Thermochemical Performance of a Lightweight Charring Carbon Fiber Reinforced Plastic

By Keiichi OKUYAMA,1) Sumio KATO2) and Hiroaki OHYA3)

1)Kyushu Institute of Technology, Kitakyushu, Japan
2)University of the Ryukyus, Nishihara, Japan
3)Kawasaki Heavy Industries, Ltd., Kakamigahara, Japan

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A new class of lightweight carbon fiber reinforced plastic (CFRP)—the lightweight ablator series for transfer vehicle systems (LATS)—has recently been developed. The LATS is fabricated by heating and pressurizing a material in which resin is impregnated in the laminated carbon fiber felt. A characteristic required to ensure the excellence of a conventional lightweight CFRP ablator of the LATS is the simplicity of the resin impregnation process. Since dried bulk density can be easily controlled, this manufacturing method is beneficial for use in the aerospace industry. Here, the ablation characteristics of this material under high-enthalpy airflow are described by a recently developed computer code to simulate the one-dimensional transient thermal behavior. The validity of the mathematical model and the applicability of the ablation code are then discussed by comparing the simulated and experimental results of arc-heated tests with the LATS. A new index adopted in this study predicted the mass loss rate; the measured and estimated values of the total mass loss rate in various test conditions are in good agreement. Thus, a heated LATS material shows excellent performance characteristics for use in re-entry vehicles, and its surface and in-depth temperatures can be estimated using the developed analysis code.

Key Words: Heat Shield System, Ablator, Carbon Fiber Reinforced Plastic (CFRP), Re-entry

Nomenclature

- \( A_k \): collision frequency, \(1/\text{s}\)
- \( B_k \): activation temperature, \(\text{K}\)
- \( C_0 \): diffusion-controlled mass-transfer constant, \(\text{kg}^{0.5}/\text{m}^2\)
- \( c_p \): isobaric specific heat, \(\text{J/(kg K)}\)
- \( C_{is} \): isobaric specific heat, \(2.3 \times 10^3 \text{J/(kg K)}\)
- \( D \): temperature, \(800 \text{K}\)
- \( D_1 \): outer diameter of specimen, \(\text{m}\)
- \( D_2 \): inner diameter of specimen, \(\text{m}\)
- \( f_k \): weighting factor
- \( h \): enthalpy, \(\text{J/kg}\)
- \( k \): thermal conductivity, \(\text{W/(m K)}\)
- \( L \): recession length, \(\text{m}\)
- \( m \): mass loss rate, \(\text{kg/(m}^2 \text{s)}\)
- \( p \): pressure, \(\text{Pa}\)
- \( q \): heat flux, \(\text{W/m}^2\)
- \( R_B \): correction radius of specimen surface, \(\text{m}\)
- \( S \): surface recession, \(\text{m}\)
- \( S_\text{s} \): surface recession rate, \(\text{m/s}\)
- \( T \): temperature, \(\text{K}\)
- \( t \): time, \(\text{s}\)
- \( V \): velocity, \(\text{m/s}\)
- \( x \): moving coordinate or in-depth distance from receding surface, \(y = S, \text{m}\)
- \( y \): stationary coordinate or in-depth distance from initial front surface, \(\text{m}\)
- \( \Delta h_{\text{pyro}} \): heat of pyrolysis per gas produced, \(\text{J/kg}\)
- \( \varepsilon \): surface emissivity
- \( \phi_{\text{blow}} \): blowing correction factor
- \( \mu_k \): reaction order
- \( \rho \): density, \(\text{kg/m}^3\)
- \( \sigma \): Stefan-Boltzmann constant, \(5.67 \times 10^{-8} \text{W/(m}^2 \text{K)}\)
- \( \theta \): diffusion-controlled mass-transfer modulus, \(\text{kg}^{0.5}/\text{m}^2\)

Subscript

- \( ab \): ablation
- \( ch \): of char
- \( cw \): cold wall
- \( g \): pyrolysis gas
- \( m \): virgin material
- \( n \): net
- \( p \): pyrolysis
- \( \text{PICA} \): phenolic impregnated carbon ablator
- \( r \): recovery
- \( \text{ref} \): reference (\(T_{\text{ref}} = 300 \text{K}\))
- \( s \): surface
- \( st \): at stagnation point
- \( t \): total
- \( w \): at wall underside
- \( w \): at wall

