
COMPUTATIONAL AND EXPERIMENTAL INVESTIGATIONS OF CARBON-CERAMIC COMPOSITE MATERIALS THERMOCHEMICAL RESISTANCE IN COMBUSTION PRODUCTS OF LIQUID ROCKET ENGINE

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Computational and experimental investigations of thermochemical resistance of carbon-ceramic composites in the combustion products of liquid rocket engine (LRE) are presented. The tests with model extensions made of the composite material (CM) were performed. The test time was about 200 s. The maximal temperature of the material fire surface was 1600 K. Physical and numerical model of silicon carbide destruction was developed.

1 INTRODUCTION

Nonmetallic CMs possess density which is a factor of 4 to 5 less than that of conventional thermoresistant metals and alloys. They have already been successfully used in LRE (Fig. 1). For example, engine 11D58M with extension of radiant cooling made of carbon composite material has a lot of successful flights since 2003 as a part of Zenit 3SL.

Carbon-based CMs are attractive for their low density and high strength which increases with temperature. Also, the use of a protective covering allows increasing considerably their resistance to oxidizing environment.

2 PHYSICOCHEMICAL DESTRUCTION MODEL

Refractory carbides and metallic oxides are considered to be utilized in coverings protecting base carbon materials at temperatures near 1900–2000 K. Relatively stable protection in this temperature range can be provided by silicon carbide.

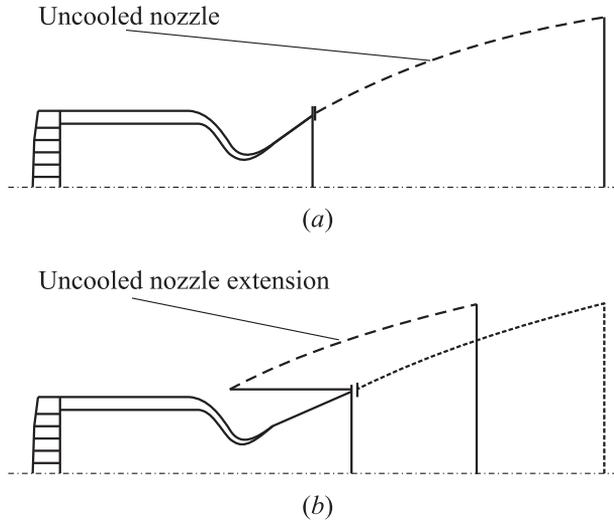
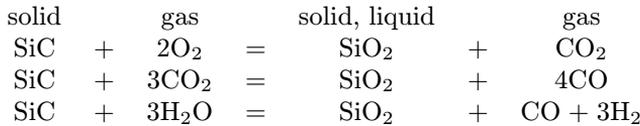


Figure 1 Possible CM applications in LRE

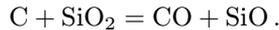
Silicon carbide contained in the protective material reacts with combustion products like H_2O , CO_2 , O_2 , and O with possible formation of a SiO_2 film.

The most thermodynamically realistic reactions are listed below:



The SiO_2 film plays a role of diffusion barrier for both oxidant components in the gas flow (interaction takes place on the SiO_2 - SiC interface) and for reaction products flow-out (Fig. 2). The film thickness is determined not only by its growth rate but also by the flow near the surface if temperatures are high enough to melt SiO_2 , so that this melt could be removed by frictional forces.

If the material surface layers contain carbon particles, the SiO_2 film will also contain carbon which can interact with SiO_2 as



This process results in thinning of the SiO_2 film. Furthermore, different impurities influence the viscosity of the SiO_2 film.

The conditions of SiO_2 film formation are often referred to as “passive” in opposite to “active” conditions when the reaction product is gas-phase SiO which cannot create a protective film.

