Thermal Response Analysis of Porous Carbon-based Non-Ablative Heatshield in an Arcjet Flow Condition

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A computational method capable of calculating radiative heat transfer in a porous carbon-based material is developed in this study. In the method, a radiative conductivity value is statistically evaluated using a three-dimensional model of the material constructed using X-ray computed tomography images. The method is applied for thermal response analysis of a non-ablative heat shield called the Non-Ablative Lightweight Thermal protection system (NALT), which is heated in an arcjet flow. The arcjet heating environment is calculated in a coupled manner between nonequilibrium arcjet flow computation and NALT thermal response analysis. The results show that the computational method developed satisfactorily reproduces the surface and in-depth temperature data measured.

Key Words: Radiative Transfer in Porous Media, Numerical Simulation, Arcjet Wind Tunnel, Thermal Protection System

Nomenclature

\[ C_p: \text{ Specific heat, J/(kg-K)} \]
\[ F(s): \text{ probability density function of ray} \]
\[ h: \text{ enthalpy, J/kg} \]
\[ I: \text{ intensity of light} \]
\[ \text{Iso.: isothermal lines, see Fig. 7} \]
\[ k: \text{ thermal conductivity, W/(m-K)} \]
\[ q_{\text{net}}: \text{ heat flux, W/m}^2 \]
\[ s: \text{ path length} \]
\[ T: \text{ temperature, K} \]
\[ t: \text{ time, s} \]
\[ \beta: \text{ optical extinction coefficient, m}^{-1} \]
\[ \varepsilon: \text{ emissivity} \]
\[ \rho: \text{ density, kg/m}^3 \]
\[ \sigma: \text{ Stefan–Boltzmann constant, W/(m}^2\text{-K}^4) \]

Subscripts

eff: effective
\infty: farfield
\text{rad}: radiative
\text{sol}: solid
w: wall

1. Introduction

A carbon-based material has gained increasing attention for use in the development of a low-density heat shield for an atmospheric entry vehicle. A typical porosity value is on the order of 90%, and such a porous carbon-based material is commercially available. An ablative heat shield was manufactured from a lightweight carbon-based material for recent NASA space missions.1,2) In Japan, a new thermal protection system is being developed using lightweight carbon-based materials.3,4)

When a highly porous material is used for high-temperature insulation, radiative heat transfer in a porous material must be known because radiation transport can be more dominant than the other two transfer methods: conduction and convection. A radiative conductivity approach is often used5,6) to calculate the amount of radiative heat transfer within a porous material. An optical extinction coefficient is necessary to obtain the radiative conductivity value. In a recent study,7) a statistical approach was used to calculate the extinction coefficient for a porous material. In that approach, a ray tracing calculation is made for a three-dimensional model with a realistic internal structure for the porous material. The model was constructed using X-ray computed tomography data for a very-small specimen extracted from a bulk material. The method is expected to be applicable for the carbon-based material targeted in the present study. Moreover, to the best of our knowledge, the applicability of radiative conductivity obtained from a micro-scale specimen to predict the macroscopic thermal response of a heat shield is unknown.

The objective of the present study is to develop a numerical method capable of calculating radiative transfer within a porous carbon-based material exposed to aerodynamic heating. A thermal energy equation for a carbon-based material is solved accounting for radiative transport using an effective radiative conductivity value. The radiative conductivity is
evaluated via an optical extinction coefficient obtained using ray-tracing simulation. A three-dimensional digital model constructed from X-ray computed tomography (CT) images is used for the ray-tracing simulation.

The present numerical method is applied to calculate the thermal response of a heat shield material, called the Non-Ablative Lightweight Thermal protection system (NALT), which is used in an arcjet heating test. NALT has been developed for a Mars Aerofly by Sample Collection mission planned by the Japan Aerospace Exploration Agency (JAXA). NALT is a thermal insulation composite layered with a Carbon-Carbon (C/C) skin composite panel, porous carbon-based material, and an aluminum honeycomb core. The C/C skin panel is coated with a Silicone-Carbide (SiC) anti-oxidation material. In Suzuki et al., NALT was heated in an arcjet wind tunnel flow at JAXA to test its thermal insulation performance. The surface and in-depth temperatures were measured during the test. The thermal response was analyzed by solving a one-dimensional energy equation for NALT with the thermophysical parameters for each material. A discrepancy in the in-depth temperature was observed between the calculation and actual measurement: the temperature ramping rate was higher for the case of measurement than that obtained through calculation, and the calculation underestimated the peak temperature measured. The cause for this discrepancy has not yet been explained. The present study tries to reduce the difference between measurement and calculation using more elaborate physical modeling, such as radiative transport within the porous carbon-based material and a two-dimensional axisymmetric thermal energy equation with appropriate boundary conditions, which was ignored in the previous analysis.