1. Introduction

Carbon fiber reinforced plastic (CFRP), which is a composite material made of carbon fiber and resin, is widely used as a heat shield material in the aerospace industry. The Galileo probe deceleration module of NASA’s Jupiter explorer was designed for a maximum heat flux of approx-
approximately 300 MW/m\(^2\) and exposed to an actual maximum heat flux of 134 MW/m\(^2\).\(^1,2\) The external surface of this spacecraft was covered with a high-density CFRP, whose virgin material density was 1,448 kg/m\(^3\).\(^2\) This high-density CFRP was used for the return-entry module (REM) capsule of Japan’s unmanned space experiment recovery system (USERS).\(^3,4\) Figure 1 shows a diagram of the USERS, which consists of the service module (SEM) and REM capsule.\(^3\) The REM capsule was carried to Earth orbit by the H2A rocket on September 10, 2002, and successful re-entry into the atmosphere took place on May 30, 2003.\(^3\)

NASA previously developed a lightweight CFRP called the phenolic impregnated carbon ablator (PICA), which has a density that ranges from 224 to 1,041 kg/m\(^3\).\(^5,6\) A PICA with a density of 270 kg/m\(^3\) was used as the heat shield material for the Stardust spacecraft,\(^7,8\) which collected a sample from the comet Wild-2. Although this spacecraft was exposed to approximately 8.5 MW/m\(^2\) of severe heat flux, it was able to return safely.\(^7,8\) The lightweight PICA functioned perfectly as the heat shield material.

Recently, Okuyama et al. developed a new lightweight CFRP called the lightweight ablator series for transfer vehicle systems (LATS),\(^9-14\) which is made of a carbon fiber felt and resin with a manufacturing method different from that of PICA. The density of the LATS ranges between approximately 200 and 1,500 kg/m\(^3\); such LATS materials are exposed to heat fluxes of approximately 200 kW/m\(^2\) to 11 MW/m\(^2\). Data on the thermal behaviors and performance of LATS were obtained by carrying out such heating tests. From the results of these tests, the LATS were considered to function as a heat shield material in a severe environment of high-enthalpy flow. In this paper, the thermal response and ablation characteristics of the LATS in such an environment are described.

Kato et al. previously developed a computer code to analyze charring ablation and thermal responses.\(^15,16\) This code simulates the one-dimensional transient thermal behavior of charring materials. In this study, this analysis code is improved to deal with lightweight heat shield materials. A mathematical model for this charring ablation code including its basic equations is outlined, and the computational method of ablation analysis is revealed. Subsequently, the validity of the mathematical model and the applicability of the one-dimensional ablation code are discussed based on an evaluation of a comparison between the simulated and experimental results of the arc-heated test. A new index adopted in this study is shown to predict the mass loss rate. A key purpose of the study is to confirm that the new index can be exploited to evaluate heat shield performance.

2. Materials

The LATS is fabricated by heating and pressurizing a material in which resin is impregnated in the carbon fiber felt. The virgin carbon felt is a polyacrylonitrile (PAN), pitch or rayon fiber whose dried bulk density is approximately 20–1,000 kg/m\(^3\). The resin is mainly a phenol or silicone resin. The LATS used for the present study is composed of a PAN carbon fiber felt with a bulk density of approximately 100 kg/m\(^3\) and a phenol resin. Heating and pressurizing are mainly carried out using the hot plate press method or the autoclave manufacturing method. The bulk density of the LATS can be adjusted by varying the quantity of resin impregnated into the felt and the pressure force of the hot plate press. In the present study, the bulk densities of the LATS are approximately 200–800 kg/m\(^3\).