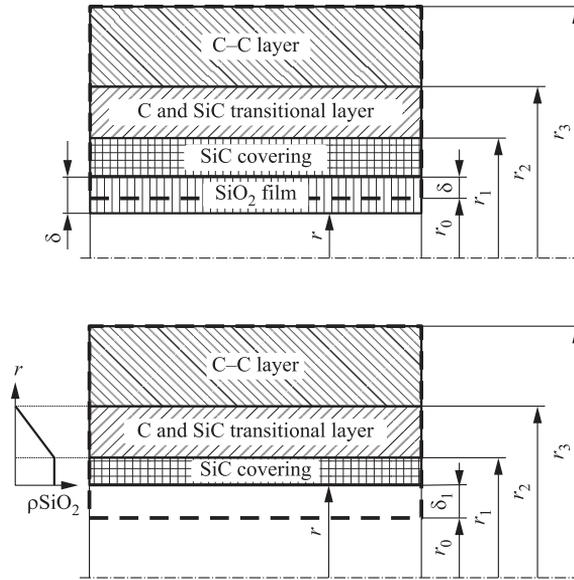
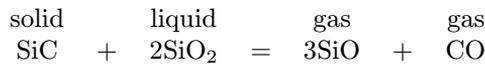


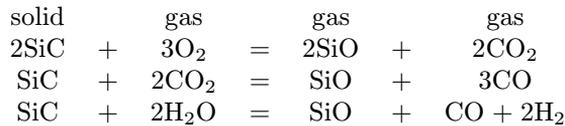
Figure 2 Schematic of carbide-ceramic CM destruction

The temperature of transition from active to passive conditions depends on the environment parameters such as pressure, concentration, and composition of oxidant components, as well as availability of carbon and other side components (including technical additives, determining the chemical bond energy between carbon and carbide during SiC covering formation) in the film. In some cases [1], the transition from active to passive conditions can be attributed to the temperature of 1967 K. More detailed information can be found in [2].

In general, in C–SiC system, the following physicochemical transformations with oxidants can take place both on the material surface and in the material itself. The film depletion process proceeds rapidly as soon as the transition temperature is reached. Its rate is determined by the SiO₂–SiC reaction which produces gas-phase SiO and CO:



Also, the film depletion rate is affected by mechanical destruction caused by the blowout of different gaseous products according to the reactions:



In “active” conditions, the covering ablation rate increases significantly as compared to “passive” conditions (refer to data in [1]).

It is worth noting that an important specific feature of this physical and thermophysical process is the existence of SiO_2 barrier film. Its formation, motion, vaporization, and interaction with other substances determine and in some cases limit the rates of other physicochemical transformations. Thus, the results of classical thermochemical experiments, although can provide some necessary data on the kinetics of individual processes, do not allow getting insight into material and protective film behavior in real LRE conditions. Dynamics of film and covering formation, moving, and destruction can be studied only at conditions which reproduce all specific features of the flow in real nozzles.

3 EXPERIMENTAL INVESTIGATION

Model extensions made of carbon-carbon material with SiC covering (Nos. 1 and 2) were tested on oxygen-hydrogen LRE (Fig. 3) to examine the specific features of the processes discussed above. The tests were performed in a vacuum chamber with diffuser. Main characteristics of extensions and test conditions are presented in Table 1.

During the tests, the temperature of extension surface was 1700 K, gas flow pressure was 30–33 kPa, and pressure in vacuum chamber was about 7.1 kPa (see Table 1). One could expect that SiC oxidation takes place in passive conditions when oxidants (in this case, water vapor, mainly) reacts with SiC creating SiO_2 layer (solid in given conditions).

The film growth rate is governed by the parabolic law $d\delta_2/dt = k/\delta_2$; consequently, $\delta_2 = \sqrt{2kt} + c$.

If the SiO_2 layer is initially absent, the integration constant $c = 0$ (for a combined layer, this constant will be equal to the Al_2O_3 layer thickness). The thickness of the reacted SiC layer (δ_1) can be then determined as

$$\delta_1 = \delta_2 \frac{\mu_{\text{SiC}}}{\mu_{\text{SiO}_2}} \frac{\rho_{\text{SiO}_2}}{\rho_{\text{SiC}}}$$

using the reaction stoichiometry.

These equations and the equations of thermal conductivity for the extension and vacuum chamber were solved together with the boundary layer equations accounting for the thermal film in the extension created by the LRE cooling jacket (solution procedure is presented in [3]).

Consider the results of experiments and numerical analysis. All the extensions tested had different ablations of material after the tests but kept their integrity.

