A STUDY OF HEAT PROOFING MATERIALS UNDER TRANSIENT CONDITIONS

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Theoretical and experimental methods of studying heat proofing materials are evaluated. Some characteristics of transient breakdown of fusible and cokable coatings are examined.

Some Problems Concerning the Transient Breakdown of Fusible Materials. Heat- and mass-transfer processes occurring during the travel of a body through the atmosphere of a planet will always be transient in nature, because the flow conditions vary. In calculating the transiency of heatup and breakdown one usually assumes the body to be at every instant of time in a stream with constant parameters and one does not consider that, besides the parameters which characterize the outer stream \( \nu_\infty \) and \( V_\infty \), there are also their time derivatives \( d\nu_\infty/dt \) and \( dV_\infty/dt \). In other words, the state of flow at every instant of time must be described not only by the density the velocity but also by their time derivatives.

For this reason, there is a need for developing an appropriate theory and then a method by which the effect of transiency on the heatup and the breakdown of a body in a stream can be accounted for.

This problem has been considered in the case of heat proofing materials destructable by fusion and evaporation (vitreous materials).

The system of equations describing the breakdown of such a material at the critical point can be represented as follows [3]:

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = - \frac{\partial p}{\partial x} - \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) + p_F \epsilon, \\
\frac{\partial p}{\partial y} = p_F \gamma, \\
\frac{\partial (\rho u x)}{\partial x} + \frac{\partial (\rho u y)}{\partial y} = 0, \\
\rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial p}{\partial t} + u \frac{\partial p}{\partial x} + v \frac{\partial p}{\partial y} + \mu \left( \frac{\partial u}{\partial y} \right)^2.
\]

For a more complete and accurate description of this process, it is necessary to add also a system of transient-state equations for the gaseous boundary layer and to solve them simultaneously. In view of the complexity involved here, these systems of equations were analyzed separately and the transiency of the ambient stream are taken into account in the change to dimensionless quantities:

\[
\eta = \sqrt{\frac{2\rho \beta (t)}{\mu_\star} y}, \quad \frac{\partial j}{\partial \eta} = \frac{u (y, t)}{u_\star (t)}, \\
\tau = \int_0^t \beta (l) dt, \quad \theta (\tau, \eta) = \frac{T (l, y) - \bar{T}}{T_\star (t)}
\]


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in the vicinity of the critical point. When changing to these dimensionless quantities, one must consider
that the velocity gradient near the critical point is a function of time. After the necessary transformations,
we have
\[-\frac{1}{2} \frac{\partial f}{\partial \eta \partial t} - \frac{\partial}{\partial \eta} \left( \frac{\mu_s}{\mu_s} \frac{\partial f}{\partial \eta^2} \right) + f \frac{\partial^2 f}{\partial \eta^2} - \frac{1}{2} \left[ \left( \frac{\partial f}{\partial \eta} \right)^2 - \frac{\rho_s}{\rho} \right] = \frac{a}{2} \left( \frac{\eta}{2} \frac{\partial f}{\partial \eta^2} + \frac{\partial f}{\partial \eta} - \frac{1}{A} \right),\]

\[-\frac{1}{2} \frac{\partial \theta}{\partial t} + \frac{\sigma_s}{\sigma_s} \frac{\partial}{\partial \eta} \left( \frac{\kappa}{\kappa} \frac{\partial \theta}{\partial \eta} \right) + f \frac{\partial \theta}{\partial \eta} + a \left( -\frac{\eta}{4} \frac{\partial \theta}{\partial \eta} + \Phi_1 \theta + \Phi_2 + \Phi_3 \right) = 0,\]

where

\[A = \sqrt{\frac{\eta}{\sigma_s}},\]

coefficient \(a = \dot{\beta} / \beta^2\) accounts for the variation of the stream parameters \((u_e, p_e, T_e)\) with time, coefficients \(\Phi_1, \Phi_2, \Phi_3\) are defined by the steady-state values of the stream parameters, \(\sigma = C_p \mu_s / \lambda_s, \lambda = \lambda / \lambda_s\).

