PESQUISA EXPERIMENTAL E MODELAGEM MATEMÁTICA DA PROTEÇÃO TÉRMICA COM EXPOSIÇÃO DE ALTA TEMPERATURA

EXPERIMENTAL INVESTIGATION AND MATHEMATICAL MODELLING OF HEAT PROTECTION SUBJECTED TO HIGH-TEMPERATURE LOADING

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ И МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ТЕПЛОЗАЩИТЫ ПРИ ВЫСОКОТЕМПЕРАТУРНЫХ ВОЗДЕЙСТВИЯХ

RABINSKIY, Lev N. [1]; TUSHAVINA, Olga V.[2*]

[1]Moscow Aviation Institute (National Research University), Department of Advanced Materials and Technologies of Aerospace Application, 4 Volokolamskoe shosse, zip code 125993, Moscow – Russian Federation
(phone: +7 499 158-27-7)

[2]Moscow Aviation Institute (National Research University), Institute of Aerospace, 4 Volokolamskoe shosse, zip code 125993, Moscow – Russian Federation
(phone: +7-499-158-58-65)

** Corresponding author*
e-mail: solgtu@gmail.com

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RESUMO

A proteção térmica do sistema espacial reutilizável, a partir do momento da preparação de pré-lançamento e até o final do programa de pouso de voo, é afetada por cerca de vinte fatores externos. Estes incluem: aquecimento aerodinâmico intenso com diferentes composições químicas da atmosfera, temperaturas altas e baixas, quedas bruscas na pressão atmosférica, cargas mecânicas causadas pela dinâmica de gases de fluxos supersônicos, inerciais e de choque. A proteção térmica confiável é a chave para o funcionamento bem-sucedido do sistema espacial reutilizável, portanto, estudos experimentais e teóricos de proteção térmica sob efeitos de alta temperatura são de particular relevância. Aqui, se propõe a metodologia para testes de alta temperatura de banco de materiais de proteção térmica reutilizáveis. Os testes foram realizados em um suporte de gás dinâmico supersônico sob a influência de fluxos de energia de alta intensidade. Como resultado do experimento, um campo de temperatura na superfície e na profundidade do material de proteção térmica foi obtido em diferentes pontos no tempo. Foi construído um modelo matemático, que descreve adequadamente a distribuição do campo de temperatura em materiais de proteção térmica sob a ação de fluxos de energia de alta intensidade sobre eles. Os resultados teóricos obtidos são comparados com dados experimentais.

Palavras-chave: *material de proteção térmica, equação de condução de calor não-estacionária, campo de temperatura, suporte de gás dinâmico supersônico.*

ABSTRACT

For the thermal protection of a reusable space system, from the moment of prelaunch preparation to the completion of the flight program-landing, there are about twenty external factors. These include intensive aerodynamic heating with the different chemical composition of the atmosphere, high and low temperatures, sudden changes in atmospheric pressure, mechanical stresses caused by gas dynamics of supersonic flows, momentum, and shock. Reliable operation of thermal protection is the key to the successful operation of the reusable space system, therefore, experimental and theoretical studies of thermal protection under high-

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temperature influences are of particular relevance. Here is offered the technique of bench high-temperature tests of heat-protective materials of repeated use. The tests were carried out on a supersonic gas dynamic bench under the influence of high-intensity energy flows As a result of the experiment, a temperature field was obtained at the surface and in the depth of the heat-shielding material at different points of time. A mathematical model adequately describing the distribution of the temperature field in heat-shielding materials is developed under the action of high-intensity energy fluxes on them. The obtained theoretical results are compared with the experimental data.

Keywords: *heat-shielding material, nonstationary heat equation, temperature field, supersonic gas dynamic stand.*

АННОТАЦИЯ

На тепловую защиту многоразовой космической системы, начиная с момента предстартовой подготовки и до момента завершения летной программы-посадки, действует около двадцати внешних факторов. К ним относятся: интенсивный аэродинамический нагрев при разном химическом составе атмосферы, высокие и низкие температуры, резкие перепады атмосферного давления, механические нагрузки, вызванные газодинамикой сверхзвуковых течений, инерционные и ударные. Надежная работа тепловой защиты является залогом успешной работы многоразовой космической системы, поэтому особую актуальность представляют экспериментальные и теоретические исследования теплозащиты при высокотемпературных воздействиях. Здесь предложена методика стендовых высокотемпературных испытаний теплозащитных материалов многоразового использования. Испытания проводились на сверхзвуковом газодинамическом стенде при воздействии высокоинтенсивных потоках энергии В результате эксперимента получено поле температур на поверхности и в глубине теплозащитного материала в различные моменты времени. Построена математическая модель адекватно описывающая распределение поля температур в теплозащитных материалах при действии на них высокоинтенсивных потоков энергии. Проведено сравнение полученных теоретических результатов с экспериментальными данными.