There are many kinds of lightweight ablators which are made of fiber reinforced plastics with a porous structure; typical materials are the Acusil series for the Comets program, the AVCORT5026 for the Apollo program, the SLRCA series for the Mars Pathfinder program, the SPA for the MIRKA program, the AQ60 for the Huygens program, the PICA for the Stardust program and so on. The only lightweight ablator which uses a carbon fiber among these is the PICA. This PICA is formed by a technique of making one sheet of thick carbon form with the impregnation a phenolic resin. The LATS is the accumulation of thin carbon felts that are impregnated with a resin. The production techniques of the PICA and the LATS are different.

Figures 2 and 3 show the temperature dependences of thermal conductivity and isobaric specific heat, respectively. The thermal conductivities from room temperature to 573 K and beyond 573 K are determined by the guarded hot plate (GHP) method and the laser flash method, respecti-
The basic equations for charring ablation are well known. Among those used in the present analysis code, the in-depth energy equation of the ablator is expressed by

\[
\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \Delta h_{pyro} \frac{\partial \rho}{\partial t} + \hat{S} \rho c_p \frac{\partial T}{\partial t} + \dot{m}_a c_p \frac{\partial T}{\partial t}. \tag{1}
\]

In Eq. (1), the \(x\) coordinate system moves because of the surface recession with the origin fixed to the surface, whereas the \(y\) coordinate system is stationary with the origin fixed to the ablator surface before heating. The terms in Eq. (1) represent, from left to right, the sensible energy accumulation rate, net conduction rate, pyrolysis energy consumption rate, convection rate of sensible energy as a consequence of coordinate motion and net rate of energy convected by the pyrolysis gas passing a point, respectively. The specific heat \(k\) and thermal conductivity \(c_p\) are calculated by

\[
k = \rho \rho_v k_v + (1 - \omega) \rho_c k_c \]

\[
\omega = (\rho - \rho_v)/(\rho_c - \rho_v) \]

\[
\rho c_p = \rho_v c_{pv} + (1 - \omega) \rho_c c_{pc}. \tag{2}
\]

The equations of mass conservation when the ablator yields the pyrolysis gas and the Arrhenius-type expression for the ablator decomposition rate are described by the following equations, respectively

\[
(\partial \dot{m}_a/\partial y)_t = (\partial \rho/\partial t)_y \tag{4}
\]

\[
\left( \frac{\partial \rho}{\partial t} \right)_y = - \sum_{k=1}^{N} A_k f_k (\rho_v - \rho_c) \left( \frac{\rho - \rho_v}{\rho_c - \rho_v} \right)^{\mu_k} \exp \left( - \frac{B_k}{T} \right) \tag{5}
\]

where \(\mu_k\) is the reaction order, \(A_k\) is the weighting factor, \(f_k\) is the collision frequency and \(B_k\) is the activation temperature. These values are assumed to be constant.

### 3.2. Boundary condition

The conditions at the ablating surface are determined by the energy balance. The energy balance equation is shown below.

\[
\dot{q}_{net} = \dot{q}_{cw} (1 - h_w/h) \phi_{blow} - \epsilon \sigma (T_w^4 - T_{ref}^4) - \dot{m}_a (h_w - h) \tag{6}
\]

The terms in Eq. (6), from left to right, represent the rate of energy conduction into the ablator at the surface, convective heat transfer rate in which a correction for blowing is included, net heat flux re-radiated from the surface and enthalpy change rate of surface ablation products leaving the surface, respectively.

### 4. Prediction of Mass Loss Rate

Metzger et al. clarified the mass loss characteristics of graphite in heated air. According to their study, the mass loss of graphite occurs in three regions. The first is the rate-controlled oxidation region in the temperature range below approximately 1,500 K, where the surface material mainly dissipates as a result of its oxidation by air. The second is the diffusion-controlled oxidation region in the temperature range above approximately 1,500 K. Park demonstrated that the surface mass loss of the graphite in both of these regions...
chiefly advances according to the reaction \( \text{C} + \text{O} \rightarrow \text{CO} \). The third is the sublimation region in the temperature range above approximately 3,000 K, where the surface mass loss of graphite predominantly occurs through the sublimation of carbon: \( 3\text{C} \text{(Solid)} \rightarrow 3\text{C} \text{(Gas)} \).

