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To cite this article: V P Petrovskiy et al 2018 J. Phys.: Conf. Ser. 946 012032

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Radio-physical properties of radiotransparent thermal protection materials in ablation mode

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Abstract. Experimental method for assessing the impact of the effects of high-temperature ablation processes on the radio physical characteristics of radiotransparent thermal protection materials (RTPM) is developed. Researches for the following RTPM with various structures of glass fillers are completed: press material (radiotransparent thermal protection press material or RTP-200); glass-fiber laminate (glass-fiber radiotransparent organic ceramic matrix or GFR-CM); reinforced composite material of class SiO₂–SiO₂ (high-temperature radiotransparent ceramic organic matrix or HTTR-OM). The influence of physicochemical transformations in the surface layer of RTPM on transmission and reflection coefficients of electromagnetic waves of RTPM samples and on the value of their complex permittivity is determined.

1. Introduction

The wide use of the aboard receiving indicator and antenna feeder equipment in modern rocket-space technology leads to a necessity for studying results of influence of the extreme heat loads to efficiency of radiotransparent nose cones and radomes of the transmit-receive radiotechnical devices [1, 2].

In the present paper we describe the method of physical modeling to evaluate consequences of highly intensive aerodynamic heating to the electrophysical properties of the radiotransparent thermal protection materials.

2. Radiotransparent thermal protection materials

Radiotransparent thermal protection materials (RTPM) are designated to protect the antenna feeder devices placed at the flying vehicle (FV). Their main function is to provide a reliable radio communication with ground and satellite stations. Depending on the purpose of FV and the disposition place of components from RTPM (antenna windows, inserts, radomes and so on) the highly intensive heat flows and pressures can act on these components. To provide the reliable
Table 1. Comparative characteristics of the radiotransparent materials.

<table>
<thead>
<tr>
<th>Name of characteristics</th>
<th>RTP-200</th>
<th>GFR-CM</th>
<th>HTRC-OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.75–1.85</td>
<td>1.6–1.65</td>
<td>1.6–1.65</td>
</tr>
<tr>
<td>Breaking point (MPa)</td>
<td>90–100</td>
<td>80–120</td>
<td>70–90</td>
</tr>
<tr>
<td>Permittivity on a frequency of $10^6$ Hz</td>
<td>3.8–4.5</td>
<td>3.2–3.4</td>
<td>2.9–3.1</td>
</tr>
<tr>
<td>Loss-angle tangent on a frequency of $10^6$ Hz</td>
<td>0.02–0.04</td>
<td>0.005–0.008</td>
<td>0.003–0.005</td>
</tr>
<tr>
<td>Change of permittivity up temperature 1500 K, no more (%)</td>
<td>20</td>
<td>15</td>
<td>$\leq$ 5</td>
</tr>
</tbody>
</table>

radio communication and withstand the aerodynamic loads these materials should have high and stable dielectric characteristics in the wide range of working temperatures in combination with the high thermo-chemical resistance to an action of high temperature heat flows [3].

Depending on matrix and structure of the applied glass filler RTPM are classified into: press materials; glass-fiber laminates; reinforced composite materials of SiO$_2$–SiO$_2$ class, the typical representatives of which are such materials as RTP-200 (radiotransparent thermal protection press material), GFR-CM (glass-fiber radiotransparent organic ceramic matrix) and HTRC-OM (high-temperature radiotransparent ceramic organic matrix).

It should be noted that under the action of the highly enthalpy aerodynamic loads these materials work in the ablation mode.

The material HTRC-OM belongs to the class of the radio-transparent ceramic-matrix composite materials and differs from the materials mentioned above by the absence of the organic component in its composition. The main comparative characteristics of the materials are represented in table 1.

