Variable Leading Edge with Adaptive Thermal Barriers and Its Heat Transfer Behaviour

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Abstract. At present, the hypersonic vehicles cannot be adapted to all the flight phases perfectly, and the aerodynamic heating and lift - to - drag ratio are contradictory to the shape of the vehicles. From the perspective of aerodynamic heating, a blunt shaped body is desired to reduce the heat flow of the hypersonic vehicles. However, the lift - to - drag ratio demands a sharp leading edge. In this paper, a scheme of variable leading edge which could satisfy with both the requirements of aerodynamic heating and lift-to-drag ratio was investigated, and an adaptive thermal barrier was proposed based on the features of the variable leading edge hot structure. According to the heat flux calculated from a certain trajectory by computational fluid dynamics, the heat transfer behaviour of the variable leading edge with adaptive thermal barriers was analyzed by the finite element method. The results indicated that the temperature peak of the panel reached 1428.2 K at 400 s, temperature of the adaptive thermal barriers approached 1418.4 K at 420 s, and the temperature of the internal insulation increased to 667.86 K finally. At the end of trajectory, temperature distribution in the thermal barrier and internal insulation tended to be balanced respectively, which exhibited an excellent thermal property and a promising prospect in complex environment.

1. Introduction

Hypersonic vehicles are always threatened by severe aerodynamic heating when re-entering from orbit. In this process, the speed of the vehicles reduced from more than Mach 25 to 0, and thermal protection system (TPS) is required to prevent the fuselage and devices of the vehicles from being burnt down [1]. As a result, blunt shaped heat shield was designed for the re-entry capsule of spacecraft to moderate aerodynamic heating, as well as the shape of nose cap and leading edge for the Shuttle [2]. The problem with this scheme is that it reduces the lift - drag ratio $K$ of the aircraft, which leads to the decrease of the maneuver performance of the vehicles in the low speed state.

In the 1960s, variable sweep wings were adopted by Northrop Grumman developed F-14 Tomcat (Figure 1) [3]. To reduce the drag for high subsonic to supersonic speed, variable sweep wings of the F-14 are set at 20° for taking off and landing, and 68° for loitering, changing automatically. Some concepts of morphing aircraft was proposed like Z-wing morphing UAV [4]. Although many gaps are produced during variable sweep wings changing, the aircraft does not have to cope with the problem of aerodynamic heating - the maximum speed of the F-14 Tomcat is only Mach 2.4, which is far less than the spacecrafts back from the orbit and no problem with aerodynamic heating.
If the same idea is applied to hypersonic vehicles, a series of new gaps will be generated on the exterior and interior of thermal protection system. High temperature air flows into the interior structure through the gaps and the fuselage facing with the ultra-high temperature will be burnt down, take space shuttle Columbia for example [5]. To seal the gaps in large scale is an urgent problem, many researchers studied on the seals for control surface [6] [7], rocket motor [8] and vehicle surface [9].

However, much of the research up to now has been descriptive in gaps without morphing. In this study, a scheme of leading edge hot structure with adaptive thermal barrier was investigated, which could change the configuration of leading edge and accommodate with different status such as hypersonic re-entry and low speed landing for spacecrafts. In addition, heat transfer behaviour of this scheme in a certain trajectory was analyzed by finite element method.

2. Scheme of Variable leading edge

2.1. Heat flux of stagnation point for leading edge

In order to identify the factors influencing on aerodynamic heating, heat flux of stagnation point for leading edge area was firstly studied. The aerodynamic heating flux could be estimated by

\[
q_w = \rho_{\infty}^N v_{\infty}^M C
\]

(1)

Where, \(q_w\) is heat flux of the surface, \(\rho_{\infty}\) is density of free stream, \(v_{\infty}\) is speed of free stream. \(N, M\) and \(C\) are given different values at different conditions respectively.

For the stagnation point, \(M = 3, N = 0.5\), \(C\) is given by

\[
C = 1.83 \times 10^{-8} R^{-0.5} \left(1 + \frac{h_w}{h_0}\right)
\]

(2)
Where, $R$ is radius of the stagnation point, $h_0$ is enthalpy of air flow, $h_w$ is enthalpy of air flow at surface temperature $\theta_w$. Therefore, heat flux of the surface $q_w$ is proportional to $R^{-0.5}$.

Meanwhile, the heat flux distribution in the leading edge area was simulated by computational fluid dynamics (CFD) in a certain flight state with the radius of the stagnation point 100 mm and 80 mm respectively, and the results were shown in Figure 3. The CFD simulation revealed that the maximum heat flux in the leading edge was 128 kW/m² with 100 mm the radius of the stagnation point, compared to 164 kW/m² with the radius of 80 mm.