Ключевые слова: *теплозащитный материал, нестационарное уравнение теплопроводности, поле температур, сверхзвуковой газодинамический стенд.*

INTRODUCTION

For the thermal protection of a reusable space system, from the moment of prelaunch preparation to the completion of the flight program-landing, there are about twenty external factors (Afanasyev *et al.*, 2004; Afanasyev and Chudetsky, 2012). These are intensive aerodynamic heating with the different chemical composition of the atmosphere, high and low temperatures, sharp changes in atmospheric pressure, mechanical loads caused by gas dynamics of supersonic flows, cosmic radiation, solar radiation, etc (Manannikov *et al.*, 2017). The issues of heat protection and heat transfer under the action of high-intensity energy fluxes on the aircraft were considered in detail in these works (Polezhaev and Yurevich, 1976; Fei and Riddell, 1959; Fenster, 1965; Avduevsky and Kalashnik, 1967; Pasichny *et al.*, 2001; Gofin, 2003; Konkov *et al.*, 1969; Georgiev, 1964; Frolov *et al.*, 1981; Kudryavtsev et al., 1961; Frolov *et al.*, 1984).

Each stage of operation of a spacecraft is characterized by its determining parameters of external influences (Formalev *et al.*, 2017; Formalev *et al.*, 2015). These include intensive aerodynamic heating with the different chemical composition of the atmosphere, high and low temperatures, sudden changes in atmospheric pressure, mechanical stresses caused by gas dynamics of supersonic flows, inertia, and shock.

The influence of external high-intensity energy flows and high temperatures during operation causes, so-called "aging" of thermal protection materials. With the realization of this "harmful" process, microcracks appear on the surface of heat-shielding materials, local chemical reactions take place in the volume of materials with the disruption of intermolecular bonds, chemical reactions with the external environment. All this causes a change in the strength and other properties of the materials that compose the thermal protection.

At the stage of preparation of space systems for launch, the thermal protection coating is under the direct influence of all climatic factors, however, the most dangerous from the point of view of aging and destruction are high-intensity energy flows and high temperatures. Therefore, here, first of all, the effect of high-intensity heat energy fluxes on the surface of heat-shielding materials is considered.

MATERIALS AND METHODS

Tests of heat-shielding materials were carried out on a supersonic gas-dynamic test bench as shown in Figure 1. A similar installation with tests of heat-shielding material was used in the work (Afanasyev and Tushavina, 2016).

The algorithm for high-temperature tests is compiled as a single technological chain of testing when several simultaneous or consecutive experiments are reproduced on the stand. Such a technological chain includes a heat resistance test that realizes the heating element of the thermal protection structure to a certain temperature and maintains it with a subsequent performance check at the selected temperature. The heating temperature is defined as the sum of the annual maximum temperature and possible solar overheating in the specified operating conditions (Afanasyev *et al.*, 1994; Lituga *et al.*, 1986; Frolov *et al.*, 1978). The holding time of the product at the test temperature is calculated after the temperature has reached the stationary value. It is determined by the duration of the continuous finding of the product during operation under such conditions, taking into account the level of its thermal inertia. The test procedure for the elements of the thermal protection design for heat resistance includes heating up to the set temperature.

As follows from the tests carried out, the value of the activation energy necessary for determining the time of the experiment is determined from the change in the parameters characterizing the operability of the element under test, or the properties of the materials involved.

If it is necessary to reproduce the accumulation of damage caused by random temperature changes and cause a decrease in mechanical strength, the calculation of the number of cycles with the selected temperature amplitude is based on comparison of the accumulated damage values with respect to the actual test conditions (taking into account the plastic, viscoelastic and other material properties). An approximate estimate of the number of cycles can be based on a comparison

of the accumulated cycles.

When carrying out the above types of temperature tests, the following schemes are involved in this stand:

1) the test sample 11, which is a large-scale model measuring 250 × 250 mm (thermal protection design element), is mounted on the working table of the rotary rod 12.

2) heating of the materials under study to the specified temperatures is achieved by using an infrared heater Figure 2 positions 6. The general view of the infrared heater installed in the vacuum chamber is shown in Figure 3:

The infrared heater has a power of 73 kW with three rows of emitters. Quartz lamps of KG-220-1000 type are used as emitters. The area of the beam reflector is 480 × 320mm.