3. Physical modeling of high-temperature processes at RTPM surface

At the surface of the radiotransparent elements of the contemporary FV the heat flows of 1–20 MW/m$^2$ are realized. Besides, temperatures producing the thermal ablation of the radiotransparent elements of constructions reach values 2000–2500 °C. To provide such temperatures with modeling the high velocity flowing around we need to have the flows with a power density reaching tens of MW/m$^2$. The realization of such conditions at the areas $10^2–10^3$ cm$^2$ with the required time duration (≈ 100 s) under laboratory conditions is practically impossible at the present time.

From the point of view of composition and structure of material realized levels of temperature, gradient of temperature and values of the gas-dynamic action on are more important rather than character and reasons of the external actions. Just a level of temperature determines processes taking place in the material: thermal expansion, melting, evaporation (sublimation), chemical reactions, and in the first turn oxidation (burning), a change of the phase state, caking, deformations, diffusion and so on. Note that the influence of a value of the temperature gradient (density of a heat flow) for composite materials capable to withstand a high level of thermal stresses is less essential.

Taking into account the above-mentioned reasons we use in this work the method to reach the required level of temperatures with the help of the stationary heating of samples and products under the conditions modeling the operational ones at relatively small levels of the heat flow density and pressure (about 1 MW/m$^2$). In this case we use a heating of samples by the flow of combustion products, i.e. by the mixture of CO$_2$ and H$_2$O with the known and controllable coefficient of the oxidizer (oxygen) excess—$\alpha$. The presented method allows us to
model physically the character of the thermal-chemical processes at the extensive surfaces for the required time duration.

The realization of this method is accomplished by the use of the gas burner of the stoichiometric burning in which the preliminary prepared mixture of fuel and oxidizer with the prescribed ratio is burned. The last one is especially important for investigating processes of the thermal ablation at a surface of the studied materials when it is of prime importance to realize a simultaneous occurrence of processes of the thermal and chemical destruction of a material. Due to these reasons in this work we have selected the investigation of operational high temperature processes at the surface of the radio transparent elements of FV using the propan-oxigen burner of the stoichiometric burning PKG-01 developed in JIHT RAS [4].

The burner PKG-01 generates the flow of combustion products of the prescribed composition with the adiabatic temperature of the propane burning in oxygen 2535 °C. Its thermal power is up to 50 kW, propane flow rate is up to 1 g/s, diameter of a jet of combustion products is about 35 mm at a distance 50 mm from a nozzle (figure 1).

The block diagram of stand-imitation equipment for modelling operating thermal ablation processes on the surface of radiotransparent elements of FV is presented in figure 2.

4. Radio-physical properties of RTPM samples
The impact evaluation of the effects of high-temperature ablation processes on the radio-physical characteristics of RTPM objects and samples was carried out by means of measuring the changes of following properties: transmission coefficient of electromagnetic (EM) wave, reflection coefficient of EM wave, effective complex permittivity.

The systems of radiotransparent materials based on the composite structures 100 mm and 200 mm square size were the measurements objects. Appearances of RTPM samples in initial state and after high-temperature treatment are presented in figures 3–8.
Figure 2. Block diagram of stand-imitation equipment: 1—burner PKG-01; 2—rotameter; 3—water cooling system of burner PKG-01; 4—oxygen tanks; 5—propane tanks; 6—micropyrometer EOP-66; 7—infrared thermometer Testo 835-T2; 8—chromel-alumel thermocouples; 9—millivoltmeter; 10—unit under test.

Figure 3. RTP-200 sample in initial state.

Figure 4. RTP-200 sample after high-temperature treatment.

Figure 5. GFR-CM sample in initial state.

Figure 6. GFR-CM sample after high-temperature treatment.

Figure 7. HTRC-OM sample in initial state.

Figure 8. HTRC-OM sample after high-temperature treatment.
Figure 9. Scheme of stand-imitation equipment: 1—Rohde & Schwarz ZVA40 vector network analyzer (4 ports); 2—PC; 3,4—wideband lens horn antenna P6-23M; 5,6—wideband lens horn antenna P6-64; 7,8—metal diaphragms of different size with a multi-layer radio absorbing material coating on them; 9,10—pyramidal microwave absorber; 11—rubidium frequency standard SRS FS725; 12—RTPM test sample.