Meanwhile, based on the mass loss characteristics of the graphite, Potts studied the mass loss characteristics of carbonized CFRP in air. Okuyama et al. confirmed that graphite, Potts studied the mass loss characteristics of carbonized CFRP in air.19,22) Okuyama et al. confirmed that the mass loss and the in-depth temperature of the LATS presumably depend on the surface temperature and stagnation pressure, test pieces are subjected to measurements at various surface temperatures and stagnation pressures. The experimental conditions in Table 1 are used to test the LATS. A to C shows the test conditions of the JUTEM, ARD of JAXA and the L3K of DLR, respectively. Under these conditions, the heating tests are performed on test pieces with virgin LATS densities of approximately 200–1,500 kg/m\(^3\) for the JUTEM, 200–700 kg/m\(^3\) for the ARD of JAXA and the L3K of DLR are segmented.

5. Heating Test

5.1. Test facility

Several heating tests are performed using the arc-heating equipment owned by the Japan Ultra High Temperature Material Center (JUTEM), the Aerospace Research and Development Directorate (ARD) of the Japan Aerospace Exploration Agency (JAXA), and Deutsches Zentrum für Luft- und Raumfahrt (DLR) of Germany.27)

The arc heater of the JUTEM is a Huels-type heater with a maximum discharge power of 20 kW. The arc heaters of the ARD of JAXA and the L3K of DLR are segmented with maximum discharge powers of 750 kW and 6 MW, respectively. As for the test gas of this study, air is usually heated using electrical arc discharge to generate a high-temperature plasma stream. These arc heaters allow the determination of test parameters with high reproducibility.

The cold-wall heat flux rate and the pressure of the high-enthalpy airflow are measured using a flat face cylindrical copper calorimeter and a Pitot tube that stems the airflow and measures the stagnation pressure. The surface temperature is measured using an infrared thermometer (pyrometer), which is a sensor that detects the infrared radiation from the surface of the material. A photograph of a CFRP surface at the L3K of DLR is shown in Fig. 5.

5.2. Test conditions and specimens

Given that the mass loss and the in-depth temperature of the LATS presumably depend on the surface temperature and stagnation pressure, test pieces are subjected to measurements at various surface temperatures and stagnation pressures. The experimental conditions in Table 1 are used to test the LATS. A to C shows the test conditions of the JUTEM, ARD of JAXA and the L3K of DLR, respectively. Under these conditions, the heating tests are performed on test pieces with virgin LATS densities of approximately 200–1,500 kg/m\(^3\) for the JUTEM, 200–700 kg/m\(^3\) for the ARD of JAXA, and 200–700 kg/m\(^3\) for the L3K of DLR.
The cylindrical specimen assembly used for the heating test is depicted schematically in Fig. 6, and details of the structure are indicated in Table 2. The assembly consists of an evaluated part and a support structure. The virgin LATS material is placed at the front of the evaluated part and subjected directly to frontal heating. The support structure insulates the LATS piece from side heating and reinforces one-dimensional heat flow in the evaluated part. The support structure consists of an outer heat shield tube made of high-density CFRP or Bakelite, and an inorganic porous insulator with low thermal diffusivity. This tube is covered with inorganic cloth to reduce heating of the specimen from the side. Using these procedures, a one-dimensional analysis becomes possible. In Table 2, \( D_1 \) and \( D_2 \) refer to the diameters of the outer heat shield tube and the LATS material, respectively. Measurements of the weight, diameter, and thickness are taken before and after each test to determine the surface recession and mass loss of each model assembly.

### 6. Results and Discussion

#### 6.1. Thermochemical performance

Several LATS materials are heated under the conditions shown in Table 1. As noted previously, the heating tests are carried out at three facilities; i.e., the JUTEM, ARD of JAXA and L3K of DLR. The two common LATS densities used in the heating tests implemented at these three facilities are approximately 300 and 500 kg/m³.

