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THE DESTRUCTION RATE ESTIMATION OF SPACE DEBRIS BY AERODYNAMIC HEATING DURING RE-ENTRY TO ATMOSPHERE

The article presents a mathematical model and calculation results of the object surface ablation when moving in dense layers of the Earth's atmosphere. The relevance of research is due to the development of new active and combined methods for the removal of space debris. In a number of such methods an object is diverted from a low Earth orbit into the Earth's atmosphere where it burns down. The effectiveness of such methods depends on the size of the removed object and the type of structural material. The paper estimates the rate of thermal destruction of the surface of an object during aerodynamic heating. As investigated materials carbon fiber reinforced plastic, steel, tungsten and niobium alloys are considered. A simplified one-dimensional mathematical model is proposed and the results of numerical simulation of unsteady temperature fields in different materials are presented. In solving the heat problem a change of variables was used that allows one to construct a calculation algorithm without tracking the motion of the phase transition front. Based on the solution of the thermal problem the rate of thermal destruction (ablation) is determined. The calculation results are important for determining the range of space debris objects for which burning in the atmosphere can be effective.

Ablation of a space object surface during aerodynamic heating has a significant effect on the temperature distribution in the structural material. Due to the entrainment of heat by the mass of the destroyed material, the temperature field gradient increases, which contributes to the localization of heat in the surface layer. The temperature field and the rate of destruction of the material take on a "quasistationary" character with time.

The parameter that significantly affects the rate of thermal destruction of objects when moving in the Earth's atmosphere is the thermal activity of the material. The rate of thermal destruction for refractory materials (molybdenum and niobium alloys) is one two orders of magnitude lower than for steel, which has a significantly higher thermal activity.

Keywords: Space Debris, Atmospheric Entry, Ablation, Mathematical Model.

Introduction. The space debris is becoming one of the most pressing problem of the modern aerospace industry. The large number of non-functioning objects and their fragments in the orbits poses a serious danger to Earth-based navigation [1,2]. Nowadays the search for ways to clear the Earth's orbits from space debris is an urgent task addressed by the efforts of leading aerospace agencies and companies in the world [3].

Methods and tools for removing space debris from low Earth orbits are presented in [4–8]. A number of spacecraft removal methods utilize the removal of non-functioning spacecraft and their elements from low Earth orbits into dense atmospheric layers. It is assumed that due to the intense heating of the structural material and the increase in aerodynamic loads, thermal fragmentation, melting and the final destruction of the object in the atmosphere are occurring. However, the effectiveness of this approach is due to many factors: the size of the object, thermophysical properties and strength characteristics of structural materials, the presence of elements of thermal protection, the parameters of the trajectory, etc.

Thus, the choice of methods and techniques for removing the space object from its orbit requires an analysis of the processes of thermal destruction during movement in the atmosphere.

References review and problem statement. Describing all the physical effects that occur during the bodies movement in the atmosphere requires the use of complex physical and mathematical models for example [9,10]. The interaction of the body moving in the atmosphere at high speeds and the approaches to calculating such processes are discussed in detail in monographs [11, 12].

When applying active or combined methods to remove artificial non-functioning objects or their fragments into dense atmospheric layers, the trajectories of motion that maximize aerodynamic heating of the objects must be ensured. In [13], it was considered the ballistic aspects of the motion of such objects in the atmosphere. In [14], it is shown that the trajectory of motion significantly affects the process of aerodynamic heating of the object. The temperatures that develop in structural materials due to the high thermal load on the surface affect the physical and mechanical properties of the materials. As the temperature increases, the time resistance and elastic modulus are reduced, which will intensify the mechanical destruction of the object. In particular, reducing the modulus of elasticity leads to a decrease in the structure rigidity. There are may be stresses in structural members due to thermal expansion of the materials if the system is statically indeterminate.

