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A New Method for Estimating the Mass Recession Rate for Ablator Systems

Bianca A. Szasz, Keiichi Okuyama

***Abstract*—**As the human race will continue to explore the space by creating new space transportation means and sending them to other planets, the enhance of atmospheric reentry study is crucial. In this context, an analysis of mass recession rate of ablative materials for thermal shields of reentry spacecrafts is important to be carried out. The paper describes a new estimation method for calculating the mass recession of an ablator system made of carbon fiber reinforced plastic materials. This method is based on Arrhenius equation for low temperatures and, for high temperatures, on a theory applied for the recession phenomenon of carbon fiber reinforced plastic materials, theory which takes into account the presence of the resin inside the materials. The space mission of USERS spacecraft is considered as a case study.

***Keywords*—**Ablator system, mass recession, spacecraft, atmospheric reentry.

I. Introduction

A reentry vehicle is subjected to a severe aerodynamic heating environment when reentering the Earth's atmosphere. As a consequence, the study of the effects of the aerothermodynamic environment over the reentry spacecraft has a crucial importance.

According to [1], the Thermal Protection System (TPS) of a reentry vehicle is one of the key components of its design. The TPS is made either by ablative materials, as in the Apollo missions or non-ablative materials, such as the ceramic tiles used on the space shuttle.

For protecting the spacecraft, the ablative materials are used as thermal shield for the reentry spacecraft. The principle behind the use of ablators is the following: the energy absorbed by the removal of the material from the surface is not used to heat the TPS, thus keeping the vehicle at a relatively "cold" carbon matrix [1]. In particular, as remarked in [2], an ablator made of phenolic carbon fiber-reinforced plastics (CFRP) is known to possess superior resistance against aerodynamic heating.

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. According to [2], carbon ablators are proposed for numerous planetary entry missions, such as Mars Science Laboratory (MSL), Crew Exploration Vehicle (CEV), and Venus missions.

As an example, the Galileo probe deceleration module of NASA's Jupiter explorer was designed for a maximum heat flux of approximately 300 MW/m^2, exposed to an actual maximum heat flux of 134 MW/m^2, and its external surface was covered with a high-density CFRP, whose virgin material density was 1,448 kg/m^3. As noted in [3], this high-density CFRP was also used for the return-entry module (REM) capsule of Japan's unmanned space experiment recovery system (USERS) which is shown in Fig. 1.

The REM capsule (Fig. 2) was carried to Earth orbit by the H2A rocket on September 10, 2002, and the successful re-entry into the atmosphere took place on May 30, 2003. According to [2], 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.

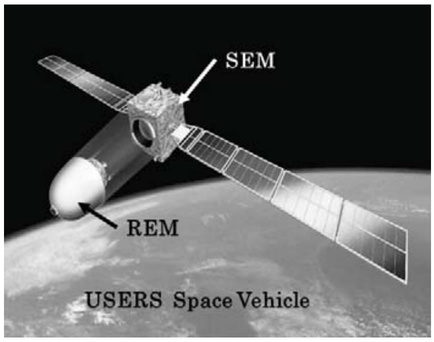

Fig. 1 USERS space system [2]

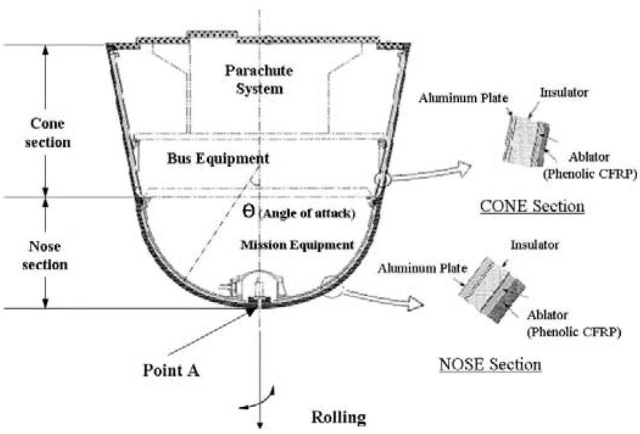

Fig. 2 REM capsule of USERS spacecraft [4]