Figure 10. Measuring of transmission coefficient of test sample in the frequency range from 24 to 40 GHz.

Figure 11. Measuring of reflection coefficient of test sample in the frequency range from 3 to 24 GHz.
Figure 12. Transmission (a) and reflection (b) coefficients of material GFR-CM, transmission (c) and reflection (d) coefficients of material HTRC-OM, transmission (e) and reflection (f) coefficients of material RTP-200.
The transmission and reflection coefficients and also effective complex permittivity of submitted samples at normal incidence of EM wave in the frequency range from 1 to 40 GHz were measured by the instrumentality of certified methodology [5]. This measuring procedure is based on the material samples measuring of reflection $S_{11}$ ($S_{44}$) and transmission $S_{21}$ ($S_{43}$) coefficients of quasi-plane EM wave by means of ultra-wideband diaphragmatic lens horn antennas and vector network analyzer R&S ZVA40.

Sample test material was placed in the aperture of radio-absorbing metal diaphragm positioned in the near field of lens horn antenna P6-23M (P6-64) with a view to minimize the impact of the diffraction at the edges of the test sample and at the edges of the horn antenna. During the measurement process of reflection coefficient matched load has been mounted in the area behind the diaphragm—radio-absorbing material (RAM) like a three-dimensional pyramid-type block with low value of reflectivity in the operating bandwidth (minus 50 dB no more) in order to exclude additional parasitic reflections from the ambient space. A time selection of clutter reflections (Time Domain) with a suppression of Gibbs phenomenon was exploited in a digital signal processing for eliminating multiple reflections between sample test material and horn antenna.

Measurements of reflection and transmission coefficients and effective permittivity in the frequency range from 2 to 40 GHz were carried out for samples with dimensions $200 \times 200$ mm$^2$. Measurements for samples with dimensions $100 \times 100$ mm$^2$ were carried out in the frequency range from 3 to 40 GHz using the small-sized diaphragm 80 mm in diameter. With a view to assessing electrodynamic homogeneity and possible anisotropy of RTPM samples the measurements of each sample at two positions corresponding E- and H-polarization of electromagnetic field were conducted. These positions differ from each other in rotation by 90 degrees around a surface normal of a test sample. The block diagram of measuring bench is presented in figure 9. The process of measuring radio-physical properties of test samples through the measuring bench is presented in figures 10 and 11. As results the comparative dependences of reflection coefficient, transmission coefficient and complex permittivity of RTPM samples in initial state and after high-temperature treatment are shown in figure 12.
Frequency dependences of complex permittivity of RTP-200 and HTRC-OM samples are represented in figures 13 and 14 respectively. Designation T means thermal treatment.

5. Conclusions
(i) Experimental method for assessing the impact of the effects of high-temperature ablation processes in the surface layer of RTPM is developed.
(ii) Researches for the three following RTPM with various structures of glass fillers are completed: RTP-200, GFR-CM, HTRC-OM. It is established that reinforced quartz material HTRC-OM with no organic component is the most stable material after high-temperature treatment.
(iii) Radiotransparency of HTRC-OM samples remains essentially unchanged with tendency to improve, especially in the short-wave region of EM spectrum, through the removal of construction water from inside the material. It is shown that changes of modulus of transmission and reflection coefficients in initial state and after the high-temperature treatment make 1–2 dB of order of magnitude in the frequency range from 2 to 40 GHz for HTRC-OM. Whereas these changes of magnitude reach no more than 4 dB for GFR-CM and reach no more than 14 dB for RTP-200.
(iv) High-temperature treatment has led to increase dielectric losses in RTP-200 and GFR-CM. This fact is probably associated with emergence of semiconducting carbonaceous layer as a result of high-temperature physicochemical transformations on the surface of materials.

References