The relationship between the densities of virgin and carbonized materials is shown in Fig. 7. In the virgin density of the LATS ranging between approximately 200–700 kg/m³, the carbonized LATS density \( \rho_{ch} \) is expressed as a function of this virgin LATS density \( \rho_m \) in Eq. (9). All of these data are acquired using the heating test at the JUTEM.

\[
\rho_{ch} = 0.716\rho_m
\]
proximately 1,500–3,500 K. Therefore, these specimens are in the diffusion-controlled oxidation region.

The surface temperatures which are shown in Fig. 8 are measured values in heating ends. Many researchers have demonstrated the performance of charring ablative materials using the effective heat of ablation $H_{\text{eff}}$ in Eq. (10).

$$H_{\text{eff}} = \frac{\dot{q}_{\text{cw}}}{V_s \rho_m}$$  \hspace{1cm} (10)

Here, $\dot{q}_{\text{cw}}$ is the stagnation point cold-wall convective heat flux and $V_s$ is the surface recession velocity.

Figures 9–11 show the relationships between the surface temperature $T_s$ and the effective heat of ablation $H_{\text{eff}}$ of the LATS, the high-density CFRP used as the heat shield material for the REM capsule, and the PICA, respectively.

The effective heat of ablation $H_{\text{eff}}$ has been used in many studies to evaluate the thermochemical performance of charring ablators. However, Figs. 9–11 show that $H_{\text{eff}}$ does not strongly depend on the surface temperature $T_s$. Hence, it is shown that as the heat flux $\dot{q}_{\text{cw}}$ increases, the surface temperature $T_s$ increases. Therefore, $H_{\text{eff}}$ is not an index of the charring ablators which is used in severe heating environments.

A model of charring ablative materials is illustrated schematically in Fig. 12. The model shows three distinct zones: a surface char layer, a pyrolysis layer and a virgin layer. The total mass loss rate $\dot{m}$ of the charring ablative material is determined via the following equation.

$$\dot{m} = V_s \rho_{ch} + V_{ch}(\rho_m - \rho_{ch}) + V_p(\rho_m - \rho)$$  \hspace{1cm} (11)
Here, $V_{ch}$ and $V_p$ are the char interface and pyrolysis inter-
face velocities, respectively. The density $\rho$, which is cal-
culated from Eq. (5), is a value at the pyrolysis interface. In the case of the LATS with the virgin density ranging between approximately 200–700 kg/m$^3$, $\rho_{ch}$ is 0.716$\rho_m$ and $\rho$ varies from $\rho_m$ to 0.716$\rho_m$. The first term of this equation constitutes the char-removal rate. The second and third

terms represent the rates of vapor production in completely and partially degraded materials, respectively.

When the charring ablative material has a very thin pyrol-
ysis zone under all test conditions, the third term of Eq. (11) can be ignored. Note that under steady-state conditions, $V_s = V_c = V_p = V$, and Eq. (11) becomes the following simple equation.

$$m_t = V\rho_m$$

Equation (12) is the denominator of Eq. (10). The estimated total mass loss rate $m_t$, based on measured values of the surface recession speed $V_{ch}$ and virgin density $\rho_m$, is not in precise accord with the measured total mass loss rate $\dot{m}_t$. It is assumed that the effective heat of ablation $H_{eff}$ is inaccurate. In the diffusion-controlled oxidation re-
region, it can be said that Eq. (8) is more suitable than Eq. (10) for predicting the total mass loss rate of charring ablative materials.

Figures 13–15 show the relationships between the total mass loss rate $\dot{m}_t$ and $(P_e/R_b)^{0.5}$ of the LATS (density of virgin LATS: approximately 300 kg/m$^3$), the heat shield material (density of virgin CFRP: 1,470 kg/m$^3$), and the PICA (density of virgin PICA: approximately 300 kg/m$^3$).
respectively. The $\theta$ value of the LATS is approximately identical to that of the heat shield material and the PICA.

The measured and estimated values of the total mass loss rate $m_t$ in each test condition are shown in Fig. 16. The values are in good agreement, suggesting that Eq. (8) can be used to estimate the total mass loss rate.