In the late years, lightweight ablators started to get more attention since their performance equals the performance of heavyweight ablators. According to [3], when a lightweight ablator series plastic (density of ~300 kg/m^3) and a CFRP used for the re-entry module capsule (density of ~1,500 kg/m^3)

Bianca Szasz, Ph.D Candidate, and Kei-ichi Okuyama, Professor, are with the Kyushu Institute of Technology (e-mail: szasz.bianca@gmail.com, okuyama@ise.kyutech.ac.jp).

were heated under a heat flux rate of 2.0 MW/m^2, the surface and in-depth temperatures of the two plastics were almost identical. Using lightweight ablator, the mass of the spacecraft, and hence the cost, is reduced.

Recently, Okuyama et al. developed a new lightweight CFRP called the lightweight ablator series for transfer vehicle systems (LATS). The new lightweight CFRP is made of a carbon fiber felt and resin with a manufacturing method different from that of PICA, which was developed by NASA. 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. As noted in [3], from the results of heating tests, the LATS were considered to function as a heat shield material in a severe environment of high-enthalpy flow.

In studying the performance of an ablator system, the mass loss characteristics play a crucial role. In this context, developing new methods to estimate the mass recession rate would lead to a more efficient design of the future ablator systems for reentry spacecrafts.

II. Estimation Methods for Mass Recession Rate

For determining the mass recession rate, a multitude of factors have to be taken into consideration like the complex chemical ablation and particle erosion components, each of which being dependent upon surface temperature, near surface material density, and the time point (altitude, velocity, environment).

There were several studies in the past for determining the mass recession rate. According to [5], the mass loss of graphite occurs in three regions. The first region 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. The third is the sublimation region in the temperature range above approximately 3,000 K, where the surface mass loss of graphite predominately occurs through the sublimation of carbon: 3C(Solid)→C3(Gas). As noted in [2], regarding the first two regions, Park demonstrated that the surface mass loss of the graphite advances according to the reaction C+O→CO.

For the first region, the following formula based on Arrhenius equation is widely used by scientists [6]:

$$m_R = a_R \cdot \ X_{O_2} P^{\ 0.5} \cdot exp\ -E_R/\ R \cdot T_W \quad (1)$$

where $a_R = 4.71 \times 10^5\ \ g\ \ (cm^2 s)$, $X_{O_2} = 0.21$ – mole fraction (partial pressure) of oxygen in air, $E_R = 44 \times 10^3$ *cal/mole*, R is the universal gas constant, 1.987 *cal/mole K*, P is the pressure and T_W is the wall temperature.

There should be noted that (1) has a meaning only for the lowest ablating temperature range [6]. For the second region, above 1,500 K, (1) gives inaccurate results.

According to [3], for the second region of diffusion-controlled oxidation, the total mass recession rate m_t in the diffusion-controlled oxidation region of the graphite is formulated as follows:

$$m_t = C_0\ \ \overline{P_{st}\ \ R_B} \quad (2)$$

where C_0 is the diffusion-controlled mass-transfer constant, P_{st} is the stagnation pressure (Pa) and R_B is the curvature radius of the specimen. When the front surface of the specimen is flat, the correction radius R_B is 2.46 times the actual radius.

However, (2) contains flaws. As noted in [3], given that the graphite does not contain resin, the diffusion-controlled mass-transfer constant C_0 is fixed. However, the LATS contains resin, and its quantity depends on the density. The resin of a heated LATS decomposes; a portion of the resin becomes gas and covers the material surface [3]. In conclusion, (2) cannot be applied to CFRP since CFRP contains a resin that undergoes thermal decomposition by heating [3].

