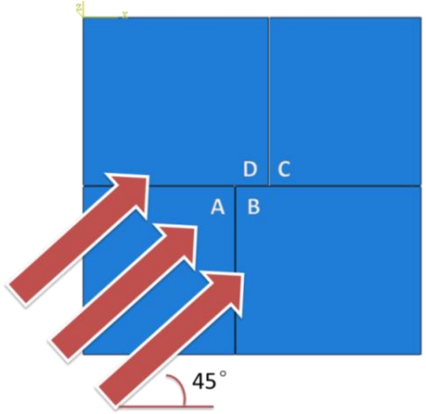


Fig.4 Tiles array orientation

When there is a drift angle between the orientation of flow and tiles gap, the three-dimensional flow field becomes too complex and difficult to calculate accurately. In order to simplify the problem, the method of equivalent width is used, considering the temperature history of the gap wall surface caused by the two-dimensional and three-dimensional gap flow were approximately the same as reference [11] shown. By means of the equivalent width conversion (in Fig.5), the gap width can be converted from 0.8mm to 1.13mm, and the depth is still 60mm.

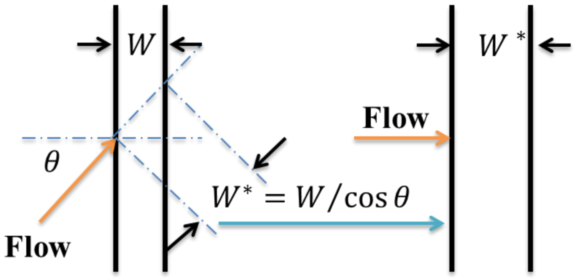


Fig.5 Conversion of equivalent gap width

The hypersonic airflow mainly affects the top area of gap, and the effective depth is about 2.5 times of the gap width, that is, the heat flux in the gap below 2.8mm is quite little that can be ignored. Then the relative heat flux on the windward and leeward surfaces of gap wall in 2.8mm depth was calculated integrally respectively, which is 0.16 and 0.06 of the local surface heat flux according to Burggraf's theory.

In the thermal analysis, a uniform thermal heat flux is applied on the TPS surface. To be specific, the surface heat flux was corrected from cold wall heat flux (in Fig.6), involved the recovery enthalpy, wall temperature and external thermal radiation, written by the user defined subroutine in Fortran. The gap wall surfaces are applied as cavity radiation boundary. The initial temperature and the environment temperature are 300K. All the other boundaries are assumed to be adiabatic boundary.

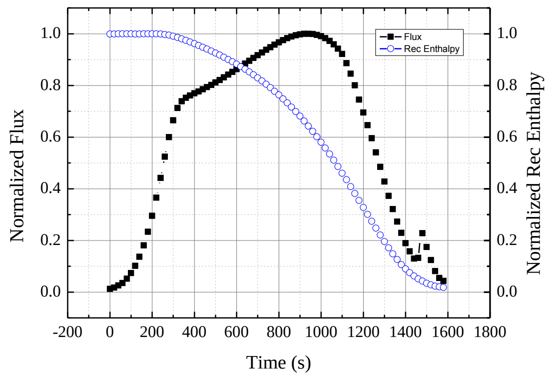


Fig.6 Thermal load of a trajectory

In the stress analysis, the metal skin edges are fixed and a uniform pressure of 11kPa is applied on the TPS top surface. All the other boundaries are set to be free.

2.3 TPS Structure Responses Analysis

To obtain the thermal-mechanical responses required for the design constraints of the TPS component, heat transfer and structural analysis is performed.

As shown in Fig.7, the max temperature appeared on the top surface to the TPS tiles at 910s, and local thermal increment arose in the windward side.

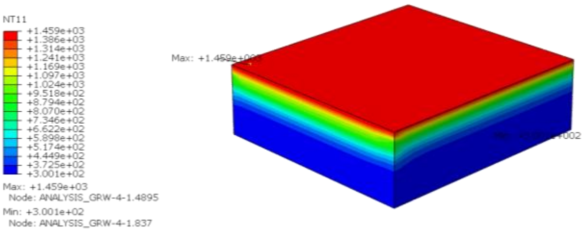


Fig.7 Thermal field of the "B tile" at 910s

The temperature field of the TPS component at 1580s is shown in Fig.8. It can be seen that the maximum temperature is 1058K appearing on the surface of the tiles, which is 21K higher than that of without gap (1037K). Because of the heat radiation effect, the temperature near the gap is lower than the tile surface at 1580s.The temperature field of SIP is shown in Fig.9. The max temperature of SIP is 305K in gap cross region, 4K higher than that of without gap. The local heat increase is caused by the cavity radiation in the gap.