Figure 17 shows the time course of the surface temperature for 120 s under a heat flux of 2.0 MW/m$^2$, whereas Fig. 18 shows that of the in-depth temperature under the same conditions. The measured results for a high-density CFRP (approximately 1,470 kg/m$^3$) are also shown in Figs. 17 and 18. These figures show that the time courses of the surface and in-depth temperatures of the LATS and CFRP are almost identical. The maximum heat flux used when designing the REM capsule is approximately 3.1 MW/m$^2$, whereas the real heat flux at re-entry is approximately 1.5 MW/m$^2$. A comparison of the in-depth temperatures for LATS materials with densities of approximately 300 and 600 kg/m$^3$ is shown in Fig. 19. This figure confirms that the heat shield performance of the LATS depends on density. Appropriate preference of the virgin LATS density can even control the extent of temperature increase inside the heated materials.

In designing a re-entry vehicle, one of the most important issues is determining the thickness of heat shield materials. It is desirable that the in-depth temperature increase and the mass loss rate of heated materials be small. The previously described high-density CFRP was adopted as the heat shield material of an REM capsule used for an atmospheric re-entry flight. Given that the in-depth temperature elevation
6.2. Ablation analysis results

Ablation analyses of the test models are carried out according to a method similar to that in Ref. 14).

The input data to calculate the thermal behavior of a specimen using the one-dimensional ablation analysis program include parameters such as heating environment conditions, ablator thickness and thermal properties of the materials. These parameters are specified based on measured data and data obtained from the literature.

The cold-wall heat flux, enthalpy and impact pressure are determined based on data measured during the heating test. The thickness of the specimen and the virgin density of the ablator are based on measurements of each model. The char density of each ablator model is determined from the measured carbonized density of the LATS ablators with a virgin density of approximately 200–700 kg/m$^3$. The emissivity of the char surface is set to 0.85.\(^{19,22}\)

The reference value for the thermal conductivity of a virgin material $k_{\text{ref}}$ is constructed from the measured value of the LATS materials with a density of approximately 300 kg/m$^3$ (Fig. 2). These data are combined with literature data for the PICA\(^{3,6}\) multiplied by a constant, $c_{\text{PICA}} \times k_{\text{PICA}}(T)$, where $k_{\text{PICA}}(T)$ is the thermal conductivity of the PICA with a density of approximately 300 kg/m$^3$ and $c_{\text{PICA}}$ is a constant to connect the two sets of data smoothly. The reference value for the thermal conductivity of the char material $k_{\text{chref}}$ is assumed to be the same as that of the virgin material $k_{\text{ref}}$ ($k_{\text{chref}} = k_{\text{ref}}$).

The isobaric specific heat of the char material $c_{\text{pch}}$ is determined from the data of Refs. 19) and 22). It is expressed by

$$c_{\text{pch}} = c_\infty \frac{T}{\sqrt{T^2 + D^2}}$$

where $T$ is the temperature (K), $c_\infty$ is $2.3 \times 10^3$ J/(kg K) and $D$ is 800 K. The specific heat of the virgin material $c_{\text{pv}}$ is then given by $c \times c_{\text{pch}}$, where $c$ is a constant determined by considering the measured data of the specific heat of the ablator. The specific heat of the pyrolysis gas $c_{\text{pg}}$ is set to a constant value of 1,674.6 J/(kg K).\(^{19,22}\) The coefficients in the Arrhenius equation [Eq. (5)] are determined from the TGA data of the LATS ablator.\(^{13}\) The values of $N = 2, A_1 = 0.1, f_1 = 3.5 \times 10^9$ s$^{-1}, B_1 = 1.1 \times 10^4$ K, $\mu_1 = 100.0, A_2 = 0.9, f_2 = 7.0 \times 10^3$ s$^{-1}, B_2 = 1.1 \times 10^4$ K and $\mu_2 = 3$ are used in the calculation.

In particular, for test models with densities that differ from 300 kg/m$^3$, the thermal conductivities of virgin and charred materials are assumed to differ from $k_{\text{ref}}$ and $k_{\text{chref}}$, respectively. For each test model, the reference thermal conductivities $k_{\text{ref}}$ and $k_{\text{chref}}$ are multiplied by constants, and the new thermal conductivities $c_{k_\text{v}} \times k_{\text{ref}}$ and $c_{k_\text{ch}} \times k_{\text{chref}}$ are used for numerical calculations via the analysis program. The constant coefficients $c_{k_\text{v}}$ and $c_{k_\text{ch}}$ are tuned so that the measured and calculated temperatures agree well.