Application of the approach proposed for the NALT thermal response is believed to be an important step toward understanding the aerodynamic heating processes in the porous carbon-based material considered in this study. Based on the configuration of the NALT test specimen, the carbon material is not directly exposed to a high-temperature shock layer because the C/C skin panel is attached to the heating surface of the carbon material. This configuration is believed to be more appropriate to validate the radiative conductivity approach proposed in a sense that the events are separable and potentially susceptible to the material’s response, such as surface recession, the influx of arcjet freestream into the material itself, etc.

2. Physical and Numerical Modeling

2.1. Three-dimensional X-ray CT model of a carbon-based material

A carbon-based material (Donacarbo rigid insulation, Osaka Gas Chemicals) is scanned using an X-ray CT facility (FLEX-M345, Beamsense). The X-ray tube voltage and current were set at 60 kW and 100 μA, respectively. The view number was 720. The scanned samples were rectangular parallelepipeds, with each side measuring approximately 3 mm × 3 mm × 10 mm. Each of the samples was manually cut from its bulk material. A typical CT data for the carbon-based material is shown in Fig. 1. An effective region of the image is defined in this study to avoid potential artifacts in the edge region of the image and is 800 × 800 pixels, approximately 1.8 mm square. The effective region is shown in Fig. 1 by the white square. A three-dimensional voxel-based model was constructed for this study using a binarization procedure. In the binarization procedure, a threshold value was chosen to divide the histogram distribution of the gray-scale values over all of the tomography scan data so that the voxel model obtained had a porosity value of approximately 93%, which is a nominal value of its bulk material. A typical example of the voxel model is shown in Fig. 2. In the procedure, several isolated solid voxels were inevitably generated, which were likely irrelevant to the real structure of the carbon-based material. Thus, such voxels were searched and eliminated by a labeling method. The voxel model had a cubic shape with the side length approximately 1.8 mm and a spatial resolution of approximately 2.27 μm. This model was used for ray-tracing calculations, which are explained later.

The volume size of the voxel model used in this study is believed to be enough to obtain an effective optical extinction coefficient for this carbon-based material. We analyzed
the so-called Representative Elementary Volume (REV) for the carbon-based material. Several voxel models with different volume sizes were generated using an iterative thresholding method only for the purpose of REV analysis. Although detailed results are not shown in this paper, the REV analysis showed that a porosity of the voxel model converged to a finite value when the side of the cube is more than approximately 1.16 mm. The present voxel model, with a side of approximately 1.8 mm as explained earlier, is larger than this value.

2.2. Ray-tracing calculation for obtaining a radiative extinction coefficient

A ray-tracing calculation was made using the three-dimensional voxel model. The data will be used to statistically evaluate the optical extinction coefficient for the carbon-based material. Although we followed a similar method given in Petrasch et al., the method is also explained briefly here. In the method, the Beer-Lambert Law is applied to deduce the optical attenuation characteristics within the carbon-based material under the assumption that the carbon-based material is taken to be a homogeneous semi-transparent material. When the Beer-Lambert Law is applicable, the ratio of the intensity of light at a given path length, s, from an origin to an initial intensity of light, $I_0$, is given as:

$$\frac{I(s)}{I_0} = \exp(-\beta s), \tag{1}$$

where, $\beta$ is an extinction coefficient. In this method, the left-hand side of Eq. (1) is interpreted using the ray-tracing data as the number of rays extant after propagating up to the path length to that of the rays initially emitted from a source.

Rays are emitted from a given source every 15 deg in all global directions within the voxel model. The position of the source is determined randomly within the model. A number of ray-tracing simulations are carried out by placing the source at different positions. In order to obtain a physically meaningful result, a number of sources are needed. In the present study, the number is determined by trial-and-error processes, and was found to be 50,000.