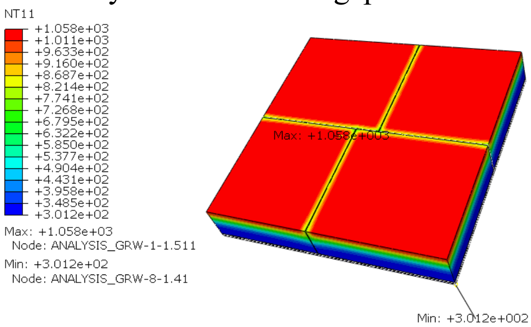


Fig.8 Thermal field of TPS at 1580s

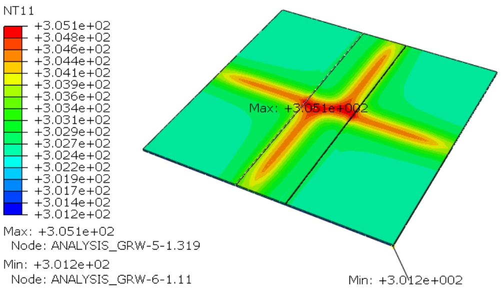


Fig.9 Thermal field of the SIP at 1580s

The temperature history curves at different depths of the gap under two conditions of considering and neglecting the gap (expressed by points and lines, respectively), as shown in Fig.10.

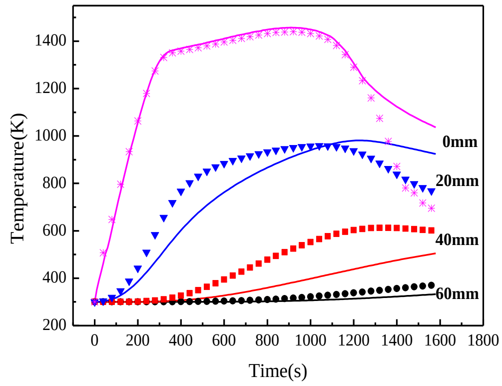


Fig.10. Temperature histories in two conditions

It can be seen that temperature response is generally consistent with the heat load. The local heat increase in the range of the gap depth of 40~60mm is relative obvious, because of the radiation heating from the upper wall surface in the gap. Therefore, the local effect of radiation should be considered in the design of TPS components.

The gap distance and contact pressure of tiles are respectively shown in Fig.11 and Fig.12.

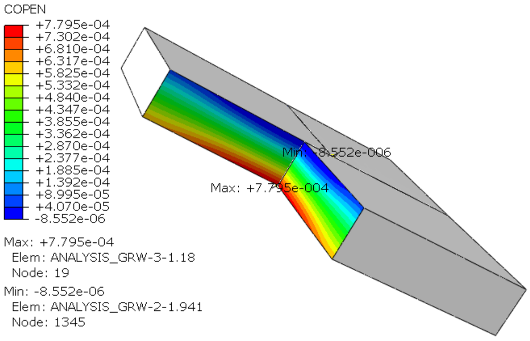


Fig.11 Gaps distance of tiles

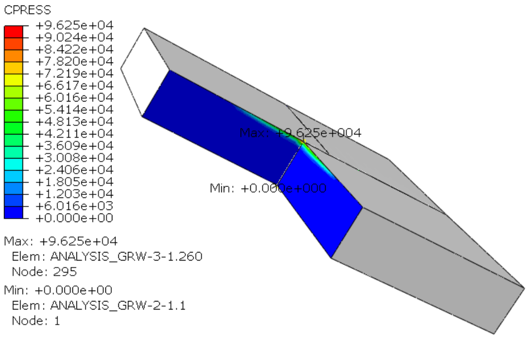


Fig.12 Contact pressure of tiles

It is obvious that the contact pressure at the upper edge of the gap is 96 kPa and the gap is closed by the effect of the external aerodynamic load, which may cause inner TPS structure damage. Because the insulation tile is relatively fragile and the damage tolerance is relatively low, the contact stress should be avoided or less than the maximum capacity of the insulation tiles in the design of TPS components.