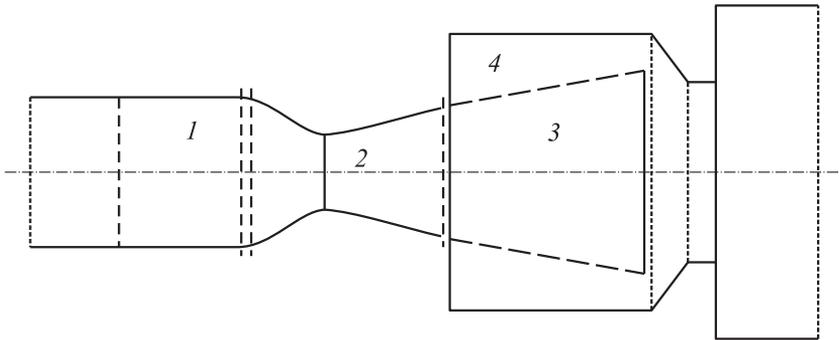
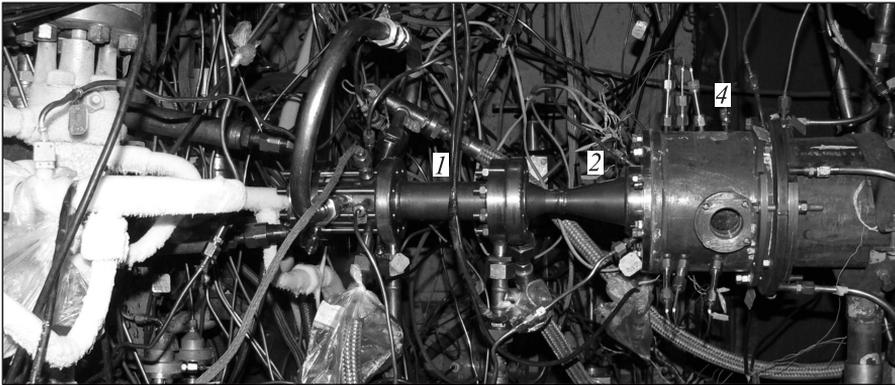


Figure 3 Model LRE with vacuum chamber and diffuser: 1 — model engine; 2 — cooled nozzle; 3 — uncooled extension; and 4 — vacuum chamber

Table 1 Main characteristics of extension and test conditions

Extension	P_c , MPa	P_{vc} , kPa	P_{ce} , kPa	T_{max} , K	k_m	Time, s
No. 1 C/C + SiC covering + Al ₂ O ₃	9.06	7.1	32.6	1640	7.4	205
No. 2 C/C + SiC covering + Al ₂ O ₃	8.3	10.4	30.4	1600	8.5	205

Remark: P_c — pressure in combustion chamber; P_{vc} — pressure in vacuum chamber; P_{ce} — gas flow pressure in the interface between cooled nozzle and extension; T_{max} — extension maximum temperature; and k_m — component ratio.

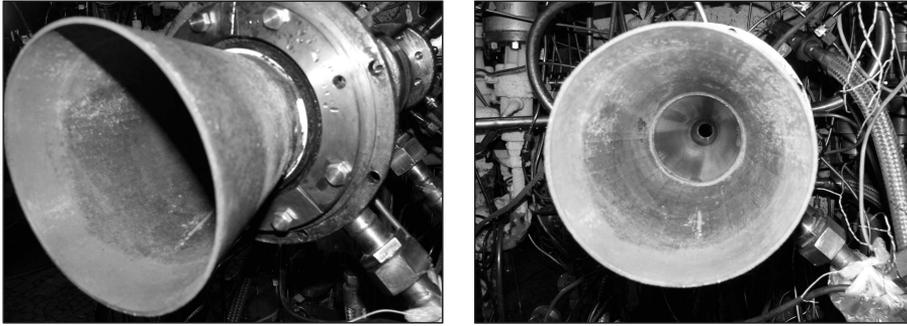


Figure 4 Extension No.1 after testing

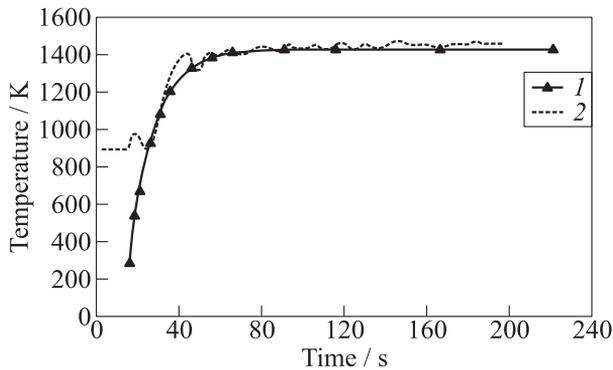


Figure 5 Calculated (1) and measured (2) temperature histories of the extension outer surface

For example, Fig. 4 shows extension No.1 after the test. Considerable amounts of SiO_2 were found during chemical analysis of the surface layer.