Along with mechanical destruction, thermal destruction occurs. Thermal destruction means a complex of different physical mechanisms, the degree of their manifestation depends on the material type. Often the term ablation is used to describe such destruction [10,15].

When designing methods for removal of space debris elements in general, there is uncertainty about the shape and geometric dimensions of the elements, as well as the condition and characteristics of structural materials. Therefore, it is necessary to carry out variational calculations for a wide range of determining parameters. The purpose of this work is an approximate theoretical estimation of the ablation intensity of various structural materials during aerodynamic heating.

Research Method. To evaluate thermal fracture, we use a simplified model, which generally reflects the main process features. Consider this process as part of a one-dimensional model for a half-bounded body. The use of a one-dimensional approach is justified if the depth of warming is significantly less than the distance along the surface at which the same temperature change occurs. The one-dimensional equation of thermal conductivity has the form

$$\rho c(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right), \quad \tau > 0, \quad x \ge 0 \tag{1}$$

where τ – time, ρ – density of material, c – heat capacity, λ – thermal conductivity. The origin of the x-axis is located on the body surface and the axis is directed inside the material (Fig. 1).

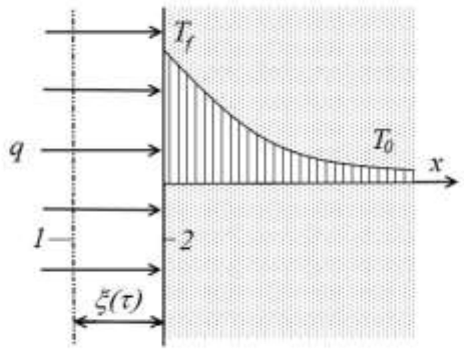


Fig. 1. The scheme for the calculation of thermal destruction: 1 - initial position of the surface; 2 - the current position of the surface

To equation (1) we add the equation of thermal balance in the absence of physicochemical transformations on the body surface

$$q = -\left(\lambda \frac{\partial T}{\partial x}\right)\Bigg|_{x=\xi(\tau)} + \varepsilon\sigma_0 T_f^4 + \rho w \Delta Q_{\text{meltdown}} \qquad (2)$$

where q is the heat flow supplied to the surface; $\varepsilon\sigma_0 T_s^4$ – radiation from the surface; $\Delta Q_{\text{meltdown}}$ –thermal effect of ablation; T_s – surface temperature; ε – material black ratio; σ_0 – Stephan-Boltzmann constant. In this case every kilogram of mass carried along with the gas stream absorbs a certain amount of heat $\Delta Q_{\text{meltdown}}$,. w – linear velocity of movement of the body surface during phase transformation.
The value q is determined from [14]. Linear velocity is determined as

$$w = \frac{d\xi}{d\tau},$$

where ξ is the thickness of the material layer that melted over time τ. Accordingly, the value ξ is determined by the formula

$$\xi = \int_0^\tau w d\tau .$$

Initial and boundary conditions must be added to solve (1). Assume that at the beginning of the destruction the temperature field is known

$$T\big|_{\tau=0} = T_0 . \qquad (3)$$

We assume that the condition at a distance from the inner point is satisfied

$$\left.\frac{\partial T}{\partial x}\right|_{x\to\infty} = 0. \quad (4)$$

Throughout the melting period the surface temperature remains constant and equals to T_f

$$T|_{x=0} = T_f . \quad (5)$$

It should be noted that a large number of structural materials used in space rocket technology are composite, whose components have different thermochemical stability. However, for most such composite materials there is an effect of equalizing the linear rates of destruction of the various components of the material, thus there is an overall rate of destruction of the composite during heating.

Solving the problem of thermal state of the body with the phase transformation presence on its boundary is complicated by the uncertainty of the surface position. The application of mass from the outer surface leads to a constant adjustment of the temperature field and, thus, it will not be self-driving. This effect will be particularly pronounced in the high temperature range that occurs when aerodynamically heated.