Each ray is propagated until it intersects the surface of a solid voxel, and the intersection is interpreted as the extinction of light. Using the ray-tracing data obtained, the ratio of the number of rays that are extinct at path-length $s$ to the total number of rays emitted is counted as a function of $s$. The ratio is also regarded as a probability density function of the path-length, $F(s)$. The probability that a ray is extant up to the path-length is given as

$$1 - \int_0^s F(s)ds.$$ 

Finally, we obtain

$$\frac{I(s)}{I_0} = \exp(-\beta s) = 1 - \int_0^s F(s)ds. \tag{2}$$

In application, the furthest left-hand side of Eq. (2) obtained using the ray-tracing data is curve-fit to evaluate an extinction coefficient $\beta$.

In order to examine the accuracy of the results calculated, the extinction coefficient for a porous material model given in Petrasch et al., was calculated in this study and the value obtained was compared with the one given in Petrasch et al. Although not shown here, the results revealed fair agreement between the two extinction coefficients. Thus, the accuracy of the in-house code used in this study is believed to be satisfactory.

Scattering effect was not accounted for during this ray-tracing calculation. In order to examine scattering effect, a radiative transfer equation needs to be solved as a function of wavelength. However, such an analysis is far beyond the scope of this study. Nevertheless, this approximation is likely valid for this study. We conducted a preliminary calculation of the extinction coefficient with scattering and absorption following the method proposed by Coquard et al., although the details are omitted here. The results showed that the extinction coefficient obtained was nearly constant over all wavelength regions of interest. Additionally, the difference between the extinction coefficient with and without scattering was only slight. It should be noted that the present preliminary results were found to be consistent with those reported in Bailis et al., even though a porous carbon-based material different from the one used in this study was analyzed in their study. Based on this observation, the effect of scattering on the radiative conductivity value is believed to be small.

The ray-tracing data represented by Eq. (2) was curve-fit using an appropriate $\beta$. The data is plotted against the path-length in Fig. 3 for the cases of five different X-ray CT data for the carbon-based materials. The coefficient of determination is approximately 0.99 for all cases. The average value of the extinction coefficient over the five sets of data is $4692 \pm 882 \text{ m}^{-1}$.

For this study, the effective extinction coefficient was determined using five X-ray CT data for the carbon-based material. The number of CT data necessary to obtain a physically meaningful extinction coefficient is presently unknown. Investigating that number is beyond the purpose of this study. Although the results are not shown in this pa-
per, ray-tracing calculations for an additional five different voxel models of carbon-based material were conducted. The effective extinction coefficient was deduced similarly using the original and an additional 10 sets of data: the value changed by approximately 2% compared to that of original five sets of data.

### 2.3. Effective thermal conductivity for the carbon-based material

An effective thermal conductivity, $k_{eff}$, was obtained by summing the apparent thermal conductivity for radiation and conduction. Each of the conductivities is plotted against temperature in Fig. 4, respectively. The effective conductivity value was calculated using

$$k_{eff} = k_{sol}(T) + k_{rad}(T) = k_{sol}(T) + \frac{16\sigma T^3}{3\beta}.$$  

(3)

The extinction coefficient, $\beta$, is used in $k_{rad}$. It should be noted that radiative transfer within the carbon material was calculated using a diffusion approximation, as is explained in the next subsection. In such an approximation, the radiative conductivity formula defined in Eq. (3) is applicable.11) As indicated from the figure, radiative transfer within the carbon-based material can have a dominant mode at the time of overall energy transfer over approximately 1500 K; that is, the radiative conductivity becomes higher than solid conductivity from this temperature.

Because the temperature dependence of the $k_{rad}$ value is presently unknown, in particular, for high temperatures, the following approximation was made: the $k_{sol}$ value less than 1000 K was obtained using a linear function extrapolated from data measured at temperatures ranging from 300 to 530 K.31) The solid thermal conductivity over 1000 K was obtained using a linear function extrapolated following approximation was made: the radiative conductivity becomes higher than solid conductivity from this temperature.

This treatment is likely reasonable based on an independent analysis made using the manufacturer’s specification data for the effective thermal conductivity, $k_{spec}$, of the carbon-based material. We examined the temperature variation of the $k_{spec} - k_{rad}$ value from approximately 800 to 2200 K. Although the results are not shown here, it was shown that the $k_{spec} - k_{rad}$ value was nearly constant in the temperature range examined. In the Results section, we present a better prediction performance of in-depth temperature data measured when using this treatment.

