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Review on determination of Carbon Phenolic composite structure thickness under aero-thermal loading.

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Abstract: Composite structures are used in many part of aerospace structures for their unique characteristics and properties. This composite structures are design and fabricated to protect payloads from severe aerodynamic loading and heating during their performance. Carbon-epoxy is used for internal layer because of its structural properties whereas Carbon-phenolic (C–Ph) composites are well fabricated to meet the requirements of thermal protection system. In this review paper, behavior of thermal protection system under aero-thermal load during re-entry at hypersonic speed through earth atmosphere has been studied. Vehicles shapes design, velocity, trajectory and heating rate experienced are the factors that are playing important role in performance of Thermal protection systems has been studied. Modeling of blunt body using CAD and imported to simulation software USIM to visualize different properties of the atmosphere and blunt body model. The pyrolysis and erosion of the ablator was simulated by implementing finite element models. Through the studied of velocities, shapes and heat flux conditions, the rate of ablation, surface temperature, residual thickness of the material has been estimated.

1. Introduction

Re-entry vehicle structure comprises of a nose tip and four sections namely Section 1, Section2, Section 3 and section 4 as shown in figure 1. The RVS sections namely Section 1, Section2 and Section 3, have the inner shell of carbon epoxy structure to take care of the structural loads. Section 4 of RVS is having a metallic inner shell to take the structural loads. The outer of all the sections are made up of carbon phenolic to take care of thermal loads by ablation process. The metallic inner shell of section 4 is manufactured by machining the aluminum alloy forged ring n0. Of stages. The carbon epoxy structural layer will be realized by filament winding process and the outer carbon phenolic ablative layer by tape winding process.
The structures is subjected to kinetic heating continuously during entire flight duration. The severest heating takes place during re-entry phase. The heating prior to re-entry is negligible. The temperature distribution through the thickness of composite shell at each section is obtained by heat transfer analysis.

The RVS system is subjected to a severe aero thermal environment during its flight. These thermal loads can potentially harm critical component if adequate protection is not provided. Thus the design of suitable thermal protection system is an important part of the overall vehicle design.

2. Analysis

[1] In carbon phenolic composite structure phenol is used as a matrix and carbon is used as a reinforcement in the form of fibers. During the reentry ablation rate of matrix is higher than the carbon fibers in C-Ph composites. A series of chemical reaction occur at the surface of the re-entry vehicle due to aero thermal loading. Heating of resin releases gas as by product (pyrolysis gas) leaving behind char. Gas pressure in the Pyrolysis zone forces the Pyrolysis gas to flow through the char into the boundary layer. [3]The surface of the blunt body is eroded due to the surface shear force and pressure gradient. The effect of heat flux on composite material can be investigated by measuring amount of ablation and pyrolysis.

[5] During the Re-entry of the RVS in high dense earth atmosphere surface of the structure suffer high friction due to the air flow. This causes increased in the temperature of the surface. Due to this high temperature phenol from the carbon phenolic decomposes into gases and form a protective shield around the structure this mitigate heat flux into the material. Decomposition of Phenol is measured using NASA's Phenolic Impregnated Carbon Ablator (PICA) and detailed species production during pyrolysis is determined. In this review known thermodynamic data for species it is found that mixture of ablation gases, atmosphere air and carbon phenolic are rich in O,N,C and H. Determination of species found in carbon phenolic is very important in prediction of response of ablative material with atmospheric re-entry. [4]In this review paper surface recession of ablator is studied, it is found that the surface recession is the function of the pyrolysis outgassing rate. The surface of the blunt body increases up to 2800 K, literature shows that the internal oxidation of the material did not observed during low pressure. Evaluation of the surface recession reveals after pyrolysis only low thermal conductivity char is formed and no sign of phenolic resin found. [6]Carbon Phenolic composite structure have great thermal stability and ablative properties. It shows strong interfacial interaction after pyrolysis between phenolic matrix and layered carbon structure. The use of carbon phenolic structures prove to be best result in the thermal diffusivity, thermal stability and rate of ablation with respect to other material available. During re-entry this structure had constant thermal diffusivity at different temperature and improved charred formation and ablation rate.

