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Fluid-Thermal-Structure Coupled Analysis of Radome for Hypersonic Flight Vehicle

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Abstract: In this paper, the radome of 3/4 power series generatrix is taken as the object of study, and fluid-thermal-structure coupling field of it is simulated and analyzed with sequential coupling method. The aerodynamic load under Ma=6 flight condition is calculated using $k-\varepsilon$ standard model. Then the finite element method is used to make structure thermal analysis and simulate the temperature field and strain field. The results show that the maximum thermal stress, strain and deformation of the structure always occur at the tip of the structure where the thermal expansion effect is obvious. The calculation results can provide an effective theoretical reference for the design of hypersonic vehicle structures and thermal protection systems.

1. Coupling Theory

Separation method is widely used in calculation of multi-field coupling. And the direct solution is uniting the fluid domain, solid domain and coupling in the same control equations and solving all variables at the same time step. But this method will make the calculation load increased exponentially, mainly confined to two-dimensional coupling problem. At the same time, about data transfer, fluid-solid coupling analysis can be divided into two directions, one-way coupling and two-way coupling. And according to different order of solution, two-way coupling is divided into simultaneous solution method and sequential solution method.

2. Parameters Setting of Numerical Simulation

2.1. Geometric Model

The radome of hypersonic vehicle consists of a cover body, a boot on the head and a ring connecting the radome and the vehicle body. Thereinto, the boot on the head avoids the damaging effect of raindrops on the radome when the vehicle is flying at high speed, and the ring connects the radome to the air vehicle body. This paper analyses some structural properties of the radome and Simplifies the connecting ring. The figure below shows the geometric model and some dimension parameters of the radome of 7mm thickness.

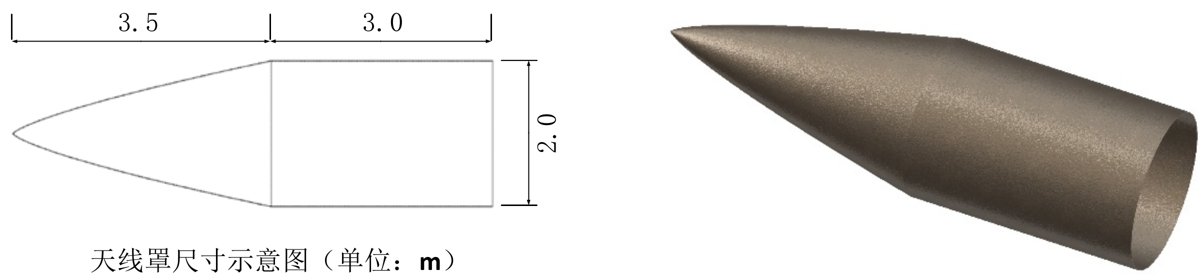


Figure 1 The geometric model and dimensions of the radome.

This paper refers to experimental data of hypersonic flight in the literature that the flight time is 490 seconds on the height of 20-24 kilometer and the flight speed is between Mach2 and Mach6. The following table lists flight data at several time points.

Table 1 The flight test date at some time points.

Time(s)	90	179	246	266	276	280	295
Height(km)	20.2	21.1	22	22.2	22.1	22.6	23.3
Ma	2.7	4.1	5.1	5.7	6	5.5	5

When the Mach number reaches 6 during the whole flight, the aerodynamic load is the biggest. So the simulation analysis of this paper is carried out under the condition of Mach6.

2.2. The Establishment of Flow Field Model

The establishment of flow field model mush ensure that the boundary does not disturb the flow field shock wave around the radome. So the far field is designed as a semi ellipsoid which the radius is two times of the constructed structure, 13m, and the distance between the far field boundary and the head of the radome is twice the diameter of the vehicle. In addition, the design of semi ellipsoid far field can avoid plotting the far field at different attack angles later. In this way, the flow field is divided into 1,600,000 structured grids. Then, make grids of the wall boundary layer and the top denser, and ensure the mesh size varies slowly at the same time.