The maximum surface temperature obtained on heat-shielding materials when irradiated with an infrared heater was 1700K. The highest rate of change in temperature during heating was 70 deg/sec. Changes in the density of radiant heat flow on the surface of the model were carried out by regulating electric power, consumed by the lamps. The uneven distribution of the heat flux density over the surface of the model did not exceed 3%.

RESULTS AND DISCUSSION:

To calculate the heat flux and the temperatures of the inner layers of the heat-shielding material, we will use the nonstationary heat Equation 1 (Polezhaev and Frolov, 2005; Podstrigach and Kolyano, 1976).

Here ρ, c, λ, T – density, heat capacity and thermal conductivity of the material and temperature field; c_g, G_g – heat capacity and rate of release of gaseous decomposition products of the binder; τ – heating time; V_∞ – linear velocity of mass carryover and its quasi-stationary value; q_0- convective heat flow to a surface with temperature *Tw* ; q_{vd} – the the rmal effect of injection, c_q is the velocity of propagation of the thermal wave.

In the general case, Equation 1 takes into account the heat transfer with a velocity equal to the rate of destruction of the surface $V_{\infty}\frac{\partial T}{\partial x}$, heat absorption by filtering gaseous decomposition products of the binder $G_g\frac{\partial T}{\partial x}$, as well as the volume flow of heat due to the thermal effect of physical and chemical conversions ΔQ^* (we further assume that this item is zero). (Index Σ means that the thermophysical properties, in this case, correspond to the cumulative system: a porous medium plus gaseous products of physic-chemical transformations). The external load is shown in Figure 4.

The initial and boundary conditions have the form Equations 2 – 4. The boundary conditions (Equation 3) include two tasks: 1 the boundary value task (Equation 5) and 2 the boundary value task (Equation 6)

Equation 6 of heat balance, which includes heat fluxes from the blowing effect ($q_{вд}$), surface radiation ($es\,T_w^4$), the thermal effect of surface transformations ($G G_S D Q_w$), heat removal for the heating of internal layers of the material (q_l) and the heat flow supplied from the outside (q_0). We represent equation 1 in the form Equation 7. In this Equation 8. To solve Equation 5, we use the integral Laplace transform with respect to time t as Equation 9. Applying transformation Equation 7 to Equation 5, we obtain an ordinary differential equation in transformations $T^*(s)$ (Equation 10). The solution of this equation is (Equation 11). To solve the problem, we use the first boundary-value task. Substituting the transformations of the boundary conditions in (Equation 11), we obtain Equation 12. Then the transformations of the temperature field can be represented in the form (Equation 13). We find the original expression (Equation 11) using the properties of the Laplace transform and tables (Equation 14) (Ditkin and Prudnikov, 1965; Medvedsky and Rabinsky, 2007). Where $*$ the operation of convolution by time is designated t. In this expression Equations 15, 16. Here Equation 17. Where $H(\tau)-$ the function of Heaviside, $J_1(\tau)-$ Bessel function of the first kind. Using the procedure of convolution by time t in the relation (Equation 16) we finally obtain (Equation 18). Figure 5 shows the nonstationary distribution of the temperature field as a function of time t in the different sections $x$heat-shielding element. The dashed line indicates the distribution of the temperature field obtained as a result of the experiment at the equipment (Figure 1-3) on the surface of the heat-shielding sample. The parameters are shown in Figure 5 are dimensionless and are determined in a standard way by reducing Equation 1 to the dimensionless form.

CONCLUSIONS:

On the basis of the obtained results, it was concluded that the proposed methods and experimental means for carrying out high-temperature tests of heat-shielding materials for multifactorial screening tests of elements of heat-shielding structures of the plate type can be used to correctly evaluate their performance in conditions of ground testing.

The obtained results of mathematical modeling of the unsteady behavior of the heat-protective material under high-intensity influences adequately describe the conducted experimental studies. On the basis of the performed studies, it is possible to draw a conclusion that the calculation of the finite speed of distribution of a thermal wave allows to describe with a sufficient degree of accuracy the distribution of the temperature field in a heat-shielding material. These results are consistent with experimental studies.