As shown in Fig.13, there is little stress concentration on the skin because of existence of SIP, which coordinates the deformation between the insulation tile and the Al alloy skin well. The maximum Mises stress of the metal skin is 16.3MPa, far less than the allowable value (340MPa) of Al alloy.

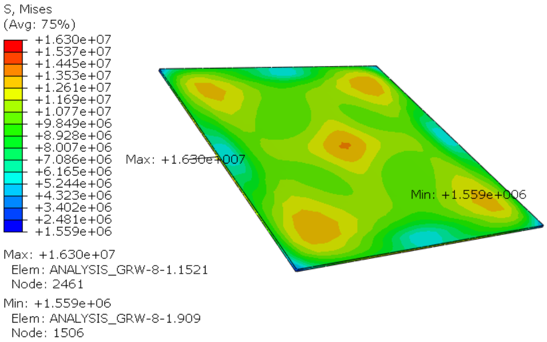


Fig.13 Stress of the Al alloy skin

After the thermo-mechanical coupling analysis, it has been found that the squeezing between the tiles occurs on the upper gap, because of the thermal expansion caused by the aerodynamic heating and the metal skin deflection caused by the aerodynamic pressure. In addition, the initial design does not make full use of the materials performance: the temperature of the tiles middle area is less than 600K while the SIP and metal skin temperature remain about 300K. The metal skin maximum Mises stress is 16.3MPa, far less than the allowable value. To improve the structure efficiency, it is necessary to optimize and redesign the initial TPS components.

3. TPS Structure Optimization Design

3.1 Optimization Model Definition

Although there are many factors that influence the design of the TPS, the basic design of TPS structure should be considered from the aspects of heat, deformation, stress and so on.

- The temperature of the aircraft structure should not exceed the allowable temperature of the material, for aluminum skin, the maximum temperature is no more than 420K.
- The maximum stress of the structure should not exceed the allowable value, for aluminum skin, the maximum Mises stress is no more than 340Mpa.
- The deformation of the thermal protection structure panel should be controlled to delay the turbulent flow transition, that is, the maximum deflection should not exceed 1% of the diagonal span of the whole panel.

It must be pointed out that the thickness of insulation tiles should be as thin as possible to ensure the flight performance and the weight of the whole structure should be as light as possible to save the flight cost.

According to the TPS structure design requirements, the mathematical description of the thermal-mechanical coupling optimization model is shown in Table.2.

Table.2 Optimization mathematical descriptions

Design variables	
Tile height	$15\text{mm} \le h \le 60\text{mm}$
Gap width	$0.2\text{mm} \le w \le 3\text{mm}$
SIP thickness	$1\text{mm} \le t_{SIP} \le 4\text{mm}$
Constraints	
Skin temperature	$T \le 420\text{K}$
Skin Mises stress	$\sigma \le 340\text{Mpa}$
Tiles deformation	$u \le w_{gap}$
Panel bending	$\delta/\sqrt{2}L \le 1\%$
Optimization objective	
TPS structure mass	$M = f(h, w_{gap}, t_{SIP}) \rightarrow min$

3.2 Optimization Model Analysis

In the study, A TPS structure optimization process is developed in ISIGHT platform as shown in Fig.14. Design variables are mapped to the Python script file written to perform the thermo-mechanical coupling analysis based on Abaqus solver. The TPS components optimization is a single objective optimization problem with multi-constraint, and the gradient optimization algorithm NLPQL was used to in this optimization.

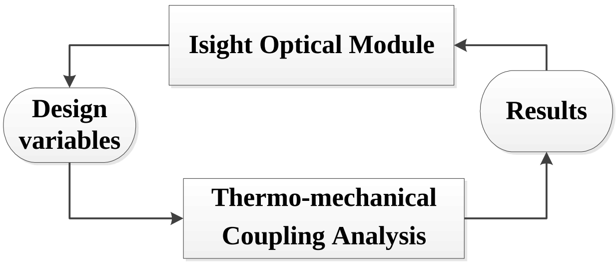
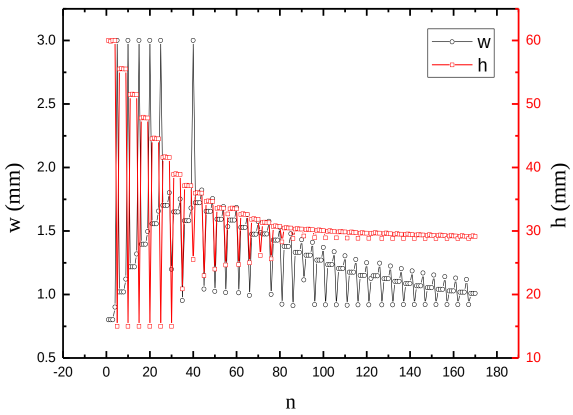
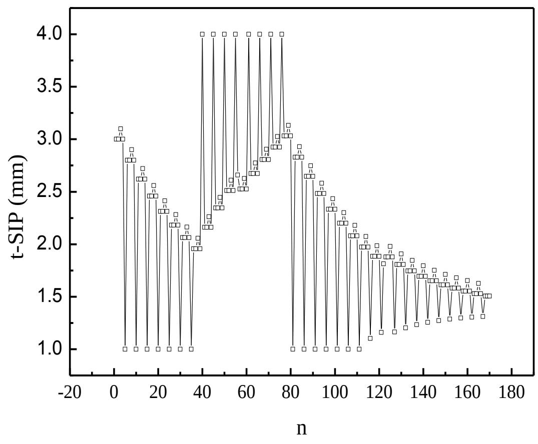