For overcoming this difficulty, the mass recession of lightweight ablator system, made of CFRP, in a nitrogen gas atmosphere, was studied and the results of this study are described in [2]. The total mass recession rates m_t of the carbonized CFRP in a nitrogen atmosphere are shown in the following equations: $m_t = 2.44 \times 10^{-5}\ \ P_e\ \ R_B\ ^{0.5}$, $1.72 \times 10^{-5}\ \ P_e\ \ R_B\ ^{0.5}$ and $0.713 \times 10^{-5}\ \ P_e\ \ R_B\ ^{0.5}$, respectively [2]. These results show that the total mass recession rate m_t becomes small as the amount of resin inside CFRP decreases [3]. Therefore, (2) is modified to (3), named in the present paper Okuyama equation.

$$m_t = \theta\ \ \overline{P_{st}\ \ R_B} \quad (3)$$

where θ is named the diffusion-controlled mass-transfer modulus ($kg^{0.5}\ \ m^2$), which can only be used in the diffusion-controlled regime and it represents a new evaluation index of the heat shield performance of ablators [2].

In the present study, θ will be taken as being 2.44 ($kg^{0.5}\ \ m^2$) since this value corresponds to a first series of tests for which no previous heating occurred [2].

The study case of the present paper is represented by the USERS model. Since the flight data (like pressure and temperature) are well-known, USERS being a successful space mission which was launched in 2002, they can be used to estimate the mass recession rate during the atmospheric reentry. The surface recession measured after landing, in point A (shown in Fig. 1), is 1.6 mm [4] and this value will be compared with the calculated values.

The considered time range is between 1430 and 2400 seconds after separation and the stagnation pressures and wall temperatures are measured each 10 seconds. The wall temperatures are below 1500°K except a period of time of 100 seconds (Fig. 3).

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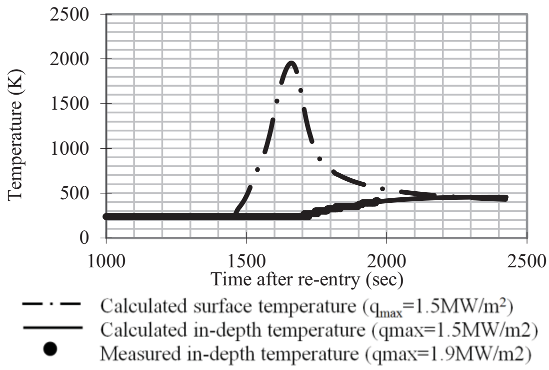

Fig. 3 Temperature flight history of USERS [4]

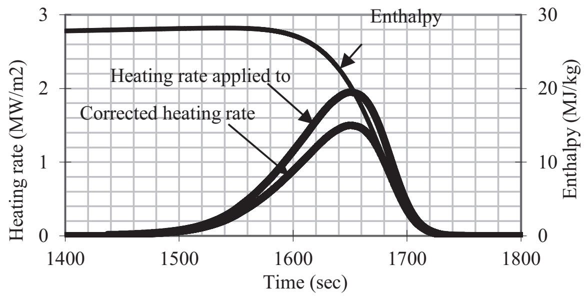

Fig. 4 Heating rate and Enthalpy flight history of USERS [4]

Also, in Fig. 4, heating rate and enthalpy history of USERS are shown and in Fig. 5 the stagnation pressure history ($\times 10^5 Pa$) together with the enthalpy history for USERS can be seen.

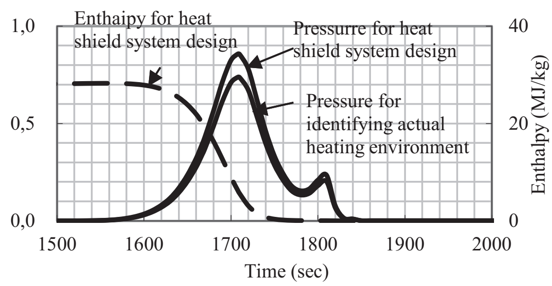

Fig. 5 Stagnation pressure ($\times 10^5$Pa) and enthalpy history of USERS [4]

Three methods for mass recession rate estimation are used in the present paper: one based on Arrhenius equation, (1), the second being based on Okuyama equation, (3) and the third one being based on a combination of both (1) and (3). More precisely, for the third method, (1) is used for wall temperatures below 1,500°K and (3) is used for wall temperatures above 1,500°K.