Note that in the general case the thermophysical properties of structural materials are temperature depended. In the first approximation we consider the dependence of thermophysical properties only on temperature. Table 1 presents the thermophysical characteristics depending on the temperature of some typical structural materials [17].

Table 1

Thermophysical characteristics depending on the temperature of some typical structural materials

Brand of material	Density, ρ , kg/m^3	An approximation formula for the coefficient of thermal conductivity λ, W /(m·K)	An approximation formula for the coefficient of heat capacity, c, J/(kg K)	Melting point, K
Steel 09X16N4B	7750	$\lambda(T) = 0.01T + 11.19$ $293K \le T \le 1273K$	$c(T) = 0.209T + 390$ $293K \le T \le 1273K$	1673
Molybdenum alloy BM1	10220	$\lambda(T) = 133.41 - 0.018T$ $293K \le T \le 2673K$	$c(T) = 0.065T + 251$ $293K \le T \le 2673K$	2873
Niobium alloy BN-2A	8700	$\lambda(T) = 0.015T + 40.97$ $293K \le T \le 2273K$	$c(T) = 0.069T + 251$ $293K \le T \le 2273K$	2673
Carbon fiber CF-UT	1700	$\lambda(T) = 6.787 \cdot 10^{-3}T + 3.47$ $293K \le T \le 3273K$	$c(T) = 0.85T + 584$ $293K \le T \le 3273K$	3273

Note. The thermal conductivity of CF-UT carbon fiber plastic is given for the normal direction from the surface.
To simplify further analysis we will use the average values of the coefficients of heat capacity and thermal conductivity

$$\bar{c} = \frac{1}{T - T_0} \int_{T_0}^{T} c(T) dT , \quad \bar{\lambda} = \frac{1}{T - T_0} \int_{T_0}^{T} \lambda(T) dT ,$$

and the coefficient of thermal conductivity $a = \dfrac{\bar{\lambda}}{\bar{c}\rho}$.

We introduce a new time frame

$$t = \frac{\tau}{\tau_h} - 1, \; t \geq 0,$$

where τ_h is the surface heating time from the initial temperature to the fracture temperature, which is determined by the solution of the heating problem. It then $t = 0$ corresponds to the beginning of the destruction process. We enter a dimensionless coordinate

$$z = \frac{x - \xi(\tau)}{\sqrt{a \tau_h}}, \; z \geq 0 .$$

Going to such coordinate it makes possible not to use the moving boundary in the formulation of the problem $x = \xi(\tau)$, since the value $z = 0$ corresponds to the surface of destruction.

Taking into account the entered variables and the received expressions after the corresponding transformations equation (1) will take the form

$$\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + w \sqrt{\frac{\tau_h}{a}} \frac{\partial T}{\partial z} .$$

For convenience of analysis we introduce dimensionless temperature and dimensionless speed of the collapsing surface

$$U = \frac{T}{T_f} , \quad W = w \sqrt{\frac{\tau_h}{a}} .$$

Thus, problem (1) - (5) is reduced to the next dimensionless dimension

$$\frac{\partial U}{\partial t} = \frac{\partial^2 U}{\partial z^2} + W \frac{\partial U}{\partial z} , \tag{6}$$

$$U\big|_{t=0} = U_h(z) , U\big|_{z=0} = 1 , \; \frac{\partial U}{\partial z}\bigg|_{z \to \infty} = 0 , \tag{7}$$

$$W = H - R + \frac{1}{m}\frac{\partial U}{\partial z}\bigg|_{z=0}, \qquad (8)$$

where dimensionless criteria are introduced $H = \frac{q_t}{\rho \Delta Q}\sqrt{\frac{\tau_h}{a}}$, $R = \frac{\varepsilon\sigma T_f^4}{\rho\Delta Q}\sqrt{\frac{\tau_h}{a}}$ та $m = \frac{cT_f}{\Delta Q}$ – thermal efficiency of the material.