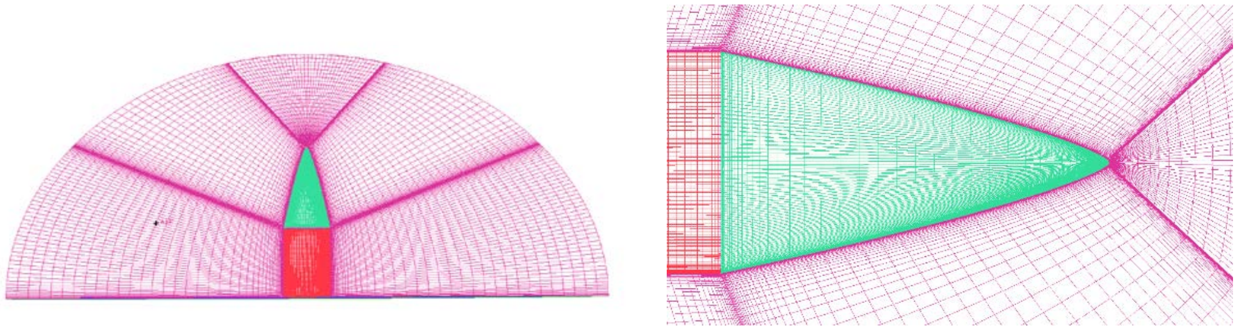


Figure 2 Structural mesh of outflow field

After geometric modelling and meshing, set the outer surfaces of the vehicle as coupled units for subsequent coupling calculations. Finally, the structured mesh is transformed into unstructured mesh which can be imported into fluent.

2.3. Selection of Radome Materials

Radome, made of natural or artificial dielectric material, protects the antenna or radar from adverse effects of the natural environment. As part of the whole communication system, it is used to protect the system from damage by external environment, and also to provide a suitable working environment for the antenna.

On the premise of meeting aerodynamic requirements, the radome need better heat resistance, transmissivity and high structural strength in a severe environment to ensure the normal operation of antennas and radars in the air vehicle. In order to achieve the requirement, this paper choose quartz ceramic which are mature in every aspect. The parameters of quartz ceramic are listed in following table:

Table 2 The parameters of quartz ceramic

Density kg/m^3	Thermal conductivity W/(m·K)	Elasticity modulus GPa	Poisson ratio	Linear expansion coefficient $\times 10^{-6}(K^{-1})$	Specific heat J/(kg·K)
2200	0.8	48	0.15	0.54	$0.75e^3$

3. Numerical Simulation Results and Analysis

In this paper, the heat flux and aerodynamic distribution at the wall are taken as coupling variables. And during flight, the external loads on the radome are divided into the following three categories:

(1) Aerodynamic force load

When flying in the atmosphere, the vehicle will be subjected to aerodynamic force include lift and drag and aerodynamic torques. They can be divided into two categories: One is the force caused by air friction, that is, resistance; The other is the force caused by the pressure difference on the surface of the vehicle, which produces both lift and drag.

(2) Inertial load

The high velocity of the vehicle and its small radius trajectory cause a huge acceleration which is perpendicular to the direction of the flight. At the same time, the lateral and axial accelerations can cause lateral and axial inertial forces on the vehicle.

(3) Aerodynamic thermal load

This kind of load is caused by the flow field that flows around surfaces of the vehicle. With the increasing flying speed of air vehicle, the aerodynamic heating during flight will have a great influence on the design of radome.

3.1. Flow Field Characteristics Analysis

The following is the calculation results at 0 angles of attack and Mach6. It can be seen that the points of high temperature and high pressure are mainly distributed in the head area of the air vehicle. In this region, the maximum pressure reaches 260KPa, the maximum temperature reaches 1602K.