Based on mass recession rate values, one important parameter can be calculated: surface recession which is defined as mass recession rate divided by charring density:

$$l = \frac{m}{\rho_{ch}} \quad (4)$$

Its value will be integrated in time and the final result will be compared with the measured result.

Since USERS has a heavyweight ablator system, the charring density is 1,180 $kg\ \ m^3$.

III. Results and Discussions

Figs. 6-11 show the results of mass recession rate and surface recession for (1) (Figs. 6 and 7), for (3) (Figs. 8 and 9) and for the new method based on (1) and (3) (Figs. 10 and 11). There can be seen that (1) gives large values for mass recession rate and surface recession and that the third method based on (1) and (3) gives large values in the transition place between the region where (1) is applied and the region where (3) is applied.

In Figs. 12 and 13, all three methods are compared with respect to mass recession rate and surface recession. If Okuyama equation based method and the new method gives similar results, the Arrhenius equation based method gives considerably higher results, which can be explained by the fact that (1) shouldn't be applied for the diffusion-controlled oxidation region.

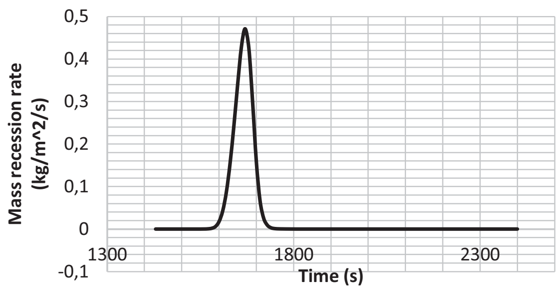

Fig. 6 Mass recession rate in time, calculated with (1)

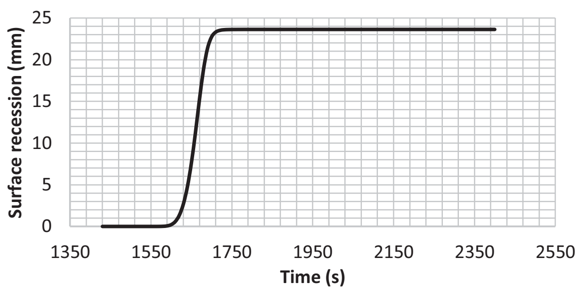

Fig. 7 Surface recession in time, calculated with (1)

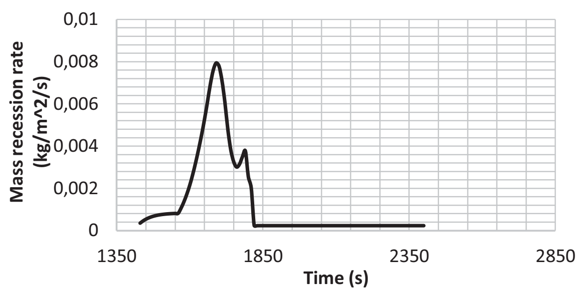

Fig. 8 Mass recession rate in time, calculated with (3)

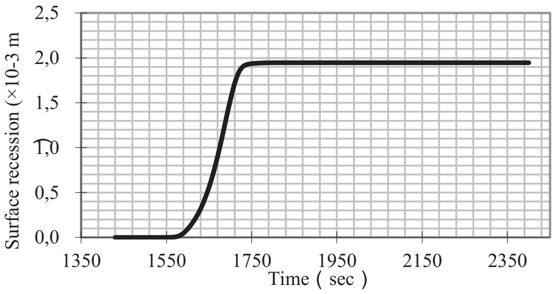

Fig. 9 Surface recession in time, calculated with (3)

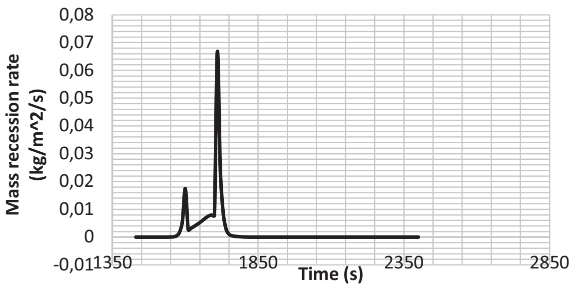

Fig. 10 Mass recession rate in time, calculated with (1) (for T<1500 K) and (3) (for T>1500 K)