Figures 20 and 21 show comparisons between the measured and calculated surface and back-surface temperatures of the LATS model with a virgin density of 544 kg/m$^3$. The heating test is carried out in the heating facility at the ARD in JAXA. The cold-wall heating rate is 0.97 MW/m$^2$ with a heating time of 60 s. In Fig. 20, the surface temperature rises rapidly to approximately 1,700–1,800 K in 10 s, and thereafter rises slightly and gradually by a small amount. In Fig. 21, the back surface (20 mm from the heating surface) temperature rises to approximately 550 K in 200 s. At approximately 35 s, the measured temperature increases rapidly—an aspect not simulated by the present program.

Otherwise, the time courses of the surface and back surface temperatures simulated by the analysis program agree well with the measured results.

Figures 22 and 23 show the comparison between the measured and calculated surface and back-surface temperatures of the LATS model with a virgin density of 536 kg/m$^3$. The heating test is carried out in the heating facility at the L3K in DLR. The cold-wall heating rate is 11.1 MW/m$^2$ with a heating time of 10 s. In Fig. 22, the surface temperature rises rapidly to more than 3,000 K in less than 1 s, and thereafter rises slightly and gradually. In Fig. 21, the back surface
(40 mm from the heating surface) temperature rises slowly to approximately 350 K in 200 s and remains mostly the same during 200–600 s. For the period of approximately 0 to 150 s, the measured temperature is slightly high—a feature not simulated by the present program. This trend is similar to the case in Fig. 21. Otherwise, the time courses of the surface and the back-surface temperatures simulated by the analysis program with a heating rate of 11.1 MW/m² were in agreement with the measured results. These results suggest that a one-dimensional mathematical model can be applied to ablation analyses of low-density ablators of the new series under a wide range of high-enthalpy flows.

7. Conclusion

A new lightweight CFRP has been developed. Lightweight ablator series specimens fabricated from carbon fiber felt and resin have densities of 200–1,500 kg/m³. For charring ablation and thermal response analysis, a computer code has also been developed to simulate the one-dimensional transient thermal behavior of charring materials.

In this paper, the thermal response and ablation characteristics of the LATS under high-enthalpy airflow were described. The validity of the mathematical model and the applicability of the one-dimensional ablation code were also discussed based on an evaluation of a comparison between the simulated and measured results of the arc-heated test. The results of the present study were as follows.

- Several heating tests were performed using the arc-heating equipment at facilities in Japan and Germany. The time courses of surface and in-depth temperatures were acquired under test conditions in which the surface temperature is approximately 1,500–3,500 K (a heat flux of 500 kW/m²–11.1 MW/m² for 10–300 s). The LATS surface thermochemistry reaction could be described as a reaction in the diffusion-controlled oxidation region.

- The total mass loss rate \( \dot{m} \) of carbon materials such as graphite in the diffusion-controlled oxidation has been expressed by Eq. (7). However, this equation cannot be applied to CFRP, which contains a resin that undergoes thermal decomposition by heating. Therefore, a new index \( \theta \) was adopted in this study to predict the mass loss rate. The \( \theta \) value of the lightweight ablator series plastic is approximately identical to that of the heat shield material for the re-entry module capsule.

- When a lightweight ablator series plastic (density of 300 kg/m³) and a CFRP used for the re-entry module capsule (density of 1,500 kg/m³) were heated under a heat flux rate of 2.0 MW/m², the surface and in-depth temperatures of the two plastics were almost identical. It is thus concluded that the lightweight ablator series is a promising heat shield material for space vehicles re-entering the atmosphere.

- Simulated results of the surface and back-surface temperatures including the in-depth temperature near the back surface for an ablator of the new series agreed well with measured results. These results suggest that a one-dimensional mathematical model can be applied to ablation analyses of low-density ablators of the new series under high-enthalpy flow.

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