### 2.4. NALT thermal response calculation

An energy conservation equation was solved to calculate the temperature within NALT. The energy equation is written in a two-dimensional-axisymmetric form as follows:

$$\rho \frac{\partial h}{\partial t} = \frac{\partial}{\partial z} \left( k_{eff} \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( rk_{eff} \frac{\partial T}{\partial r} \right).$$  

(4)

The thermophysical parameters used for calculations are summarized in Table 1. The values without the equation number are taken from Suzuki et al.3) A temperature-dependent specific heat for the carbon-based material was obtained using Potts formula2)

$$C_p = \frac{c_2 T}{\sqrt{T^2 + c_1^2}}.$$  

(5)

where $c_1 = 800$ K, and $c_2 = 2300$ J/(kg-K), respectively.

Figure 5 shows the computational grid system for the NALT test specimen. Three blocks were used and each of the blocks was allocated to the C/C skin panel, carbon-based material, and aluminum honeycomb core, respectively. The number of computational cells was 400, 1800, and 900 for the C/C skin panel, carbon-based material, and aluminum honeycomb core, respectively. The geometrical parameters of the test specimen analyzed in this study were taken from Suzuki et al.3) The boundary conditions at each of the boundaries are explained later.

The effect of the standard deviation obtained for $\beta$ in terms of the in-depth temperatures calculated is believed to be relatively small, even though the effect was not investigated in this study. In Sakai et al.,13) the thermal response of the same carbon-based material was studied experimentally and nu-

Table 1. Thermophysical parameters for NALT materials.

| Material         | Carbon-based | C/C skin | Honeycomb |
|------------------|--------------|----------|-----------|
| $\rho$ (kg/m$^3$) | 130          | 1639     | 73        |
| $k_{sol}$ (W/m-K) | Eq. (3)      | 2.8      | 0.58      |
| $k_{rad}$ (W/m-K) | Eq. (3)      | —        | —         |
| $C_p$ (J/kg-K)   | Eq. (5)      | Eq. (5)  | 1000      |
| $\epsilon$       | 0.9          | 0.9      | 0.2       |

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numerically using an approach similar to this study. The results showed that the difference between the in-depth temperatures calculated with and without accounting for deviation is approximately 5% at the most. Taking that into consideration, the agreement of the data for calculations and measurements explained later is believed to be reasonable.

### 2.5. Coupled calculation between arcjet flow and NALT

A coupled calculation was carried out for an arcjet flow and NALT thermal response using the computational grid system shown in Fig. 6. For the arcjet measurement, the NALT test specimen was affixed using a water-cooled holder. Thus, a shock layer flowfield over an assembled blunt body (i.e., NALT and the holder) was numerically simulated. For the shock-layer flowfield calculation, a thermochemical nonequilibrium flow code was used. Since the catalytic effect on the coated surface of the C/C skin panel of NALT is unknown at present, a noncatalytic condition was imposed along the surface of the blunt body for the purpose of this study: the calculation roughly traces the surface temperature measured in the arcjet testing, as will be shown later. The side surface temperature of the blunt body is taken to be constant and its value is given at the grid cell for the C/C skin panel shoulder.

In order to numerically integrate the NALT energy equation with time-dependent boundary conditions in the coupled calculation, the heat fluxes along the NALT surface (shown as “Arcjet heating” in Fig. 5) are updated at some time points. The time points were determined by trial-and-error processes so that the results calculated at different time points were smoothly connected. A total of 24 time points were used in this study: up to the first 12.5 s, \( t = 0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.25, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, \) and 12.5; and after 12.5 s, the interval of 2.5 s was used up to 60 s. The details for the coupled calculation are as follows. At first, a shock-layer flowfield calculation is made at a chosen time, \( n \), with a known wall temperature at that time point, \( T_w^n \). The flowfield solution calculated determined wall heat fluxes at time \( n \). The NALT energy equation was integrated up to the next time point, \( n + 1 \), by tentatively imposing a heat flux value at time \( n \) as a constant boundary condition. Then, the wall temperature values over the NALT surface at times \( n + 1 \) and \( T_w^{n+1} \) were obtained. Using the \( T_w^{n+1} \) values, the shock-layer flowfield calculation was repeated to determine the wall heat flux at time \( n + 1 \). It should be noted that the NALT solution at a final state was integrated into the time by interpolating the wall heat fluxes at an intermediate time using the known values at the time points chosen.