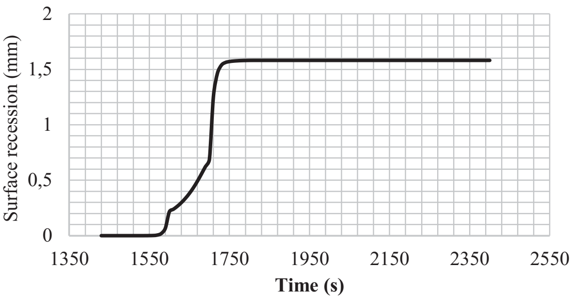

Fig. 11 Surface recession in time, calculated with (1) (for T<1500 K) and (3) (for T>1500 K)

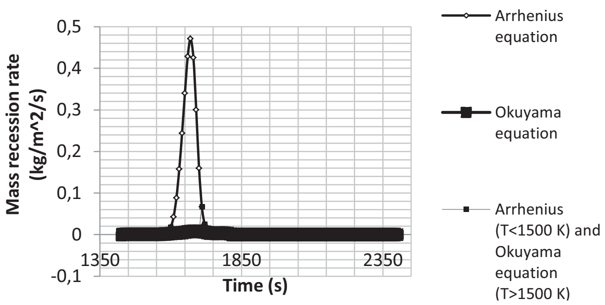

Fig. 12 Mass recession rate calculated by 3 methods: (1), (3), respectively (1) (for T<1500 K) together with (3) (for T>1500 K)

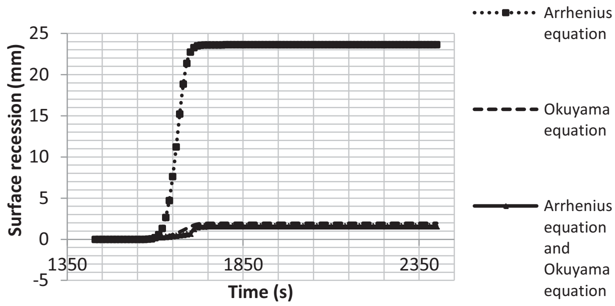

Fig. 13 Surface recession (mm) calculated by 3 methods: using (1), (3), respectively (1) (for T<1500 K) together with (3) (for T>1500 K)

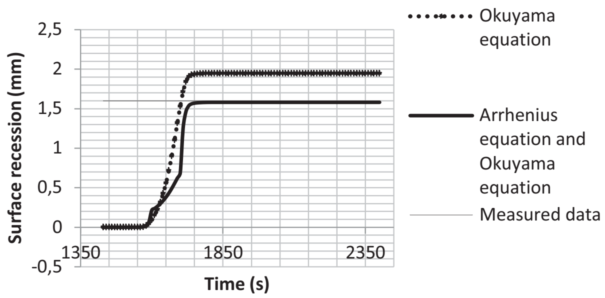

Fig. 14 Surface recession (mm) calculated by using (3), respectively (1) (for T<1500 K) together with (3) (for T>1500 K) are compared with the measured value of 1.6 mm

For validating the new method, for which (1) was applied only in the rate-controlled oxidation region and (3) was applied in the diffusion-controlled oxidation region, a comparison with the measured data was made (Fig. 14), the result by using the new method being very close to the measured data. If the measured data for surface recession is 1.6 mm, using the new method the result is 1.58 mm, whereas using only (3) the result was about 1.9 mm, giving a difference of 0.3 mm to the measured data.

IV. Conclusions

In this paper, a new method for calculating mass recession rate and the surface recession has been developed, method which is based on Arrhenius equation for low temperatures and, for high temperatures, on an equation described in [2], named Okuyama equation.

The new method was validated using the flight data of USERS spacecraft by giving the same value for the surface recession as the measured data.

Further studies and validations are recommended to prove that the new method gives accurate results for more types of ablative materials. One of the most promising types of ablative materials is the Lightweight CFRP.

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