Before analyzing the effect of "outer" transiency on the vehicle trajectory, one should first answer the question concerning the ranges of parameter values and trajectory characteristics within which this effect on the breakdown of vitreous materials is significant, i.e., to first solve the problem qualitatively. Since this would require a great amount of parametric calculations, the procedure will be somewhat modified instead.

We consider the steady-state heatup and breakdown of a heat proofing coat on the surface of a body in a gaseous stream, described by the parameters \((u_e, p_e, T_e)\) as well as by their time derivatives. This situation is physically unrealizable, as an analysis of the procedure for solving transient-state equations (by the finite-differences method with the use of the implicit scheme) indicates. The following system of equations is solved:

\[\frac{\partial}{\partial \eta} \left( \frac{\mu_s}{\mu_s} \frac{\partial f}{\partial \eta^2} \right) + f \frac{\partial^2 f}{\partial \eta^2} - \frac{1}{2} \left[ \left( \frac{\partial f}{\partial \eta} \right)^2 - \frac{\rho_s}{\rho} \right] = \frac{a}{2} \left( \frac{\eta}{2} \frac{\partial f}{\partial \eta^2} + \frac{\partial f}{\partial \eta} - \frac{1}{A} \right),\]

\[\frac{1}{\sigma_s} \frac{\partial}{\partial \eta} \left( \frac{\kappa}{\kappa} \frac{\partial \theta}{\partial \eta} \right) + f \frac{\partial \theta}{\partial \eta} + a \left( -\frac{\eta}{4} \frac{\partial \theta}{\partial \eta} + \Phi_1 \theta + \Phi_2 + \Phi_3 \right) = 0.\]

Calculations for a wide range of parameter values and trajectory characteristics show that the material wear and the temperature profile are affected most significantly by mass forces and by the transiency of the stagnation temperature. The results of calculations made for one point on the trajectory are shown in Fig. 1. Taking into account the transiency of the stagnation temperature yields lower temperatures, according to the graph, inasmuch as trajectories are considered here for which \(\delta T_e / \delta t < 0\). The opposite will occur when \(\delta T_e / \delta t > 0\), namely the vehicle will accelerate. It is to be noted that the maximum deviation in the temperature profiles \(\Delta T = (T_\alpha = 0 - T_\alpha = 1)\) corresponds to a zero deviation in the thermal flux profiles \(\theta\).

As the flight altitude becomes lower, the difference \(\Delta T = (T_\alpha = 0 - T_\alpha = 1) / (T_{W\alpha} = 0 - T_{W\alpha})\) decreases, until the surface temperature reaches its maximum, and then increases again (Fig. 2, where \(\gamma = a / \sigma_s f_\theta\), i.e., the effect of stagnation temperature transiency is most pronounced along the trajectory segments with a relatively low surface temperature. As a consequence, the effect of trajectory characteristics on the magnitude of \(\Delta T\) and thus on wear in the liquid phase becomes obvious. Inasmuch as the thermophysical properties (viscosity and thermal conductivity) of a vitreous material such as fused quartz have not yet been determined exactly, we will now analyze how the temperature characteristics of thermal conductivity and viscosity affect the deviations in the temperature profiles. Calculations show that they are affected most strongly by \(\mu(T)\) and less strongly by \(\lambda(T)\).

Thus, available test data on the thermophysical properties of this material are not sufficient for definitively evaluating the effect of these properties on deviations in the temperature profile and on wear in the liquid phase.

Cokable Heat Proofing Materials. The breakdown of intricate composite materials under heavy heat loads is accompanied by the formation of a pyrolysis zone inside, by the filtration of gaseous products to the hot surface, and by heat transfer between solid and gas. The effect of these factors on the heatup and the wear of heat proofing materials can be analyzed by means of a mathematical model of the process with the following assumptions: