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Empirical Study of the Lightweight Ablator Series for Transfer Vehicle Systems (LATS)

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For protecting the spacecraft against the severe heating during the atmospheric reentry, the ablative materials are commonly used as thermal shield. Recently, a new lightweight CFRP called the lightweight ablator series for transfer vehicle systems (LATS) was developed. Since LATS contains a resin that undergoes thermal decomposition by heating, classical methods for estimating recession cannot be applied to them. In the present paper, empirical correlations for the surface recession rate were determined. The paper presents a new curve-fit exponential equation for estimating the surface recession rate of the carbon-phenolic ablation in air, by taking into consideration its dependency with the surface temperature and density, using the measured data from the high-enthalpy heating facilities of the German Aerospace Center (DLR, Germany), Japan Ultra High Temperature Material Center (Jutem, Japan) and Japan Aerospace Exploration Agency (JAXA, Japan).

Key Words: Lightweight Ablators, High-Enthalpy Heating Tests, Surface Recession Rate, Carbon Phenolic Ablation

Nomenclature

$\dot{m}_R$	:	mass recession rate for the rate-controlled oxidation region, $\mathrm{kg/(m^2 \times s)}$
a_R	:	constant, $4.71 \times 10^5\ \mathrm{g/(cm^2 \cdot s)}$
X_{O2}	:	mole fraction (partial pressure) of oxygen in air, 0.21
P	:	pressure, Pa
E_R	:	activation energy, $\mathrm{cal/mole}$
R	:	universal gas constant, $1.987\ \mathrm{cal/(mole * K)}$
T_w	:	wall temperature, K
$\dot{m}_t$	:	mass recession rate for the diffusion-controlled oxidation region, $\mathrm{kg/(m^2 \cdot s)}$
C_O	:	the diffusion-controlled mass-transfer constant, $\sqrt{\mathrm{kg}}/\mathrm{m}$
P_{st}	:	the stagnation pressure, Pa
R_B	:	correction radius of the specimen surface, m
θ	:	the diffusion-controlled mass-transfer modulus, $\sqrt{\mathrm{kg}}/\mathrm{m}$
ρ *(char)*	:	char density, $\mathrm{kg/m^3}$
ρ	:	virgin density, $\mathrm{kg/m^3}$
Δt	:	time duration, s
h	:	specific enthalpy, J/kg
$Ldot$	:	surface recession rate, $\mathrm{m/s}$
T	:	surface temperature, K

1. Introduction

Aerodynamic heating plays a very important role in the vehicle design. Using an efficient thermal protection system (TPS) is important not only for maintaining the structural integrity, but also for preserving the payload and onboard devices. As pointed out in 1), the TPS design is a critical aspect of the spacecraft design, since its under dimensioning may result in the loss of the payload and the over dimensioning implies an increasing in weight and cost.

Ablative materials have been proved very efficient for the TPS of space vehicles. In case of a TPS made of ablative materials, the kinetic energy is converted into heat, which consumes the TPS through ablation.[2] Ablation is a very complex phenomenon related with diverse simultaneous physical processes,[3] which makes it extremely difficult to analyze and predict. Also, because the shape of the surface changes due to ablation, a small deviation in the prediction of the ablation can lead to an increase in the reentry trajectory uncertainty.[1] According to 4), a charring ablator made of phenolic carbon fiber-reinforced plastics (CFRP) is known to possess superior resistance against aerodynamic heating, having excellent thermo-physical properties and low densities. There are many kinds of lightweight ablators which are made of fiber reinforced plastics with a porous structure[5]. 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. PICA materials, made of NASA, were, at the beginning, the only lightweight ablators which had carbon fiber.

Japanese scientists, searching for new ways of improving the CFRP materials, developed a new class of lightweight carbon fiber reinforced plastics. Its name was chosen as LATS – the lightweight ablator series for transfer vehicle systems. The first space mission, in which these new materials were tested, was USERS spacecraft mission (launched in 2002). The maximum heat flux used when designing the REM capsule was approximately 3.1 $\mathrm{MW/m^2}$, whereas the real heat flux at re-entry was approximately 1.5 $\mathrm{MW/m^2}$.[5] In the USERS mission, the used LATS materials had a high density of about 1.5 g/cc, but the density of the LATS can range between about 0.2 to 1.5 g/cc .[6] Another difference between PICA materials and LATS materials is that, for obtaining PICA material, a sheet of thick carbon is made, on which a phenolic resin is impregnated, while the LATS material is made by the accumulation of thin carbon felts that are impregnated with resin.[6] The manufacturing process of LATS is based on heating and pressurizing a material in which resin is impregnated in the laminated carbon fiber felt and one of the advantages of using LATS materials is the simplicity of the resin impregnation process, because the dried bulk density can be easily controlled.[6]

According to 7), the surface recession, a consequence of the ablation phenomenon, affects the system stability and safety. The thermo-chemical ablation is the primary cause for surface recession, while the effect of mechanical erosion is secondary. Consequently, understanding the mechanism of thermo-chemical ablation is very important from the view point of structure design.[7]

Surface recession rate was subject for previous empirical determination in the past, e.g. the study for Galileo spacecraft which entered the atmosphere of Jupiter, for which high-density ablator was used.[8] In those studies, the surface recession rate was assumed to be independent of density and a linear dependency with the heat flux was found.[8]

However, in case of the ablators made of LATS materials, the density can be chosen between 0.2 and 1.5 g/cc. For a proper study, the influence of density for the determination of the surface recession rate should be taken into consideration. By using an empirical estimation of the surface recession rate, considering different heat fluxes and densities, the decision on the thickness of the ablator can be made quickly.

In the present paper, phenolic CFRP ablator are taken as study subject and an empirical correlation for the surface recession is determined. The paper presents a new curve-fit exponential equation for estimating the surface recession rate of the carbon-phenolic ablation in air, by taking into consideration its dependency with the surface temperature and density, using the measured data from the high-enthalpy heating facilities of the German Aerospace Center (DLR, Germany), Jutem (Japan) and Japan Aerospace Exploration Agency (JAXA, Japan).

2. Previous Methods to Predict the Recession Phenomenon

For solving the chemical ablation problem for charring carbon based materials, several approaches were developed to calculate the temperature of body and the surface recession caused by chemical ablation. Most of the existing models are one-dimensional studies, in which the chemical reactions are seen as equilibrium processes.[7]

According to 9), numerical prediction of ablation is ambitious and cpu-time demanding due to the complex multiphase physical and chemical processes that occur. Even in the present state-of-the-art numerical models, which couples a high-fidelity CFD flow solver with a material thermal response code,[9] some major restrictions are still present:

- Surface chemical equilibrium assumption;
- Non-ablating flow field prediction;
- Simplified diffusion modeling based on transfer coefficient.

The ablation recession rate is generally computed by the material response code using thermochemical tables and extremely simplified diffusion models based on transfer coefficients and semi-empirical relations relating mass and energy transfer. [9]

Recession depends strongly on the surface temperature so that, in its analysis, several regions have to be taken into account,[10] depending on temperatures: the first region called the rate-controlled oxidation region (below 1,500 K), where the surface material mainly dissipates as a result of its oxidation by air; the second region called the diffusion-controlled oxidation region (between 1,500 K and 3,000 K) and the third region called sublimation region where the surface mass loss predominately occurs through the sublimation of carbon: 3C(Solid)→C3(Gas). The first studies were done for graphite, but the three regions concept can be applied also for CFRP materials.

No solution for mass recession estimation have been found yet for the sublimation region. However, the Arrhenius equation have been used in the past for the rate-controlled oxidation region[11]:

$$\dot{m}_R = a_R \cdot (X_{O2} \cdot P)^{0.5} \cdot exp[-E_R/(R \cdot T_W)] \qquad (1)$$

Eq. (1) has meaning only for temperatures below 1,500 K, giving inaccurate results for higher temperatures. In case of the second region, the Metzger equation was deduced for graphite[4]:

$$\dot{m}_t = C_O \times \sqrt{P_{st}/R_B} \qquad (2)$$

where C_O is the diffusion-controlled mass-transfer constant, P_{st} is the stagnation pressure (Pa) and R_B is the curvature radius of the specimen.

Because LATS materials are different than graphite (they contain resin which undergoes thermal decomposition by heating and afterwards becomes gas and covers the material surface), another formula have been deduced for LATS.[5] Therefore, a new index θ was adopted to predict the mass loss rate. Okuyama et al.[5] confirmed the mass loss of CFRP in a nitrogen gas atmosphere:

$$\dot{m}_t = \theta \cdot \sqrt{P_{st}/R_B} \qquad (3)$$

θ is named as the diffusion-controlled mass-transfer modulus ($\mathrm{kg^{0.5}/m}$) and it can only be used in the diffusion-controlled regime, being a new evaluation index of the heat shield performance of ablators.[5)]

The accuracy of using Arrhenius equation together with the new equation for the diffusion region (named Okuyama equation) for calculating the mass recession, has been proven in the case of USERS spacecraft.[12)] It is worth noting that mass recession was considered independent on density. However, it was observed that there is a dependency between surface recession rate and density. Consequently, an empirical method for a first estimation of the surface recession rate is required to be developed, including its dependency with the density. The recession rate of ablating materials is often expressed as an empirical function of surface temperature and material properties.[13)]

To analyze the performance or thermal behavior of LATS, it is important to carry out high-enthalpy heating tests.

3. Heating Tests Facilities

In developing thermal protection systems for reentry vehicles, arc-heaters are often used to simulate reentry conditions. Arcjet type arc-heaters and segmented cathode type arc-heaters are widely used. The arcjet type has the advantage that it requires almost no maintenance after several-hours operation. Therefore, arcjet type arc-heaters are convenient for basic TPS studies.[14)]

Several heating tests were performed using the arc-heating equipment at facilities in Japan and Germany, at 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 fuer Luft- und Raumfahrt (DLR) of Germany.

The tests performed for the current study of LATS materials can be classified in three groups: the tests performed for high-density ablator material (Jutem, JAXA and DLR), the tests performed for low-density ablator material (Jutem, JAXA, DLR) and the recent tests for low density ablator material performed at JAXA, in 2015. The high and low-density ablators have been tested for different flow conditions in order to prove that LATS material can perform well in different environmental conditions, no matter its density.

For the first category of tests, high-density ablators (1.47 g/cc) have been used and the main purpose was to validate the ablators for the USERS spacecraft. 42 test pieces were tested, in very different flow conditions, the stagnation pressure varying from 0.04 to 29.8 kPa and the test duration from 30 to 300 seconds.

In case of the second group, for the low-density ablators, the virgin LATS densities were of approximately 0.2-1.5 g/cc for the JUTEM, 0.2-0.7 g/cc for JAXA, and 0.2-0.6 g/cc for the L3K of DLR. Under this wide range of conditions, the time courses of the surface and in-depth temperatures were acquired, where the heat flux and duration were 500 kW/m^2-11.1 MW/m^2- and the heating time durations were 10-30 s, respectively. The test conditions can be seen in the Table 1, where by A type are denoted the test conditions at JUTEM, by B type the test conditions at JAXA and by C type the test conditions at DLR.

Table 1. Flow conditions for the second group of tests[5)].

Type	Name	ρ, g/cc	Δt, s	h, MJ/kg	Pst, kPa	Heat flux, MW/m^2
A	J3-1	0.344	150	27.4	0.533	1.0
	J3-2	0.331	150	27.4	0.533	1.0
	J5-1	0.495	150	27.4	0.533	1.0
	J5-2	0.491	150	27.4	0.533	1.0
	J5-3	0.499	150	27.4	0.853	2.0
B	A3-1	0.296	60	12.8	1.9	0.97
	A3-2	0.287	60	18.8	4.6	2.0
	A5-1	0.544	60	12.8	1.9	0.98
	A5-2	0.531	110	18.8	4.6	1.97
C	D3-1	0.341	15	14.5	19.0	5.3
	D3-2	0.296	20	14.5	47.5	8.3
	D5-1	0.566	10	14.5	47.5	8.3
	D5-2	0.536	10	14.5	85.0	11.1
	D5-3	0.561	15	14.5	19.0	5.3

In case of the third group of tests (2015), on which the current study is focused on, the tests were performed at JAXA Sagamihara campus, for evaluating the performance of the ultra-lightweight ablator (LATS), manufactured and assembled at Kyushu Institute of Technology.

For measuring the cold-wall heat flux rate of the high-enthalpy airflow, a flat face cylindrical copper calorimeter and a Pitot tube that stems the airflow were used for each test.

The impact pressure is the difference between the total pressure (or stagnation pressure) and the static pressure. In case of the arc heating facility of JAXA Sagamihara, its dependency with the distance from the nozzle was deduced based on several measurements made in the past, by JAXA staff. This dependency is shown in Fig. 1. In Table 2, the values of the distance from the nozzle, of the heat flux and of the impact pressure are given.

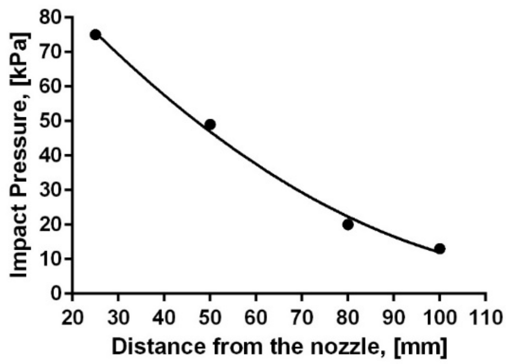

Fig. 1. Dependency of the impact pressure with the distance from the nozzle for the high-enthalpy heating tests at JAXA Sagamihara (by courtesy of JAXA).

Table 2. The distance from nozzle, heat flux and impact pressure.

Specimens	Distance from nozzle, mm	Heat Flux, MW/m^2	Impact Pressure, kPa
A1,B1,C1,D1	100	5	12
A2,B2,C2,D2	75	7.9	25
A3,B3,C3,D3	67	11.9	32
A4,B4,C4,D4	35	13.7	62

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.[5)] The test matrix, where the flow conditions can be seen for each test, is given in Table 3.

The ablators which were used in the third group of study are of the following five types:

- Type A : density of 0.3 g/cc;
- Type B: density of 0.5 g/cc, 1st method of manufacturing;
- Type C : density of 0.5 g/cc, 2nd method of manufacturing;
- Type D: two layers - one layer of 10 mm length, with density of 0.3 g/cc and another layer of 20 mm length, with density of 0.5 g/cc, glued together by an epoxy-based adhesive.
- Type E: two layers - one layer of 10 mm length, with density of 0.3 g/cc and another layer of 20 mm length, with density of 0.5 g/cc, glued together by an epoxy-based adhesive.

The two methods of manufacturing, mentioned in case of B and C models refer to the fact that they were manufactured by two different teams of workers. The structure of the ablators can be seen in Fig. 2. All the models have a diameter of about 19.9 mm and the length of the test holder is 80 mm (Fig. 2). In order to prevent the lateral sides of the ablator specimen against the high heat, the test piece was covered with a Bakelite sleeve. Inside the specimens, the thermocouples were installed for measuring the temperatures during the test, in the direction of the heat flow (Fig. 3).

The ablator specimens are subjected directly to frontal heating during each test. The Bakelite tube is covered with inorganic cloth to reduce heating of the specimen from the side. Minimizing in this way the lateral heating, a one-dimensional analysis becomes possible and the analytical results can be compared with the test results afterwards. Measurements of the weight, diameter, and thickness were taken before and after each test and these measurements are used to determine the surface recession and mass loss rate for each specimen.

There are 4 models of type A (A1, A2, A3, A4), 4 models of type B (B1, B2, B3, B4), 4 models of type C (C1, C2, C3, C4), 4 models of type D (D1, D2, D3, D4) and 4 models of type E (E1, E2, E3, E4). The models with the name having the number 1 are used for a heat flux of 5 MW/m^2, those with number 2 for 8 MW/m^2, those with number 3 for 12 MW/m^2 and those with number 4 for 13.5 MW/m^2 (Table 3). In case of D and E models, 2 densities are presented in Table 3, D and E models being composed of 2 parts of different densities. The first density which is mentioned in the table corresponds to the front layer of 10 mm length and the second density to the second layer of 20 mm length.

Table 3. Test Matrix for the third group of tests.

Run	Name	ρ, g/cc	Δt, s	h, MJ/kg	Pst, kPa	Heat flux, MW/m^2
1	A2	0.3	15	12.98	25	8
	B2	0.5	15	13.16		
	C2	0.5	15	12.97		
2	D2	0.8; 0.5	15	12.97	25	8
	E2	0.3; 0.5	15	13.13		
3	A3	0.3	15	13.13	32	12
	B3	0.5	15	13.10		
	C3	0.5	15	13.04		
4	D3	0.8; 0.5	15	13.19	32	12
	E3	0.3; 0.5	15	13.12		
5	A4	0.3	15	12.95	62	13.5
	B4	0.5	15	13.00		
	C4	0.5	15	12.93		
6	D4	0.8; 0.5	15	13.35	62	13.5
	E4	0.3; 0.5	15	13.34		
7	C1	0.5	15	12.93	12	5
	D1	0.8; 0.5	15	12.88		
8	A1	0.3	15	12.91	12	5
	B1	0.5	15	12.92		
	E1	0.3; 0.5	15	13.07		

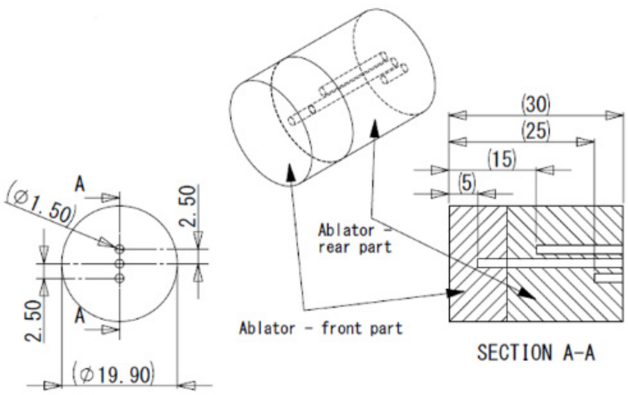

Fig. 2. The structure of the ablator (2 layers of 10, respectively 20 mm length for D and E models, 1 layer of 30 mm in case of A, B and C models).

As can be seen in the Table 3, ablators with different densities have been tested. Fig. 4 shows a picture from the high-enthalpy heating test and Figures 5, 6 and 7 show the models A4 (density of 0.3 g/cc) and C4 (density of 0.5 g/cc), tested in a high heat flux flow (13.5 MW/m^2) .

In Fig. 7, one can see also the char layer which was formed in the front side of the specimen. A black region (pyrolysis later) was formed between the char layer and the virgin layer.

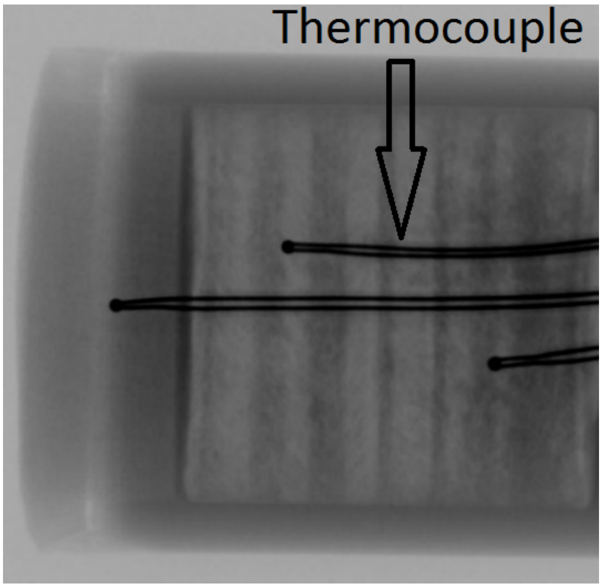

Fig. 3. X-ray picture after the high-enthalpy heating tests at JAXA Sagamihara campus (2015).

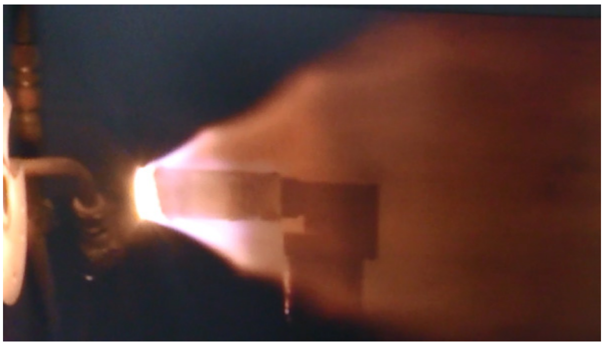

Fig. 4. Picture from the high-enthalpy heating tests, performed at JAXA Sagamihara campus (2015).

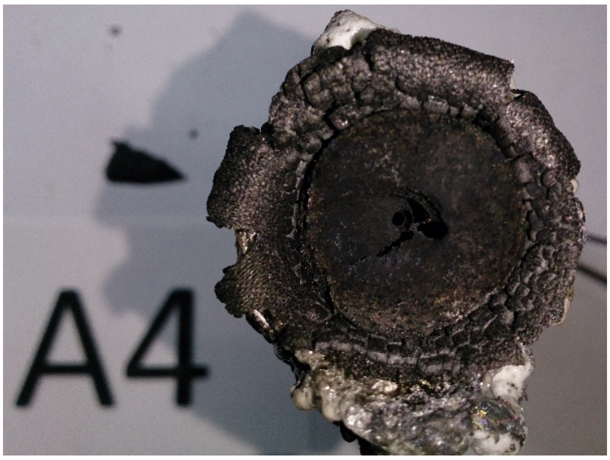

Fig. 5. Lowest density ablator (0.3 g/cc), after being heated with 13.5 $\mathrm{MW/m^2}$ heat flux.

Fig. 6. Ablator with density of 0.5 g/cc, after being heated with 13.5 $\mathrm{MW/m^2}$ heat flux.

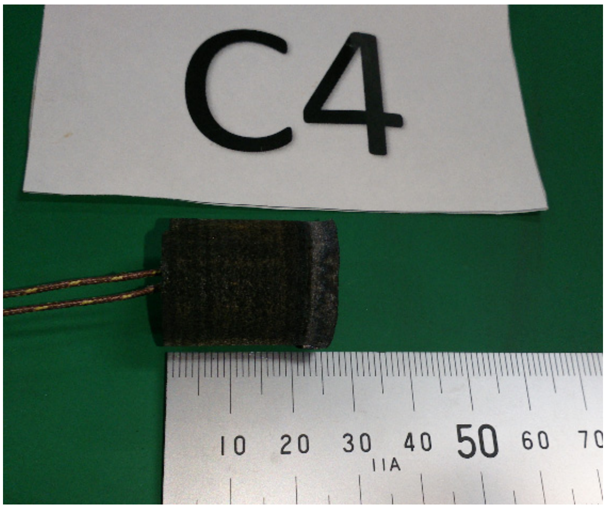

Fig. 7. Visualization of the char layer after the test (C4 model).

4. Results and Discussions

The last results of the tests performed at JAXA Sagamihara in 2015 fit very well with the results of the older tests, made in the past, at Jutem, JAXA and DLR, regarding the relation between the surface temperature and the heat flux, which can be seen in Fig. 8. The temperatures values show that the LATS specimens heated under the specified conditions of Table 1 reached approximately 2,000 – 3,500 K at the surface, most of these temperatures being in the diffusion-controlled oxidation region (1,500 – 3,000 K).

A linear dependency between the measured mass loss rate and $\sqrt{P_{st}/R_B}$ can be established for the diffusion controlled oxidation region. For the previous tests, the slope of the linear function was found to be $2.0 \times 10^{-4}\ \sqrt{\mathrm{kg}}/\mathrm{m}$ for low density LATS materials.[5)] Comparing the results of the last tests at

JAXA Sagamihara with the previous tests (Fig. 9), the dependency can still be established using the new test results from 2015, and the found slope has the same value of $2.0 \times 10^{-4}\ \sqrt{\mathrm{kg}}/\mathrm{m}$.

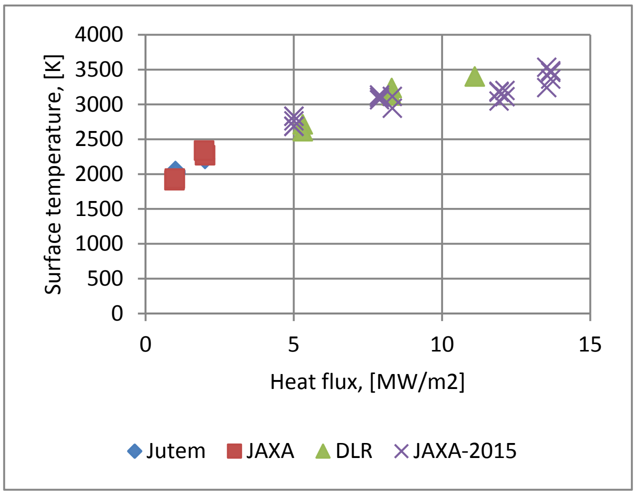

Fig. 8. Dependency of Surface Temperature with the Heat Flux for low-density LATS materials.

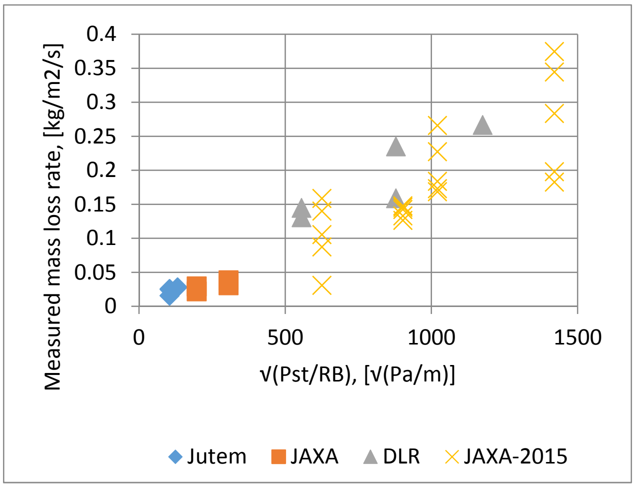

Fig. 9. Relationship between total mass loss rate and $\sqrt{P_{st}/R_B}$ of low-density LATS materials: distribution for different tests performed at Jutem, JAXA and DLR.

There have been found a linear dependency between the mass recession rate and the square root of P_{st}/R_B.

However, in case of the surface recession rate, an empirical method could be established, taking into consideration its dependency with the density. In Fig. 10, there can be seen the relationship between the product of surface recession rate and density with the surface temperature for different tests performed with high and low-density LATS materials and, in Fig. 11, an exponential dependency can be clearly seen. *Ldot* is the symbol for the surface recession rate, measured in m/s and *ρ(char)* is the char density, measured in $\mathrm{kg/m^3}$.