![Figure 3. Distribution of heat flux in leading edge with different radius of the stagnation point ($R$).](image)

![Figure 4. Scheme of the variable leading edge hot structure: (a, left) aerodynamic heating phase; (b, right) low speed phase.](image)
2.2. Scheme of the variable leading edge

Heat flux in leading edge and lift-drag ratio of hypersonic vehicles are both influenced by the radius of stagnation point $R$, which is a parameter related to the aerodynamic shape of the vehicles. A growing radius of the stagnation point $R$ leads to a decrease of heat flux of the surface $q_{sw}$, and lift-drag ratio $K$ goes down as well which does harm to the maneuver performance of the vehicles.

To balance the needs of aerodynamic heating and lift-drag ratio of hypersonic vehicles, a variable leading edge hot structure was investigated, which could keep a relatively low heat flux in aerodynamic heating phase with a blunt area towards the air flow and a relatively good maneuver performance in low speed phase with a shaper edge towards the air flow. The variable leading edge hot structure was shown in Figure 4, which consisted of revolvable panel, fixed panels, adaptive thermal barriers and internal insulation (Figure 5).

![Figure 5. Components in the variable leading edge hot structure.](image)

For each section of variable leading edge, revolvable panel (Figure 5 (a)) and fixed panels (Figure 5 (b) and (c)) were fabricated by C/SiC composites which can withstand temperatures above 1900 K. Fixed panels were bonded to the fuselage by super alloy fasteners. Adaptive thermal barriers (Figure 5 (d) and (e)) manufactured by whiskers modified woven alumina fibers and alumina fibers braided ropes by different diameters was applied to resist high temperature air flowing into the interior.
structure through the gaps between revolvable panel and the fixed one, which exhibited excellent compression-recovery performances at temperatures above 1700 K. The adaptive thermal barriers were compressed to seal the gaps between the revolvable panel and the fixed ones, as shown in Figure 4 (a). While the adaptive thermal barriers recovered from compression, after a rotation of the sharper edge of the revolvable panel towards the air flow, and hot air could not flow into the leading edge yet. Internal insulation (Figure 5 (f)) made from alumina fibers was applied to resist the cavity radiation and heat conduction from the panels. Meanwhile, during the aerodynamic heating stage, the internal insulation was compressed in case of air stream flowing into the hot structure. Both adaptive thermal barriers and internal insulation were constrained to the fixed panels by inorganic high temperature adhesive and fasteners.

As shown in Figure 6, the revolvable panels of the variable leading edge hot structure were driven by universal joints mounted on the fuselage to turn to the other side through the axis simultaneously, when aerodynamic heating was almost negligible.

![Figure 6. Rotating of the variable leading edge hot structure driven by universal joints.](image)

### 3. Methodology

#### 3.1. Heat transfer theory

According to heat transfer theory, the basic equation of energy conservation for general three-dimensional heat conduction problems is given by [10]

\[
\int_V \rho U \, dV = \int_S q \, dS + \int_V \rho \frac{d}{dt} \theta \, dV
\]  

(3)

Where, \(\rho\) is density of material, \(U\) is the derivative of the internal energy to time, \(S\) is the surface of material, \(V\) is the boundary of the solid structure, \(q\) is heat flux per unit area flowing into solids, \(r\) is the heat obtained per unit volume.

The finite element method was used to predict the heat transfer character of the variable leading edge. Thermal conductivity considered separately, the equation (1) obtained by Galerkin method is given by

\[
\int_V \rho U \, dV + \int_V \frac{\partial \theta}{\partial \tilde{x}} \, \frac{\partial \theta}{\partial \tilde{x}} - \int_S \theta \, dS + \int_V \rho \frac{d}{dt} \theta \, dV
\]

(4)

Where, \(\tilde{k}\) is thermal conductivity matrix, \(\tilde{x}\) is space locations.

Solid temperature field equation approximated by element interpolation function is given by

\[
\theta = N^\theta (x) \theta^\theta, N = 1, 2, \cdots
\]

(5)

Where, \(\theta\) is nodal temperature.

Hence, the final solution equation is given by
\[ \int \nabla \cdot \rho \dot{U} \, dv + \int \left( \frac{\partial \nabla}{\partial x} - \frac{k}{\partial x} \right) \, dV = \int \nabla q \, dS + \int \nabla N \, r \, dV \] (6)

Boundary conditions are generally a mixture of three types of boundary conditions.