2.1 Modelling and Simulation

3D Model of Blunt body is created using Trelis Pro 16.1 according to the dimensions specified. Geometry is a circular cone with smaller circle is 118.15mm radius, base circle radius is
283.65 mm and length of cone is 938.5 mm. Model is meshed with High-end Hexahedral meshing. The geometry is divided into 27140 elements. Boundary conditions given to the meshed model.

[10] Carbon Phenolic material properties is assigned to the geometry. The thermal properties are:

| Property      | Units   | Value  |
|---------------|---------|--------|
| Density       | Kg/m³   | 1400   |
| Specific Heat | J/kg-K  | 937.8  |
| Conductivity  | W/m-K   | 0.5598 |

Last step in modelling is to export the mesh for the analysis. USIM support only genesis format i.e .g. USIM is used to solve, a two-dimensional axisymmetric Navier-Stokes equation. Solutions with various surface boundary conditions were obtained to study the effects on surface composition and ablation rate of blunt body.[9]. The simulation is performed at an altitude of 61 km, the speed, angle of attack, free stream density, temperature are 7650 m/s, 0°, 2.816*10⁴ kg/m³, and 244.3 K respectively.[8] The fluid contains 7 air species and carbon phenolic atoms. The reactions and atomic data are given in the external text data file air7SpeciesAbCarbon.txt in USIM.

2.2 Results and Discussion.

![Figure 2.1-D & 2-D Analysis of Aerodynamic load distribution from tip to aft end](image)

In the analysis the maximum aerodynamic loading due to air friction at the tip during entry of rocket in earth atmosphere is observed as 1706 N at a re-entry speed of 7650 m/s². The variation of aerodynamic loading along the length of the ablative surface is shown in the fig.2

| Distance (m) | 0.0 | 0.05 | 0.075 | 0.1 | 0.2 | 0.5 | 1.0 |
|--------------|-----|------|-------|-----|-----|-----|-----|
| AbSurface Prop Load (Max) (N) | 1.66 x 10³ | 1.62 x 10³ | 1.6 x 10³ | 1.62 x 10³ | 1.58 x 10³ | 1.26 x 10³ | 460 |
| AbSurface Prop Load (Min) (N) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table. 2 Aerodynamic Load at various locations.
The variation of aerodynamic loading at different location from tip to aft end is shown in the table. It is observed that at tip (0 m) blunt body experienced maximum aerodynamic load of 1.66 x 10^3 N and minimum of 0.02 x 10^3 N. At 1 m of length aerodynamic load is least 460 N. Due to this excessive load at the nose temperature of surface increases.

![Figure 3. 1-D & 2-D Analysis of Chemical Energy from tip to aft end](image)

In fig. 3, X-axis is the length of the blunt body and Y-axis is the Chemical energy. The variation of chemical energy along the surface of the ablative material can be observed from the figure above. The maximum value of chemical energy is 4.748 x 10^004 J and min value is 1.623 x 10^-003 J respectively. The basic chemical reaction is described in the below reaction module. The Pyrolysis reaction and formation of char depends on the chemical energy of this reaction.

| Distance (m) | 0.0  | 0.05 | 0.075 | 0.1  | 0.2  | 0.5  | 1.0  |
|--------------|------|------|-------|------|------|------|------|
| Chem Energy (Max)x10^3(J) | 47   | 21   | 18.6  | 11.2 | 5.3  | 3.84 | 5.5  |
| Chem Energy (Min)x10^3(J)  | 0.5  | 0.5  | 0.2   | 0.2  | 0.05 | 2.36 | 0.5  |

The rate of chemical energy at different station is plotted in the table. It is observed that at the tip maximum value is 47 x 10^3 J and this value is decreases at 1 m of length it reaches to 5.5 x 10^3 J. This chemical reaction is responsible for the heat flux generation, Pyrolysis reaction and the char formation.
**Figure 4.** 1-D& 2-D Analysis of Electron Pressure from tip to aft end

In fig. 4. X-axis is the length of the blunt body and Y-axis is the Electron pressure. Electron pressure variation can be observed from the figure above. The maximum value of electron pressure is 15.92 N/m² and the minimum value is $1.255 \times 10^{-9}$ N/m². Initially electron pressure is maximum then fall linearly becoming constant along the length of the blunt body.