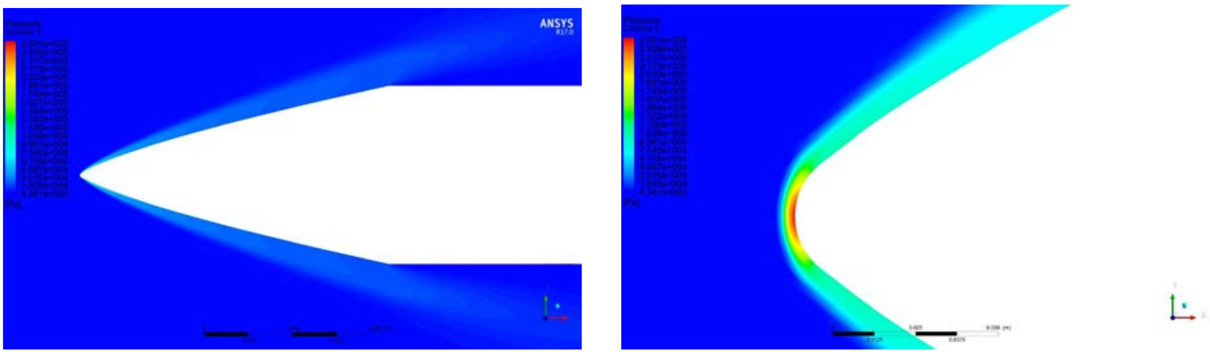


Figure 3 The distribution of flow field aerodynamic force

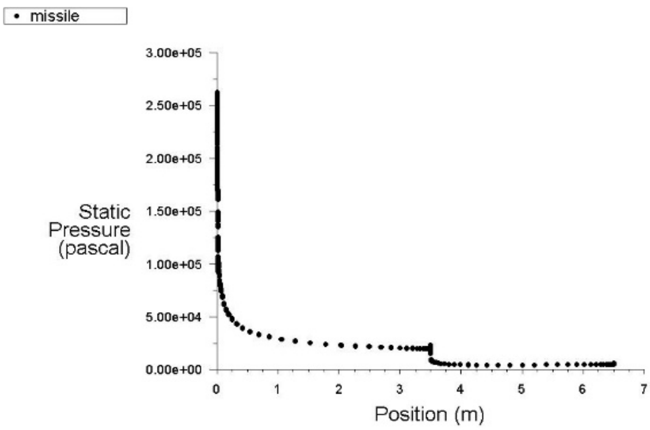


Figure 4 The variation trend of flow field aerodynamic force on the wall

Hypersonic gas through the top of the vehicle make a shock wave where pressure and temperature rise rapidly, resulting in higher temperature at the front of the air vehicle. On the other hand, the air passes through a bend at the walll, an expansion wave is formed, and after the expansion wave, the pressure and temperature decrease rapidly. So there are two mutations in the temperature and pressure distribution.

3.2. Results of Temperature Field

According to the calculation of the flow field, the heat flux of the front part is the biggest where the aerodynamic heating phenomenon is most serious. The following are diagrams of the heat flow and temperature distribution, which show trend on radome walls.

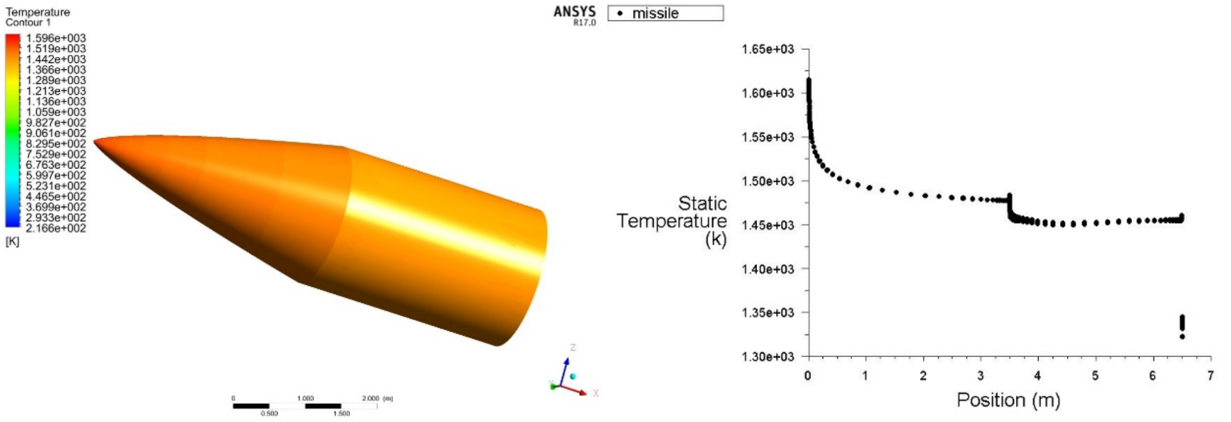


Figure 5 The distribution of flow field temperature

Figure 6 shows that the temperature field which is calculated by fluent is loaded on the quartz ceramic radome to obtain the temperature distribution of the structure. Because of the limited thermal conductivity of materials, the temperature in different parts will have different effects on the deformation of the structure.