A radiative cooling boundary condition was imposed at the internal surfaces of the NALT test specimen, as shown in Fig. 5. The boundary condition is used provide an approximate simulation of the experimental conditions in the blunt body model used for measurement, there was a gap between the water-cooled holder and the side surface of the carbon-based material and the NALT aluminum honeycomb panel. When calculated, the following energy balance was accounted for:

\[
q_{\text{net}} = \begin{cases} 
\varepsilon\sigma(T_w^n - T_\infty^4) & \text{for } T_w > T_\infty \\
0 & \text{for } T_w \leq T_\infty 
\end{cases}
\]

In this study, \( T_\infty \) is the constant value of 300 K. By setting this value, the in-depth temperatures measured at a sufficiently longer time after the heating test can be replicated, as will be shown later.

The inflow condition of the arcjet freestream was calculated independently using an integrated numerical method. In this method, an arc heater flowfield is first calculated from the upstream end of the arc heater to the nozzle throat. In Table 2, the results of calculations are compared to actual data measured. In the arc heater calculation, the mass flow rate and electrical power input were given as inputs. Although the calculation overestimates the mass-averaged enthalpy value measured by approximately 20%, satisfactory agreement between the measured and calculated data can be seen.

Secondly, a nozzle-expanding flowfield downstream of the nozzle throat was calculated. For this calculation, the arc heater flowfield solution at the nozzle throat was imposed as an inflow boundary condition. The nozzle flow calculation was extended up to a test chamber section. The test chamber was represented by a virtual nozzle that extends downstream from a physical nozzle exit. Finally, a steady-state nozzle flow solution was obtained, and the flow solution at the position where the blunt body was placed in the arcjet test was used as the arcjet freestream conditions. In Table 2, pitot pressure and cold wall heat flux values are compared for

| Properties | Experiment | Calculation |
|------------|------------|-------------|
| Mass flow rate, g/s | 10 | 10 |
| Power input, kW | 260 | 260 |
| Heater pressure, kPa | 46.1 ± 0.2 | 48.5 |
| Mass-averaged enthalpy, MJ/kg | 11.7 | 14.3 |
| Pitot pressure, kPa | 1.90 | 1.95 (evaluated from blunt body calculation) |
| Cold wall heat flux, MW/m² | 0.97 | 0.53 |
the experiment and numerical calculation. Fair agreement was obtained, although the cold wall heat flux was slightly underestimated.

It should be noted that radial non-uniformity of the arcjet flow calculated was ignored for the shock layer flow calculation: the nozzle flow solution at centerline was imposed uniformly for the entire region of the inflow boundary condition. This approximation is presumably valid because the radial properties of the arcjet flow are nearly uniform over the radius of the blunt body model. The calculation shows that the total enthalpy value decreased by approximately 6% and the pitot pressure is nearly constant from the centerline to the shoulder of the blunt body model.

3. Results

Calculations were carried out for cases with and without the radiation conductivity of the carbon-based material. The results computed were compared with the temperatures measured on the surface and in-depth.

3.1. Overall features of calculation results

The temperature contours for the calculations are shown in Fig. 7 for a case with radiation conductivity. For the flowfield solution, a translational-rotational temperature was plotted. The contour lines are depicted at intervals of 100 K over the temperature range from 400 to 3000 K to clearly show the temperature field within NALT: two isothermal lines of 400 and 1500 K inside the carbon-based material are specifically indicated for reference. It can be seen from the figure that the shock wave is clearly visible in the flowfield, and that heat is transferred in-depth from the heated surface of the NALT test piece as time elapses. From Figs. 7(b) and 7(c) for the cases at 20 s, and 60 s respectively, the in-depth temperature near the interface between the C/C skin panel and the carbon-based material was more than 1000 K. This temperature range includes a condition that radiative transfer may have affected overall energy transfer within the carbon-based material during the arcjet testing analyzed in this study. In addition, the contour lines calculated were not parallel inside the carbon-based material after 20 s. The trend observed is attributed to the boundary conditions considered in the present study. This result also suggests that the present two-dimensional axisymmetric thermal response analysis is important for the purpose of comparing calculations and measurements, which was not done in Suzuki et al.3)

The radial distribution of the surface temperature computed is shown in Fig. 8. As expected, the surface temperature is nearly uniform except for the shoulder of the NALT test specimen. The surface temperature changed only slightly after approximately 20 s. This result implies that the heating condition reaches a quasi-steady-state condition.