**Table 4** Electron Pressure at different stations

| Distance (m) | 0.0 | 0.05 | 0.075 | 0.1 | 0.2 | 0.5 | 1.0 |
|--------------|-----|------|-------|-----|-----|-----|-----|
| **Electron Pressure (Max)** (N/m²) | 15.6 | 6.5 | 5.0 | 3.0 | 1.5 | 0.32 | $200 \times 10^{-9}$ |
| **Electron Pressure (Min)** (N/m²) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

During the Pyrolysis chemical reaction massive heat is generated due to this reaction ionisation takes place of the adjacent air and the carbon phenolic surface. The maximum electron pressure is 15.6N/m² at the tip and minimum electron pressure is $200 \times 10^{-9}$ N/m² at the aft end.

**Figure 5.** 1-D & 2-D Analysis of Gas Pressure distribution from tip to aft end
In fig. 5, X-axis is the length of the blunt body and Y-axis is the Gas Pressure. It is the pressure developed during re-entry of the blunt body surrounded by the high velocity gases. Figure 10.5 shows the maximum gas pressure $1.150 \times 10^4$ N/m$^2$, minimum pressure as 11.25 N/m$^2$, and pressure along the blunt body surface. It is clear that the pressure is at peak initially and reduces gradually along the surface.

| Distance (m) | 0.0 | 0.05 | 0.075 | 0.1 | 0.2 | 0.5 | 1.0 |
|--------------|-----|------|-------|-----|-----|-----|-----|
| Pressure (Max) X $10^3$ (N/m$^2$) | 12.0 | 6.0 | 4.6 | 2.95 | 2.0 | 1.90 | 24.7 |
| Pressure (Min) X $10^3$ (N/m$^2$) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.12 | 19.8 |

Gas pressure at the tip of blunt body is $12 \times 10^3$ N/m$^2$; it decreases and then increases at the aft end about $24.3 \times 10^3$ N/m$^2$ as shown in the table 5. Gas pressure is due to the different gas present in atmosphere. This pressure is total pressure acting on the re-entry vehicle.

Figure 6. 1-D & 2-D Analysis of Specific heat at constant pressure distribution from tip to aft end

In fig. 6, X-axis is the length of the blunt body and Y-axis is the Specific heat at constant pressure. Specific heat at constant pressure are obtained from simulation case with a wall temperature of 300K. Thus depicting the cold wall heat flux for that location. Maximum and minimum Specific heat at constant pressure is $1288 \times 10^3$ J/kg-K and $1007 \times 10^3$ J/kg-K resp.

| Distance (m) | 0.0 | 0.05 | 0.075 | 0.1 | 0.2 | 0.5 | 1.0 |
|--------------|-----|------|-------|-----|-----|-----|-----|
| CP Avg (Max) x $10^3$ J/kg K | 1.28 | 1.26 | 1.245 | 1.235 | 1.255 | 1.137 | 1.00915 |
| CP Avg (Min) x $10^3$ J/kg K | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 | 1.076 | 1.00880 |

The specific heat at constant pressure at different location is shown in the table.6. At the tip it is observed $1.28 \times 10^3$ J/kg K with small variation to the aft it is observed $1.00915 \times 10^3$ J/kg K.
Figure 7. 1-D& 2-D Analysis of Temperature distribution from tip to aft end

In fig. 7 X-axis is the length of the blunt body and Y-axis is the Temperature. The temperature variation of ablative material surface along the length can be observed from the figure above. It is found that the maximum value is $1.076 \times 10^4$ K and minimum value is 244.3K.

| Distance (m) | 0.0 | 0.05 | 0.075 | 0.1 | 0.2 | 0.5 | 1.0 |
|-------------|-----|------|-------|-----|-----|-----|-----|
| Temperature (Max) K | $10.8 \times 10^3$ | $9.7 \times 10^3$ | $9.5 \times 10^3$ | $9.7 \times 10^3$ | $9.3 \times 10^3$ | $6.62 \times 10^3$ | 308 |
| Temperature (Min) K | $0.4 \times 10^3$ | $0.3 \times 10^3$ | $0.3 \times 10^3$ | $0.3 \times 10^3$ | $0.3 \times 10^3$ | $4.66 \times 10^3$ | 245 |

Table 7 Temperature at different stations.

Due to thermal aerodynamic loading, chemical reaction occur in adjacent atmosphere and surface of the blunt body temperature reaches to its plasma state temperature. Here at the tip of the blunt body temperature is $10.8 \times 10^3$ K and reduces along the length of the body at one meter is found 308 K.