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$$\frac{\partial^2 T}{\partial x^2} - \left[\frac{c_g G_g + (\rho c)_\Sigma V_\infty}{\lambda}\right]\frac{\partial T}{\partial x} - \frac{\Delta Q^*}{\lambda} - \frac{(\rho c)_\Sigma}{\lambda}\frac{\partial T}{\partial \tau} - \frac{1}{c_q^2 \lambda}\frac{\partial^2 T}{\partial \tau^2} = 0 \quad (1)$$

$$\tau = 0, T(x) = T_w, \mathrm{V}_\infty = 0 \quad (2)$$

$$\tau > 0\ x = 0 \quad \begin{cases} T = T_w & or \\ \lambda \dfrac{\partial T}{\partial x} = \varepsilon \sigma T_w^4 + G G_\Sigma \Delta Q_w + q_{inj} - q_0 - q_\lambda \end{cases} \quad (3)$$

$$\begin{aligned} &\tau > 0\ x \to \infty \\ &T \to O(1) \end{aligned} \quad (4)$$

$$\to T = T_w \quad (5)$$

$$\to \lambda \frac{\partial T}{\partial x} = \varepsilon \sigma T_w^4 + G G_\Sigma \Delta Q_w + q_{inj} - q_0 - q_\lambda \quad (6)$$

$$\frac{\partial^2 T}{\partial x^2} - 2\alpha \frac{\partial T}{\partial x} - \beta \frac{\partial T}{\partial \tau} - \gamma \frac{\partial^2 T}{\partial \tau^2} = 0 \quad (7)$$

$$\alpha = \frac{c_g G_g + (\rho c)_\Sigma V_\infty}{2\lambda}, \quad \beta = \frac{(\rho c)_\Sigma}{\lambda}, \quad \gamma = \frac{1}{c_q^2 \lambda} \quad (8)$$

$$T^*(s) = \int_0^\infty T(\tau) e^{-s\tau} d\tau \quad (9)$$

$$\frac{d^2 T^*}{dx^2} - 2\alpha \frac{dT^*}{dx} - (\beta s + \gamma s^2) T^* = 0 \quad (10)$$

$$\begin{aligned} &T^*\big|_{x\to\infty} = O(1) \quad \to C_2 = 0 \\ &T^*\big|_{x\to 0} = \frac{T_w}{s}, \quad \to C_1 = \frac{T_w}{s} \end{aligned} \quad (12)$$

$$T^{*}\left(s,x\right)=\frac{T_{w}}{s}e^{\left(\alpha-\sqrt{\alpha^{2}+\beta s+\gamma s^{2}}\right)x};$$ (13)

$$T^{*}\left(\tau,x\right)=T_{w}e^{\alpha x}\left[\Phi\left(\tau,x\right)-\frac{\beta}{2\gamma}\Phi\left(\tau,x\right)*\Phi_{1}\left(\tau,x\right)\right]$$ (14)

$$F\left(\tau,x\right)=H\left(\tau-x\sqrt{\gamma}\right)\left[1-x\sqrt{\gamma}\mu\int_{x\sqrt{\gamma}}^{\tau}\frac{J_{1}\left(\mu\sqrt{t^{2}-\gamma x^{2}}\right)dt}{\sqrt{t^{2}-\gamma x^{2}}}\right],$$ (15)

$$F_{1}\left(\tau,x\right)=e^{\frac{\beta}{2\gamma}\tau}$$ (16)

$$\mu=\sqrt{\frac{\alpha^{2}}{\gamma}-\left(\frac{\beta}{2\gamma}\right)^{2}},$$ (17)

$$T^{*}\left(\tau,x\right)=T_{w}e^{\alpha x}\left[F\left(\tau,x\right)-\frac{\beta}{2\gamma}\int_{x\sqrt{\gamma}}^{\tau}F\left(t,x\right)F_{1}\left(\tau-t,x\right)dt\right]$$ (18)

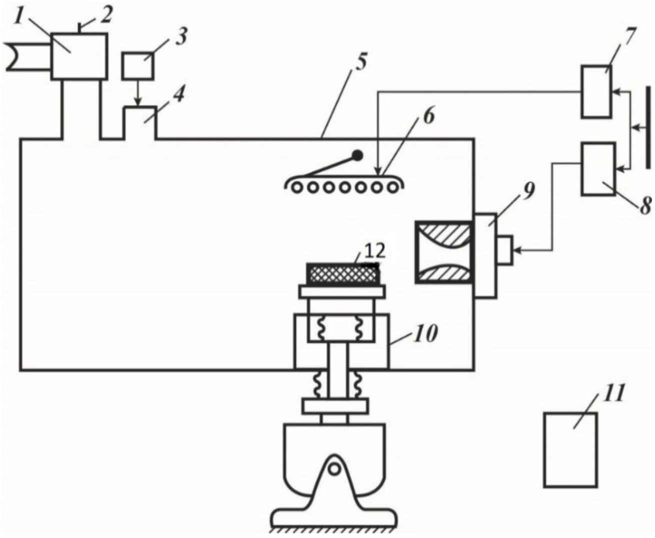

Figure 1. *Supersonic gas dynamic bench for reproduction of multifactorial influence on materials of thermal protection of space vehicle: 1 – vacuum shutter; 2 – vacuum shutter control system; 3 – the control system of the inflow; 4 – the inflow; 5 – the vacuum chamber; 6 – electric arc gas heater; 7 – infrared heater control system; 8 – control system of electric arc gas heater; 9 – infrared heater; 10 – vacuum input of the electric vibrator; 11 – power supply and power supply system; 12 – test sample*

