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Research and development of heat flux sensor for ablative thermal protection of spacecrafts

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ABSTRACT

The objective of this paper is to estimate heat fluxes on the surface of advanced materials with known thermal and thermokinetic properties using the approach based on inverse methods. In many practical situations it is impossible to measure directly heat fluxes on the surfaces of analyzed composite structures (in particular a thermal protection systems (TPS) of spacecraft) especially in the case of thermokinetic processes inside materials. The only way that can often be used to overcome these difficulties is indirect measurements. This type of measurements is usually formulated as the solution of inverse heat transfer problems. By solving such inverse problems, the boundary conditions and unsteady temperature distribution are reconstructed using interior temperature measurements in structures. Such problems are ill-posed in mathematical sense and their main feature shows itself in the solution instabilities. The general method of iterative regularization is concerned with application to the estimation of external heat flux for thermal protection of spacecraft.

1. Introduction

Moving in the planets atmosphere re-entry vehicles (RV) are influenced by large force and thermal loadings caused by gas approach flow. Frontal aerodynamic shields are used for RV protection from these influences and its effective braking; a level of loadings depends on shields lateral dimensions. A trade-off between a decrease of a level of force and thermal loadings on RV by increasing RV's lateral dimension and limitations of launch vehicle payload fairing cross section could be a frontal shield of alternative geometry [1–8].

One of the options of this aerodynamic shield with alternative geometry could be an inflatable shield (Fig. 1). In general this shield is a closed air-tight casing (or several casings) forming selected aerodynamic shape after filling it with a gas. This casing connects to a rigid frontal element of the aerodynamic shield which forms a RV's inflatable brake mechanism or inflatable re-entry drug technique (IRDT). The object is placed at the rigid frontal element designed for flight in the atmosphere. At the orbital flight IRDT is placed under the fairing in the compact volume folded position (Fig. 1a), and just before the aerodynamic deceleration phase, i.e. before the entry to the atmosphere, is brought into a state of operating unfolded position (Fig. 1b). Flexible thermal protective coating (FTPC) is used for the protection of air-tight inflatable casing, with its material destruction temperature around 500 K. Principle scheme of FTPC is shown in Fig. 2. Coating consists of two multilayered packages – one external thermal protective and one internal thermal insulting. The external layer consists of silica fabric with sublimating polymer material.

To provide mathematical simulation of IRDT the following initial data are necessary: heat flux $q_{w_i}(\tau)$ and/or external temperature variation $T_{w_i}(\tau)$ at selected points at the surface. These measurements could be done at different TPC development phases during laboratory, benchmark, full-scale (large-scale) and flight experiments and tests. Photo of RV's mockup with the IRDT installed at the test stand is presented in Fig. 3 and the scheme of suggested measurement points placing at the IRDT surface during benchmark tests is shown in Fig. 4.

Results of simulation (at the points presented in Fig. 4) of a heat flux at the RV's surface with the mass 138.5 kg and IRDT diameter 2.3 m for nominal model of the Earth atmosphere are presented in Fig. 5.

Results of calculation of FTPC heating at the Point 3 at the RV's surface at selected points on coating thickness (Fig. 2) are presented in Fig. 6.

2. Heat flux sensor development

The experimental specimen of thermal protection coating is proposed as multilayer slab in the rectangular parallelepiped shape

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Nomenclature

Latin symbols

A	Arrenious coefficient
b	length of heat flux sensor
$c(T)$	heat capacity
$C_g(T)$	heat capacity of gas
E	energy of activation
$f_m(\tau)$	temperature measurements
$H(T)$	heat effect
$\overline{g^s}$	vector of gradient minimization method at current iteration
J	leas-square minimized functional
$\bar{J}_p^{\prime(s)}$	gradient of the functional J at current iteration
M	number of thermocouples
n	power of thermo-kinetic reaction
$\bar{p}$	vector of unknown parameters
$q_1(\tau)$	heat flux at the heated boundary
$q_2(\tau)$	heat flux at the inner boundary
$q_{w_i}(\tau)$	heat flux at selected points at the surface
Q_{electr}	electrical heat at the heater
$T(\tau, x)$	temperature
$T_0(x)$	initial temperature
$T_{w_i}(\tau)$	temperature at selected points at the surface
x	spatial variable
$x_1, x_2, \ldots, x_m$	coordinate of thermocouples