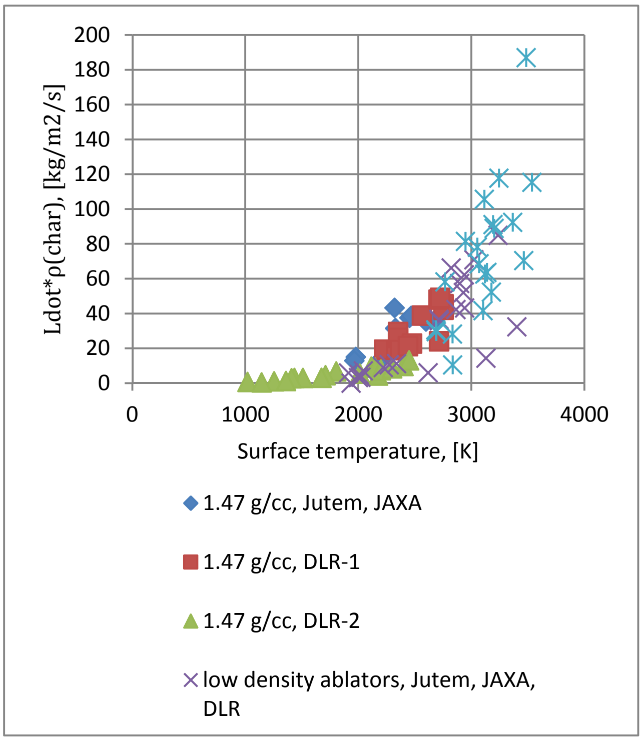

Fig. 10. Relationship between $Ldot \times \rho(char)$ and the surface temperature in case of high and low density LATS materials: distribution for different tests performed at Jutem, JAXA and DLR.

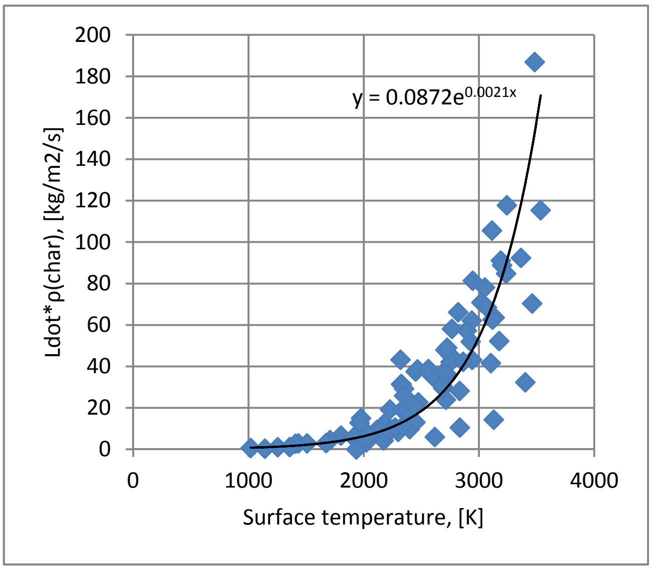

Fig. 11. Relationship between $Ldot \times \rho(char)$ and the surface temperature in case of high and low density LATS materials: the exponential dependency.

The new equation that can be written for estimating the surface recession rate is the following:

$$Ldot = 0.0872 \times (e^{0.0021 \times T} / \rho(char)) \tag{5}$$

where *Ldot* is the surface recession rate, *e* is the base of the natural logarithm, T is the surface temperature and $\rho(char)$ is the char density of the ablator. Consequently, the surface recession has an exponential dependency with the surface temperature and an indirect proportionality with the density, having low values for high-density LATS materials and high values for low density LATS materials.

5. Conclusions

Several heating tests were performed using the arc-heating equipment at facilities in Japan and Germany, at 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 fuer Luft- und Raumfahrt (DLR) of Germany. Based on the results of the tests, it can be concluded that the LATS can well function as a heat shield material even under a high-enthalpy flow.

Ablation being a very complex phenomenon, its analysis can be extremely difficult. Therefore, simple engineering methods, based on empirical results, could be extremely useful in the first estimation of the ablator recession in high enthalpy flows. As demonstrated in previous studies, a linear dependency between the measured mass loss rate and $\sqrt{P_{st}/R_B}$ can be established. The slope of the linear function was found to be $2.0 \times 10^{-4}\ \sqrt{\mathrm{kg}}/\mathrm{m}$ for low density LATS materials. This value was confirmed by the more recent tests in 2015, at JAXA Sagamihara.

In case of the surface recession rate, it was proved to be dependent with density, having an exponential dependency with the surface temperature and an indirect proportionality with the char density. The new empirical formula could be very useful in estimating the thickness of the ablative thermal shield of the reentry spacecrafts.

The empirical correlations should be backed-up in the future with the analytical models which allows extrapolation to conditions beyond ground test data base.

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