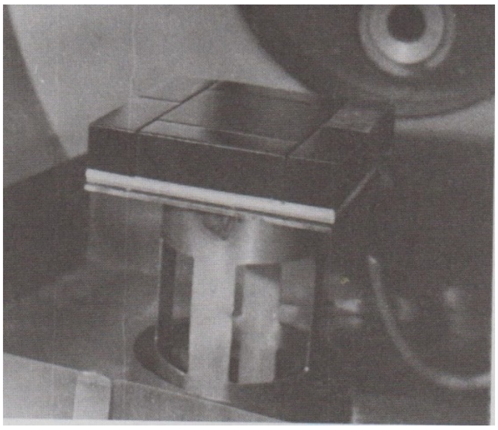

Figure 2. *General view of the test sample*

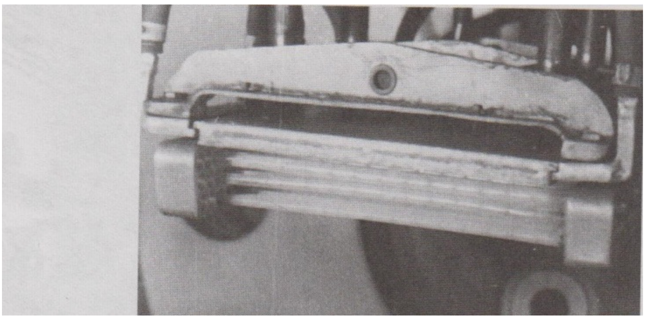

Figure 3. *General view of the infrared heater installed in the vacuum chamber of the gas dynamic bench*

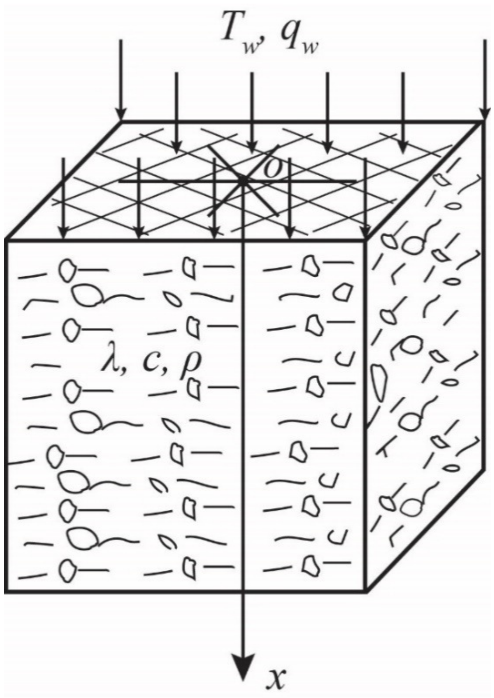

Figure 4. *The calculated scheme of heat-shielding material by the action of high-temperature fields*

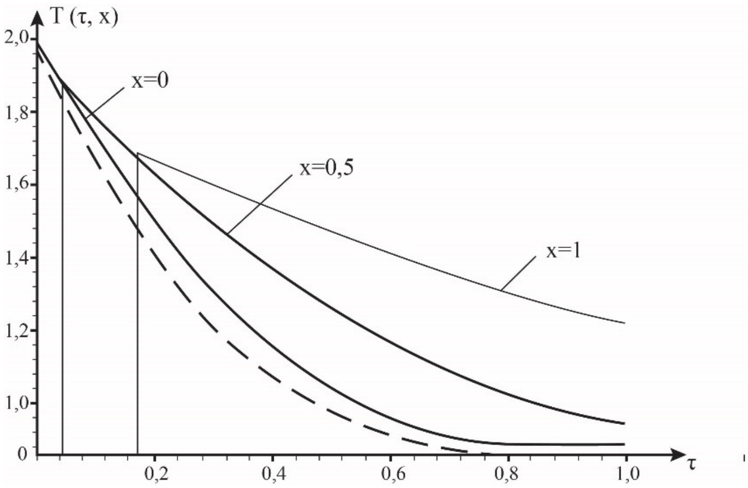

Figure 5. *Distribution of the temperature field in the heat-shielding element*