In this study, Neumann boundary condition was given by cold wall heat flux, while surface temperature of the structure was related to hot wall heat flux. The conversion equation of cold wall heat flux to hot wall heat flux is given by

\[ q_s = q_c \left( 1 - \frac{h_w}{h_r} \right) - \sigma \varepsilon \theta_w^4 \] (7)

Where, \( q_s \) is hot wall heat flux, \( q_c \) is cold wall heat flux given by initial condition, \( h_r \) is enthalpy of air flow at recovery temperature, \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon \) is radiation coefficient of structure surface. Surface temperature \( \theta_w \) and enthalpy \( h_w \) of air flow at surface temperature \( \theta_w \) are given by

\[ h_w = \begin{cases} 0.796329 \theta_w^{1.041} & 170K < \theta_w < 1748K \\ 78.4187 \exp \left[ 3.178 (\theta_w / 1748)^{1.9} \right] & \theta_w \geq 1748K \end{cases} \] (8)

\[ a = \frac{1}{2.41 + 7.09637 \times 10^2 \ln \left( \frac{p_e}{101325} \right)} \] (9)

Where, \( p_e \) is surface air flow pressure.

\[ 
\text{Figure 7. Finite element model of variable leading edge with adaptive thermal barriers.}
\]

3.2. Finite element model

The finite element model of three dimensional structure of variable leading edge for heat transfer was established taking one section of leading edge as the research object by ANSYS 13.0. Based on the geometric model of variable leading edge with adaptive thermal barriers, a finite element model was established and some details were simplified. The hexahedron dominant method was used for mesh generation for consideration of accurate solution. The model shown in Figure 7 was divided into
58461 nodes and 61592 elements. The data of thermal and physical properties of the materials applied in variable leading edge were gathered through experiments.

3.3. Boundary conditions
The heat flux obtained from a specific re-entry trajectory by equation (7) and equation (8) was applied on the surface of revolvable panel and fixed panels of the variable leading edge. The heat flux near the windward which was applied to the revolvable panel and the windward one, was 20% higher than the leeward side, and a typical heat flux during the trajectory was shown in Figure 8. To simplify the finite element model, the internal insulation was radiated from revolvable panel instead of bonded. The rest of the area in the model was free of convection and thermal radiation. Heat transfer analysis of the variable leading edge was solved by transient thermal finite element analysis program, and the distribution of temperature in each component was obtained.

![Figure 8. Heat flux applied to the surface of the variable leading edge.](image)

4. Results

4.1. Heat transfer in panels
The maximum temperature change of the panels was given in Figure 9, which grew up from 300 K to reach the highest point of 1428.2 K at 400 s and dropped to around 1100 K remained almost steady for about 140 seconds, then the temperature decreased to 798.14 K at last. Meanwhile, the minimum temperature exhibited the same trend as the maximum and reached the peak 1096.6 K at 530 s. According to equation (7), the trend of maximum temperature and heat flow displayed sin Figure 8.
with time was basically the same. However, at the second heat flow peak around 800 s, the maximum temperature did not increase, a reasonable explanation was that a great amount of heat was taken away by radiation of the panels to the ambient and heat conduction of the variable leading edge itself, and the increased heat flow was not significantly.

The heat transfer behaviour of the revolvable and fixed panels were illustrated in Figure 10. A large area of the revolvable panel and the windward panel reached the maximum temperature of 1428.2 K in 400 s, corresponding with the peak of heat flux, while the leeward panel was about 1330K. The highest temperature appeared near the connection area of windward panel to the fuselage in 530 s, with the temperature at other area decreased. The heat flux decreased obviously from 400 s to 530 s, therefore, temperature in revolvable panel and the windward panel decreased due to radiation and heat transfer for a relatively high thermal conductivity of C/SiC composites, while the temperature in connection area of the fixed panels was increased by heat transfer. As heat conduction progressed, temperature distributed more uniformly, and the highest temperature 1041.9 K occurred in the revolvable panel near the internal insulation in 820 s. At the last moment of the trajectory, 1300s, the peak of temperature of the panels was still located at the revolvable panel near the internal insulation. The temperature of the windward panel reduced to 720K with the leeward panel 700K respectively by meantime.

![Figure 10](image)

**Figure 10.** Heat transfer behaviour of the panels during aerodynamic heating.

4.2. Heat transfer in adaptive thermal barriers

The discipline of heat transfer in adaptive thermal barriers was consistent with the panels. The maximum temperature demonstrated in Figure 11 was almost the same with the panels. That is because the adaptive thermal barriers were connected to the panels, once the panels heated, the temperature transferred to the thermal barriers instantaneously.
Figure 11. Temperature change of the adaptive thermal barriers.

Figure 12. Heat transfer behaviour of the adaptive thermal barrier of the windward side.

Heat transfer behaviour of the windward side thermal barrier was revealed in Figure 12. Combining the results of Figure 11, the maximum temperature peaked at 1418.4 K in 420 s, and fell gradually to 853.01 K at the end of trajectory, with a relatively balanced state from 600 s to 850 s. During the relatively balanced state, temperature of the panels decreased by the affection of the environment and thermal conduction. The thermal conductivity of adaptive thermal barriers is lower than the C/SiC fabricated panels, indicating that the cooling rate of adaptive thermal barriers was slower than the panels. After the panel temperature lowered, the adaptive thermal barriers exhibited a higher temperature. As a result, the heat transferred from the thermal barriers to the panels with the surface temperature of the adaptive thermal barriers decreasing. At the same time, heat transfer from the exterior of the adaptive thermal barriers to the interior was still ongoing, causing a decrease of thermal...
gradient in the adaptive thermal barriers. In conclusion, the temperature of the adaptive thermal barriers was lowered and the thermal distribution tended to be more uniform. Due to the long time of heat transfer process, thermal distributed in the adaptive thermal barrier tended to be balanced.