Figure 8. 1-D& 2-D Analysis of Surface Temperature distribution from tip to aft end

In the fig. 8. X-axis is the length of the blunt body and Y-axis is the Surface temperature. Variation of surface temperature along the ablative surface can be observed from the figure above. It is found that from the simulation maximum temperature attain by carbon phenolic is 3399K which is the peak temperature and the minimum is 244.5K. It is observed from fig.8 the temperature increases and fall gradually to a constant value.
Table 8 Surface Temperature at different stations.

| Distance(m) | 0.0   | 0.05  | 0.075 | 0.1   | 0.2   | 0.5   | 1.0   |
|-------------|-------|-------|-------|-------|-------|-------|-------|
| Surface Temperature (Max) K | 3.3x10^3 | 3.25x10^3 | 3.1x10^3 | 3.05x10^3 | 3.1x10^3 | 1.98x10^3 | 264   |
| Surface Temperature (Min) K  | 0.35x10^3 | 0.35x10^3 | 0.35x10^3 | 0.35x10^3 | 0.35x10^3 | 0.26x10^3 | 244.4 |

From 3D re-entry simulation carried out by USIM different parameters were visualized. It is observed
that chemical reaction and temperature of the surrounding atmosphere is so massive that the surface
temperature of the blunt body increases. The surface temperature at the tip is 3.3x10^3 K and at the aft
264 K is observed. Further this temperature will help for the analysis of carbon phenolic ablation rate
and effect of temperature on the durability of the structure.

Figure 9. Internal Temperature of RVS

Internal temperature of RVS is to be maintained at 80°C for the sustainability of the internal structure.
This temperature limit can be achieved from the above figure 9. It is observed that the internal
temperature is maximum at nose slightly changing up to 0.5 m length of the RVS and then fall linearly
at the aft.

Figure 10. Gradient temp Vs Distance

Variation of gradient temperature along the length of blunt body can observed from the fig. 10. At the
nose maximum temperature is 2947 K and at the aft end i.e at 1 meter distance is -89 K.
Variation of Internal Temperature Vs Gradient Temperature can be observed from above fig. 11.

During re-entry, atmospheric drag slows the RV, and the kinetic energy of the RV is converted into thermal energy of the air, producing a layer of extremely hot air surrounding the RV. A small fraction of this heat is then transferred to the RV body: our calculations show that for RVs with low weight-to-drag ratios roughly 1-2 percent of the total re-entry heat will be transferred to the RV, while for modern RVs with high weight-to-drag ratios ($\beta \approx 120,000$ N/m²), 6-10 percent of the total re-entry heat will be transferred for both minimum-energy and depressed trajectories. However, the total heat transferred to the RV is significant because the kinetic energy change of strategic RVs is extremely large (~$10^9$ joules).

The variation of ablation rate during the re-entry of the RV can be observed from the figure 12. It is observed that at nose maximum ablation is 0.15 mm/sec this ablation fall along the length of the RV at 0.5 m the ablation rate is constant. The reference thickness of carbon phenolic shell is 9 mm. From the figure it is observed that the maximum ablation rate is 0.1-0.15 mm/s for re-entry duration of 30 seconds. The total thickness ablated in 30 seconds is calculated as 4.5 mm. Considering the structural safety factor, the total thickness is calculated to be 7.5 mm. Therefore through above analysis the optimization of thickness is 1.5 mm. From this thickness it is found that the weight of material has reduced compared to earlier design weight. This reduction in weight increases the performance of the vehicle in terms of weight and range.
3. Conclusion

The surface temperature, heat flux and heat penetration through the thickness is visualised using USIM software. The heat of Pyrolysis was determined using USIM software. In this review, mechanical char removal occur at test conditions depending on the mass of oxygen present in the stream and the stagnation pressure. The mechanical char removal occur for tests in air at pressures above 2.4 atmospheres. The mechanical char removal occurred at the surface of the char and did not remove the entire char layer. Through above analysis the optimization of Carbon Phenolic thickness is 1.5 mm. From this thickness it is found that the weight of material has observed to be reduced compared to earlier design weight. This estimation of reduction in weight increases the performance of the vehicle in terms of weight and range.

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