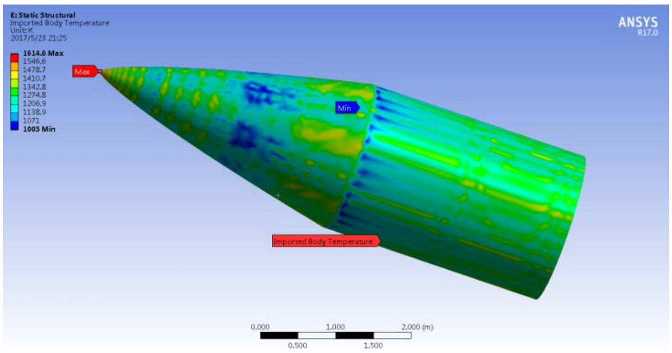


Figure 6 Temperature field of quartz ceramic radome

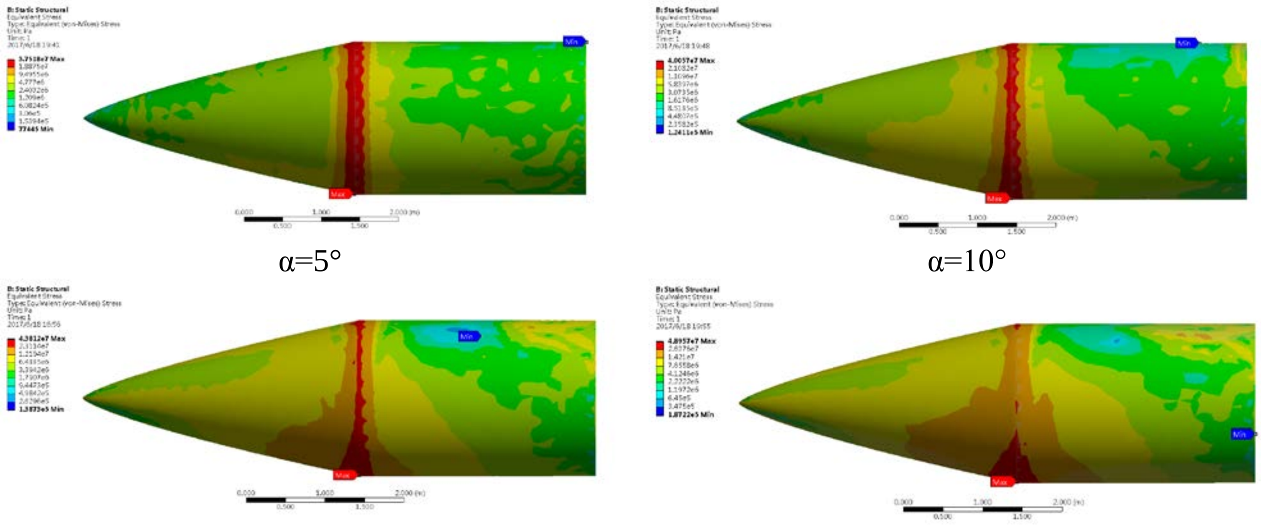
Aerodynamic heating will weaken the strength of the aircraft and produce Thermal stress, thermal strain, material erosion, etc. Moreover, with the increase of the wall temperature, the air temperature in the radome increases, thus affecting the performance of the internal components and antenna devices.

3.3. Calculation Results of Multi-Field Coupling

The finite element method is used to solve the temperature and stress distribution of the radome under the action of heat flow and force load. Through the equivalent stress distribution, it can be seen that the maximum stress occur at the joint with the aircraft body. In the design of radome, the connecting ring is the most vulnerable part.

