Journal of Engineering Physics and Thermophysics, Vol. 83, No. 4, 2010

HIGH-TEMPERATURE THERMAL PHYSICS AND PROBLEMS OF THERMAL PROTECTION

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In the middle of the 20th century, the "pioneers of practical space exploration" were confronted with the eternal Hamletian question: "To be or not to be." By that time, rockets have already furrowed "the space of the Earth's stratosphere," and ballistics experts had managed to answer with confidence S. P. Korolev's questions about the number of kilograms of rocket fuel required for acceleration of one kilogram of the "payload" mass to a velocity of 8 km/s. Quite little remained to be done: to bring back to the Earth this very "payload" safe and sound after staying in the orbit of the Earth's artificial satellite. A thousand kilometers away from Podlipki near Moscow, the Belarussian Academician A. V. Luikov, who had by that time become the father of the theory of heat conduction [1] and Director of the Institute of Heat and Mass Transfer, allowed some young enthusiasts from this Institute to conduct tests of various solid materials in the hot jets of the plasmatrons which they had just created at the time. This is, probable, how a couple of hundreds of years from now, children will be told a fairy tale about the birth of an amazing event of the 20th century when man managed to overcome the force of gravity and enter outer space. But before finishing a description of this incredible event, one should recall that nature itself was flatly against man's flights to outer space and especially against his return. Suffice it to be reminded of a magnificent spectacle — an autumn meteoric storm when millions of space travellers — meteorites — disappear without a trace on their way to the Earth, having failed to cover even 100 km in its atmosphere.

1. Increase in the temperature and density of the gas behind a shock wave in supersonic flight produces an intense growth in the heat load on the flying-vehicle surface. Compared to airplanes whose velocity is usually no higher than 1 km/s (or Mach number M = 3) the heat load of space bodies, as they return to the Earth, grows in proportion to the velocity V cubed (Fig. 1). This is equivalent to the increase in the temperature of the metal tiling to 3000–4000 K, whereas the strength of most materials sharply drops even at temperatures higher than 1200 K (Fig. 2). Clearly, it is highly improbable that such a heat-resistant tiling of reentry spacecraft will be created.

We know of six modes of removal (absorption) of heat at present: by heat conduction with the use of the heat capacity of condensed substances, by convection, mass exchange, and radiation, with electromagnetic fields, and due to physicochemical transformations that are usually called by one word — "ablation" — in the foreign literature.

Combinations of two of the indicated modes or more are widely met in practice. Nonetheless, we can evaluate the fields of their application in the first approximation using the data of Fig. 3. It follows from the figure that the absorption of heat due to the heat conduction and heat capacity of condensed substances (copper or graphite) can be applied only where the heat load q is small or it acts for a short period of time τ, i.e., when we have the integral of $Q_w = \int q d\tau \le 10^5$.

Another version of controlling the laws of descent of a reentry spacecraft in the atmosphere is realized in the presence of lifting forces and special aerodynamic elements of the wing type. The descent time increases several times, which makes it possible to similarly diminish the heat load q. We attain the reduction in the so-called equilibrium temperature of the outer surface of the descent module:

$$T_{eq} = \sqrt[4]{q/\varepsilon\sigma} \le T_m .$$

In Fig. 3, this method of thermal protection is called "radiation cooling." It has been realized on shuttles. But it was not until 20 years after the Gagarin flight that this happened. In 1961, designers placed all their hopes on the

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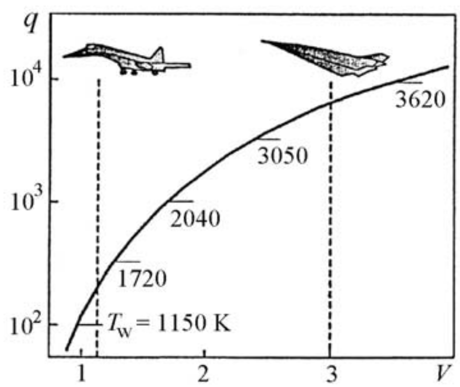

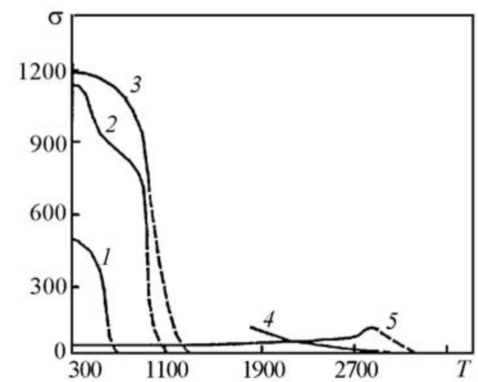

Fig. 1. Heat load q on the flying-vehicle surface vs. flight velocity V in the Earth's atmosphere. q, kW/m^2; V, km/s.

Fig. 2. Strength of the structural materials σ vs. their temperature T: 1) D16T; 2) VT9; 3) 08Kh17A5M3; 4) tungsten; 5) carbon. σ, MPa; T, K.