Greek symbols

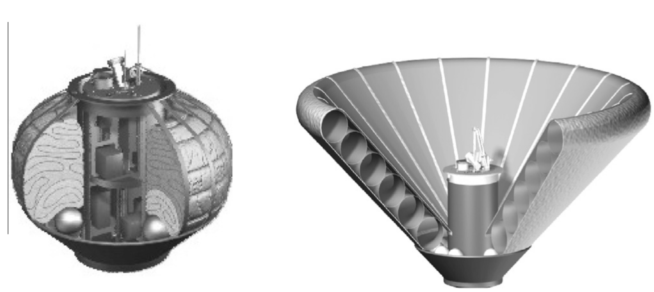
$\alpha_1, \alpha_2, \beta_1, \beta_2$	coefficients determined kind of boundary conditions (1 for left, 2 for right)
$\overline{\gamma^s}$	step descent
$\Delta T(x, \tau)$	increment of temperature
δ_f	integral error of temperature measurements
$\Phi(x, \tau)$	adjoint variable for density
$\lambda(T)$	thermal conductivity
$\rho(x, \tau)$	current density of material
ρ_0	initial density of virgin material
ρ_c	density after thermokinetic process
$\sigma_m(\tau)$	measurement variance
τ	time
τ_m	final time
τ_r	time of the beginning of thermokinetic process
τ_c	time of the end of thermokinetic process
$\psi(x, \tau)$	adjoint variable for temperature
$\theta(x, \tau)$	increment of density

made of the regular material (Fig. 7). The choice of specimen size is dependent on hardware opportunities. The important parameter is the ratio of specimen thickness to its length and width, which provides the realization accuracy of one-dimensional temperature field in the line of axis. That's why, for example, the ratio 1:10–1:15 is recommended for materials with low thermal conductivity. The scheme of thermal testing of the specimen with a sensor is shown in Fig. 7. The prototype of sensors for IRDT based on sublimating polymer material were developed and manufactured for experimental verification of sensor structure and temperature measurement processing methods at the installation TVS-2M (MAI). Sensor scheme is shown in Fig. 8.

Special device was developed at MAI for installation of internal thermocouples X_2, X_3 and X_4 into sensors during the process of thermocouples manufacturing. Thermocouples at the heated (X_0) and back (X_5) surfaces of prototypes of sensors installed during the preparation of thermal tests during the integration of experimental sample in the experimental module. Photos of some prototypes of sensors with installed inside internal thermocouples are presented in Figs. 9–11.

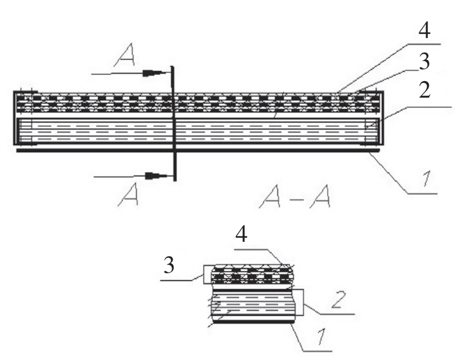
The symmetric scheme of contact heating of two samples [11] was used in tests with the using of flat heating element (HE). The scheme is shown in Fig. 11. In this scheme the protective frames of sensor samples A and B made of sublimating polymer simulate the thermal-protective covering in which the sensors are installed. The stainless steel foil was used as of HE material with size (length × width × thickness) 120 × 80 × 0.1 mm. The size of operating zone of HE equals to 80 × 60 mm. The back surfaces of sensors and thermal protective covering are covered by thermal-isolated slab made from material which thermal conductivity coefficient are much more less than investigated sensors have. It allows to model the presence of thermal-isolating under the external covering layer in consistent of real multilayered flexible thermal protective covering.

The construction and technological peculiarities of flux thermal sensor prototype designed for flexible Thermal Protection based on



(a) IRDT in a folded position (b) IRDT in an unfolded position

Fig. 1. RV with inflatable brake mechanism.



1 – air-tight casing,

2 – heat insulting package,

3 – thermal protective package,

4 – sublimating material layer.

Fig. 2. Scheme of IRDT's flexible thermal protective coating.