As can be seen from the Deformation distribution, Deformation of the radome is outward, mainly caused by aerodynamic heat effect. Effects of aerodynamic force and aerodynamic heating are in two opposite directions, and the Deformation generated by aerodynamic force is very small. In other words, the effect of heat flux on the structural deformation is much greater than that of the aerodynamic pressure in analysis of multi-field coupling.

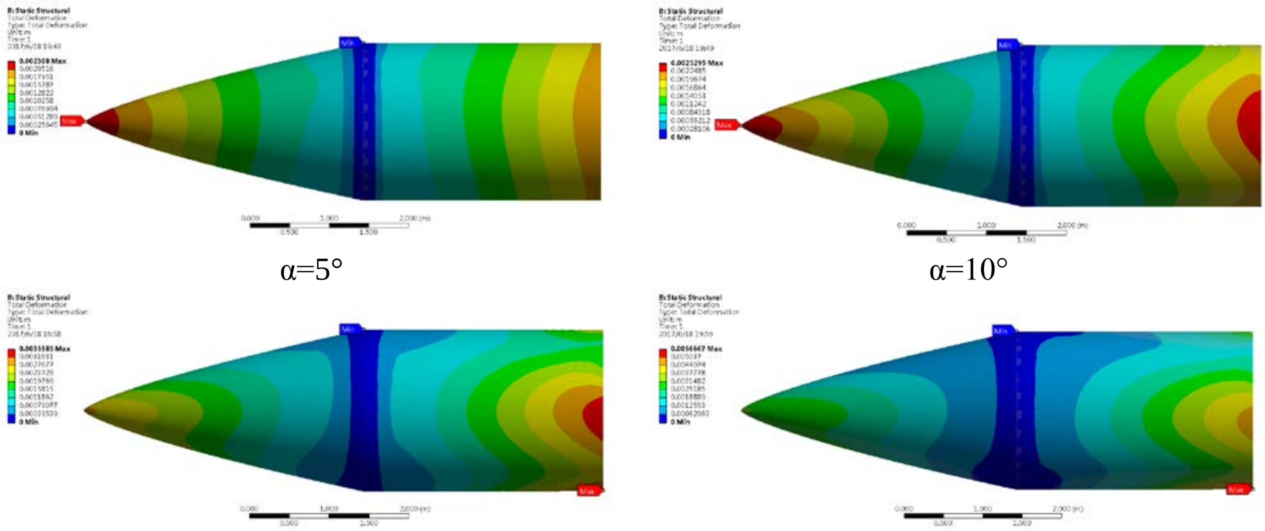
With the increase of attack angle, the radome will be subjected to more stress. The following figures show the deformation distribution and stress distribution of radome under different attack angles.



α=5° α=10°

α=15° α=20°

Figure 7 Stress distribution under different attack angles



α=5° α=10°

α=15° α=20°

Figure 8 Deformation distribution under different attack angles

Compared with different angles of attack, with the increase of the attack angle, the shock wave is closer to the lower surface and away from the upper surface. At the same time, the high temperature area of the upper surface gradually becomes smaller, and the density, temperature and pressure near the lower surface increase. Therefore, the hypersonic vehicle should keep the small angle of attack as far as possible during flight. Excessive angle of attack can cause great overload and greater thermal damage.

4. Conclusion

In this paper, the radome of 3/4 power series generatrix is taken as the object of study, and fluid-thermal-structure coupling field of it is simulated and analyzed with sequential coupling method. Then we can reach the following conclusion:

(1) Shape design of radome has significant effect to aerodynamic characteristics, volume and structure stiffness, and reasonable shape can reduce aerodynamic drag during flying, easing severe aerodynamic heating.

(2) Through the finite element methods, the stress, strain and temperature distribution of the

radome structure are obtained. The results show that in the analysis of multi-field coupling, the structure temperature increases continuously as the air heat transfer to the structure, and the front of the radome is the highest temperature area. The effect of heat flux on the structural is much greater than that of the aerodynamic pressure. Therefore, the thermal stress effect at the top should be considered in thermal protection.

(3) The maximum stress and strain occur at the connecting ring, and the connecting ring is the most vulnerable part.

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