Results and discussion. The problems (6) - (8) were solved numerically for structural materials, the characteristics of which are given in Table 1. Melting of the surface layer and deposition of the molten mass by a gas stream leads to an ablation effect that is cooling of the material. Thus, the temperature fields will be rebuilt inside the shell, which causes them to deviate from the self-similarity. The influence of mass attribution on the distribution of the temperature field inside the material is presented in Fig. 2.

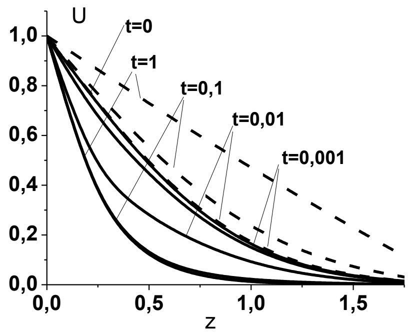
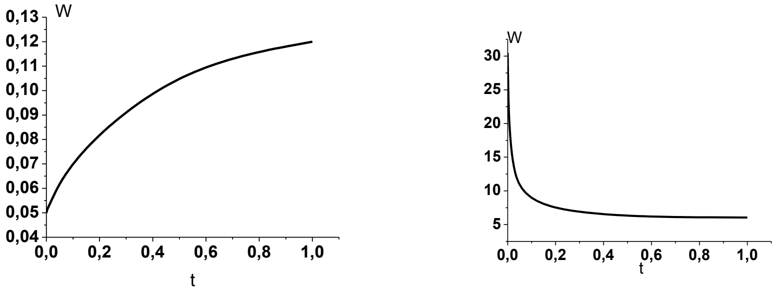


Fig. 2. Distribution of dimensionless temperature *U* of the depth of material *z* at different moments of dimensionless time *t* in the presence of ablation (solid lines) and no ablation (dashed lines)

As can be seen from the data in Fig. 2, mass attribution significantly affects the nature of the temperature field distribution. In the absence of mass assignment ($W = 0$) a gradual warming of the inner layers of the material occurs. The ablative effect of the substance weight ($W \neq 0$) leads to a decrease in the thickness of the heated material layer. In this case with increasing time the temperature field and accordingly the temperature gradient on the surface take on a "quasi-stationary" character. That is, the rate of destruction will gradually become steady.

The material destruction rate depends on the thermal efficiency of the material m. Materials with high thermal efficiency will melt faster at the initial stage of destruction and bodies with lower thermal efficiency, which include refractory materials, vice versa. In Fig.3 dimensionless melting rates are presented for a material with low thermal efficiency (Fig. 3a) and high thermal efficiency (Fig. 3b).



a) b)

Fig. 3. Variation of dimensionless melting rate *W* for dimensionless time *t* for materials with low thermal efficiency (m = 0.18) (a) and with high thermal efficiency (m = 15) (b)

The nature of the curves in Fig. 3 (a, b) shows that some time after the start the melting process is quasi-stationary, that is, the melting rate is independent of time. Large values of m correspond to larger values of the melting rate.

Table 2 shows the results of the calculation of the melting rate for various materials

Table 2

The calculation of the melting rate for various materials

Brand of material	Melting speed, mm/s
Steel 09X16N4B	0.215
Molybdenum alloy BM1	0.009
Niobium alloy BN-2A	0.012
Carbon fiber CF-UT	0.036

The presented results in the table are undoubtedly only of an estimated nature and are merely illustrative. However the proposed model can be used to investigate the process of thermal destruction of objects being discharged into the Earth's atmosphere.

Conclusions. Ablation of a space object surface during aerodynamic heating has a significant effect on the temperature distribution in the structural material. Due to the entrainment of heat by the mass of the destroyed material, the temperature field gradient increases, which contributes to the localization of heat in the surface layer. The temperature field and the rate of destruction of the material take on a “quasistationary” character with time.

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