3.2. Comparison with measurement

Two sets of data measurements are used for comparison. The difference between the two sets of data lies in the coating process on the surface of the C/C skin panel: a wet process and a dry process. The details for the surface coating are referred to in Suzuki et al.,3) and are therefore omitted here.

Because there are many available data measurements, we present in-depth measurements that cover the upper and lower bounds. Even though there is an appreciable difference of in-depth temperature data between the two coating processes in contrast to surface temperature data measurements, as will be shown later, it can be said that the data measurements tend to show a dispersive behavior that is not dependent on the surface coating processes. Consequently, for clarity, we will present the maximum and minimum intervals of the data measurements selected compared to data calculations, as is explained in Sec. 3.2.2.
In addition, the effect of the coating on the C/C skin panel is not accounted for in the present calculations.

3.2.1. Surface temperature

In Fig. 9, the time histories for the surface temperatures calculated and measured at the stagnation point of the NALT test piece are compared. The calculated results for cases with and without radiation conductivity are presented, but the difference in surface temperature between the two cases that were calculated is relatively small. A two-color optical pyrometer measurement was conducted to obtain the surface temperature.3) It can be seen that there is fair agreement among the measurements and calculations, although the calculations overestimate the surface temperature measurements by approximately 10% in the quasi-steady-state region after approximately 20 s.

The cause for this overestimation could be partially attributed to the fact that the centerline enthalpy value is higher than the experimental value. As shown in Table 2, the mass-averaged enthalpy calculation was higher than the one that was measured. Improvement in the prediction accuracy of our integrated computational approach for centerline enthalpy may be needed in the future as part of further discussions.

There are qualitative or quantitative differences in surface temperature measurements and calculations before 5 s. But the difference would not affect the in-depth temperature comparisons shown next. We conducted a thermal response analysis of NALT independently using an uncoupled manner between measurement and calculation; doing so by applying a surface heating condition in order to replicate the time history of the surface temperature measurements. Although the results are not shown here, the difference between the in-depth temperatures of the present coupled and uncoupled calculations was relatively small.

3.2.2. In-depth temperature

The in-depth temperature calculations are compared to those measured at two different positions: Fig. 10(a) inside of the carbon-based material 12 mm from the heated surface; and Fig. 10(b) at the bottom of the carbon-based material 22 mm from the heated surface. As can be seen in both figures, the in-depth temperatures calculated are higher for the case with radiation as compared to the one without radiation, as was expected. This trend is due to a higher heat transfer effect for the case with radiation.

When compared to data measurements, it can be seen that the calculations including radiation give the upper bounds. In contrast, calculations without radiation roughly trace the lower bounds. This trend is nearly consistent for both in-depth positions shown in Fig. 10.
The calculation with radiation presented here are believed to reasonably predict the overall behavior of the in-depth data measurements. As shown in Fig. 9, the present calculations slightly overestimate the surface temperature measurements, and the results were unchanged for conditions with and without radiation. This indicates that calculations overestimate the net heat input to the NALT test piece. Thus, if calculations can improve the prediction accuracy for surface temperature, reasonable agreement can only be expected when calculations are conducted that take into account the radiative transport effect in the carbon-based material.

4. Conclusion

A numerical method that calculates the effect of radiative transfer in a porous carbon-based material has been developed. The method proposed utilizes a three-dimensional X-ray CT model for the material and adds a statistically evaluated radiation conductivity value with a ray-tracing method to calculate an energy equation for the material. The method was applied to calculate the thermal response of NALT heated under one operational arcjet heating condition. Based on comparing temperature data actually measured with that calculated, surface and in-depth temperature data measurements for NALT arcjet experiments can be consistently replicated only when the effect of radiation is accounted for in the calculation.

Because the temperature condition inside the carbon-based material is relatively low, further studies focusing on high temperatures are needed to validate this radiation conductivity approach. Such studies are being carried out. Nevertheless, the present results suggest that the radiation conductivity approach developed in this study can be useful in predicting the thermal response of carbon-based materials under aerodynamic heating conditions typically encountered by a space vehicle during atmospheric entry.

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