Figure 5 shows the time histories of the calculated extension temperature and that measured by infrared (IR) camera. Clearly, in the area of vacuum-chamber window, the temperature was near 1430 K. Infrared camera measurements agree well with the calculated temperatures. Based on the measurements and calculations, the maximal temperature of the extension inner surface was found to be 1600 K (Fig. 6).

The calculated ablation value is shown in Fig. 7 by the lower curve. It is determined by two processes: by SiO_2 film growth and interaction between SiC and Al_2O_3 when temperature reaches 1473 K [4]. This estimation was made assuming that the whole Al_2O_3 layer reacted with SiC evolving gas-phase

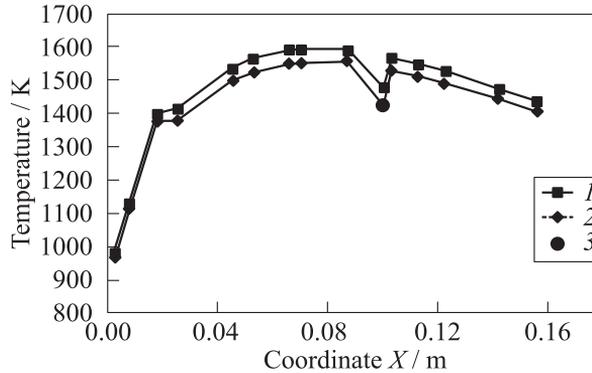


Figure 6 Temperature measured along the extension at the end of engine operation. Inner and outer surfaces: 1 — Tw1; 2 — Tw2; and 3 — IR

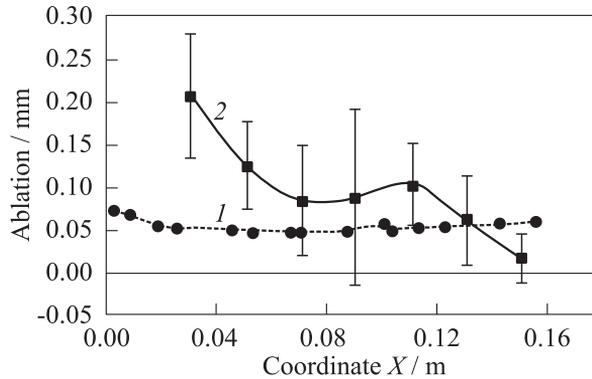


Figure 7 Calculated (1) and measured (2) linear ablation on the extension surface

products. The results of linear ablation metering agree with the estimations in the area free of heat transfer intensification ($x > 0.06$ m).

4 CONCLUDING REMARKS

Thus, the protective covering was shown to remarkably decrease the extension material ablation (by a factor of 3–5) and survived till the end of engine operation. Theoretically, it is better to use SiO_2 instead of Al_2O_3 , as it creates a diffusion barrier and does not exhibit additional interactions at the temperature range of interest.

REFERENCES

1. Williams, S. D., D. M. Curry, D. C. Chao, and V. T. Pham. 1994. Ablation analysis of the Shuttle Orbiter oxidation protected reinforced carbon-carbon. *6th AIAA/ASME Joint Thermophysics and Heat Transfer Conference*. Colorado Springs.
2. Rosner, D. E., and H. D. Allendorf. 1970. High-temperature kinetics of the oxidation and nitridation of pyrolytic silicon carbide in dissociated gases. *J. Phys. Chem.* 74(9):1829-39.
3. Volkov, N. N., and L. I. Volkova. 1999. The efficiency of gas curtain application for increasing the resistance of composite material extensions. *Rus. J. Avia-Space Machinery Technol.* 3:43-49.
4. Kislyi, P. S., A. Kh. Bodyan, V. S. Kindesheva, and F. S. Garibyan. 1981. *High-temperature metal heaters*. Kiev: Naukova Dumka Publ.