Thermal distribution of the leeward side adaptive thermal barrier shown in Figure 13 explained completely the same phenomena to the windward one, while the only difference was thermal conductive efficiency induced by heat flux. The temperature peaked at 1341.1 K in 430 s and dropped to 831.96 K at last.

**Figure 13.** Heat transfer behaviour of the adaptive thermal barrier of the leeward side.

**Figure 14.** Temperature change of the internal insulation.
4.3. Heat transfer in internal insulation

The maximum temperature change of internal insulation was given in Figure 14, which increased to 1400.5 K at 400 s from 300 K s and fell to 739.45 K at the end of trajectory, while the minimum temperature went up to 667.86 K. The temperature peak in the internal insulation was quite close to the panels, for the rise of temperature was led to the heated panels. The minimum temperature on the back side of the internal insulation began to rise gradually after 400 s on account of thickness of the insulation and low thermal conductivity.

In the variable leading edge, the thermal conductivity of the inner insulation was the lowest of all; both the heating and cooling rates were very slow. Owing to the surface of the internal insulation attached to the panels, the thermal distribution change in the surface of the internal insulation was consistent with the panels. When the temperature of the panels dropped, the interior of internal insulation began to transfer heat to the panels, which slowed down the drop rate of temperature of the panels. Thanks to a relatively large volume of internal insulation, in which more heat was accommodated, heat was more internally transmitted into the internal insulation rather than transferred to the panels. Therefore, due to the extremely low thermal conductivity, temperature in the internal insulation rose slowly, but the final temperature tended to be evenly distributed, as shown in Figure 15.

![Figure 15. Heat transfer behaviour of the internal insulation.](image1)

4.4. Global heat transfer behaviour

The global temperature distribution of the variable leading edge with adaptive thermal barriers at the peak was extracted in Figure 16 (a), the maximum temperature was located on the revolvable and windward side fixed panels. At that moment, the heat flow caused by aerodynamics (in Figure 8) was still at the peak, which maintained the temperature at a high level. And the heat on interior of the variable leading edge was conducted to from the exterior simultaneously. As time went by, temperature on the panels gradually decreased with the heat flow decreasing, and the temperature of...
the internal structure continued to rise. Therefore, the highest temperature (in Figure 16 (b) ), at the end of the trajectory, located on the adaptive thermal barrier of the windward side.

5. Conclusions

In this paper, a kind of variable leading edge with adaptive thermal barriers for hypersonic vehicles based on the analysis of the stagnation heat flow which is influenced by the stagnation radius, was investigated. The aerodynamics needs in different flight phases were satisfied by the rotation of the revolvable panel fabricated by C/SiC composites. The blunt side of the revolvable panel was utilized to mitigate the severe aerodynamic heating, compared to the sharper side during the low speed phase, and the results were proved by CFD analysis. The adaptive thermal barriers of high-temperature resistance and excellent compression - recovery performances were adopted to seal the gaps to prevent the leakage of heat flow, and the internal insulation was disposed inside the leading edge to moderate the heat transfer to the fuselage. A finite element model of the variable leading edge with adaptive thermal barriers was established based on the heat transfer theory. According to the heat flow boundary conditions corresponding to a certain trajectory, the heat transfer behaviour of the variable leading edge was studied. The peak of temperature 1428.2 K appeared on the surface of the revolvable panel and the fixed panel on the windward side in 400 s. And then temperature on the panels decreased gradually due to the thermal conduction and radiation to the ambient. The adaptive thermal barriers both on the windward and leeward side showed a similar trend on temperature change to the panels. The temperature of adaptive thermal barrier on the windward side reached 1418.4 K in 420 s, compared to 1341.1 K in 430 s on the leeward side. The thermal conductivity of adaptive thermal barriers is lower than the C/SiC fabricated panels. After the panel temperature lowered, a higher temperature was shown on the adaptive thermal barrier, and the heat transferred to the panels, with the surface temperature of the adaptive thermal barriers decreasing. The heat transfer inside the thermal barriers proceeded so that the temperature distribution tended to be uniform. The temperature peak of internal insulation dropped after approaching 1400.5 K at 400 s, and the temperature was above 667.86 K at the end of the trajectory. The variable leading edge with adaptive thermal barriers exhibited an excellent thermal property and a promising prospect in complex environment.

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