Fig.14 Optimization process

After 170 iterative calculations, the design variables and the objective are optimized as Fig.15 and Fig.16 show.



(a) Tiles



(b) SIP

Fig.15 Design variables optimization history

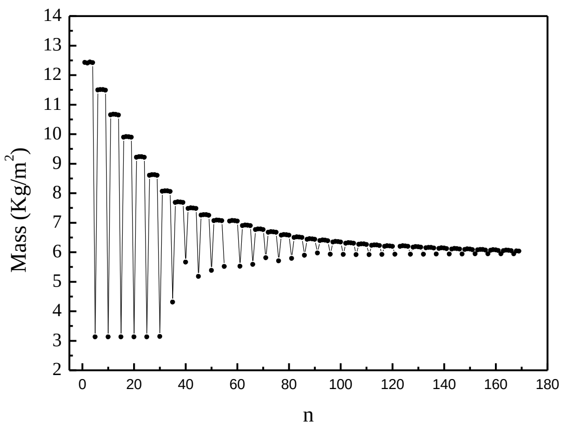


Fig.16 Objective optimization history

3.3 Results and Discussion

Two conditions of considering and ignoring the local heat effect caused by the gap were optimized. In Table.3, the size variables, response parameters and the unit area weight of initial design and optimized are listed.

Table.3 Results of the optimization design

Parameters	Initial design	Optimized design with gap heating effect	Optimized design without gap heating effect
h (mm)	60	29.14	28.60
w_{gap} (mm)	0.8	1.11	3
t_{SIP} (mm)	3	1.51	1.15
u (mm)	-0.11	0.18	2.09
$\delta/\sqrt{2}L$	0.3%	0.97%	0.95%
T_{skin} (K)	301.0	388.9	389.8
σ_{skin} (MPa)	17.8	328.3	339.8
$Mass$ (Kg/m^2)	12.43	6.04	5.85

Comparing the two optimized results of considering and ignoring the local heat effect, the gap heating effect leads to increases the thickness of tiles and SIP as well as the sectional unit area mass. The main contribution to the increases is the local heat effect caused by the local heat flux and wall radiation in the gap.

The optimized result with local heat effect shows that the tile height reduced from 60mm to 29.14 mm compared with the initial design, and the overall thickness decreased by 51.3%. The sectional unit mass decreased from 12.43 Kg/m^2 to 6.04 Kg/m^2, and the weight lost 51.4%. Also, the maximum temperature of the metal surface increased from 301K to 389K, and the maximum Mises stress increased from 17.8MPa to 328Mpa, thus the material performances were fully used. The width of the gap increased from 0.8mm to 1.1mm to protect the tiles from squeezing during the entire flight and ensure the tiles much safe and reliable. It can be seen that the comprehensive performance has been greatly improved after optimization.

4. Conclusion

The thermo-mechanical coupling analysis was conducted on an initial TPS component under a typical reentry condition to study the gap effects. The results indicate that the gaps must be controlled because of the local heat effect by the gap heating flux and radiation. The wall surface radiation in the gaps makes an obvious radiant heating in the middle and bottom of the gaps. Then the initial TPS structure with gaps was optimized using a thermal-mechanical coupling optimization model under two conditions of considering and ignoring the gap heating effect. Compared with the optimized result of ignoring the local heating effect, the gap heating increased the TPS structure overall thickness and mass, but narrowed gap width.

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