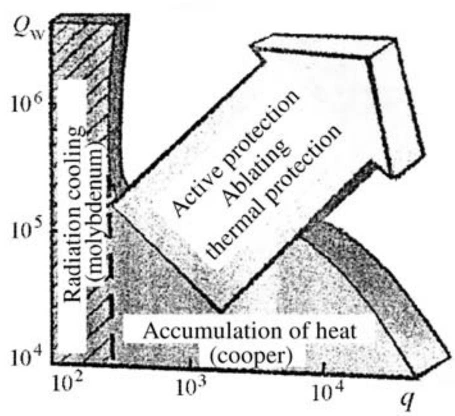

Fig. 3. Permissible levels of specific q and integral Q_w heat loads in different modes of thermal protection. Q_w, kJ/m^2; q, kW/m^2.

destroyed heat shield or the so-called sacrificial layer of a special material (asbestos-cloth laminate) which was to absorb, in the process of mass removal, the entire heat load q incoming from the outside.

2. Numerous experiments with samples of potential heat-shielding materials [2, 3] were processed, at that time, as the ratio of the heat flux q to the second loss of their mass G_Σ, which was called the effective enthalpy of the material destroyed:

$$H_{eff} = \frac{q - \varepsilon\sigma T_w^4}{G_\Sigma} . \qquad (1)$$

Theoretically the number of parameters characterizing high-velocity gas flow past a body is more than ten even without regard for the variability of the thermophysical properties of its material. The number of similarity criteria is also more than seven. It is virtually impossible to model the indicated process completely in this situation.

Thermal gasdynamic tests of the heat shield of descent modules were carried out on small-scale models as a rule, and of the two principal parameters — Mach and Reynolds numbers — preference was given to the former. This was due to the limited energy potentials of laboratory setups, which made it impossible to test large- or full-scale products at trajectory pressures behind the shock wave in them.

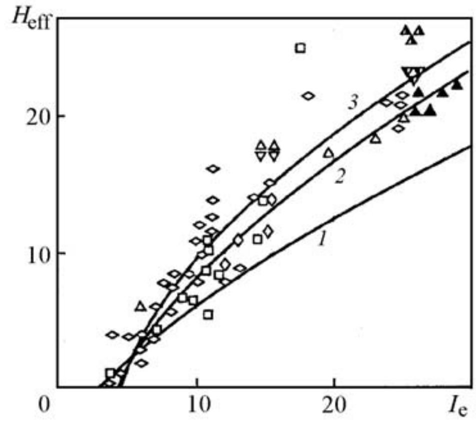

Fig. 4. Comparison of the experimental data with the results of calculating from different models of destruction of glass-reinforced plastics: 1) calculation by the method of [4], 2) by the method of [5], and 3) by the method of [6]. H_{eff}, MJ/kg; I_e, MJ/kg.

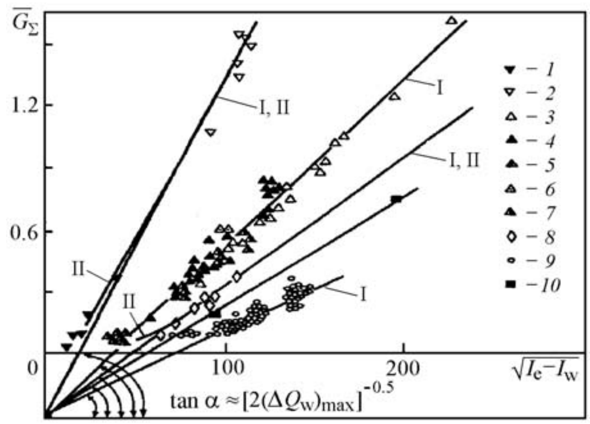

Fig. 5. Dimensionless removal rate $\overline{G}_\Sigma$ vs. stagnation enthalpy I_e and variation of the injection effect (models I and II): 1 and 2) Teflon, 3–7) glass-reinforced plastic based on epoxy binder under different heating conditions; 8) doped quartz glazed ceramics; 9) graphite; 10) carbon-fiber plastic.

Figure 4 gives results of a comparison of experimental and calculated values of the effective enthalpy of destruction of glass-reinforced plastic — a composite material based on quartz fiber and phenol-formaldehyde resin. We clearly see the tendency of the computational model of the process of destruction to be verified.

The simplest model (curve 1) takes into account that the quartz fiber on the model's surface melts and evaporates on exposure to the plasma flow [4]. Although the force action of the flow and friction forces affect H_{eff}, they do not change the flow regime in the boundary layer (in particular, no laminar-to-turbulent transition occurs). Curve 2 has been calculated with allowance for the fact that the products of thermal destruction of the resin (primarily coke particles) affect flow of the molten-glass film [5]. Curve 3 additionally allows for the chemical interaction between the coke and the glass. It shows the best agreement with the entire volume of experimental data obtained on different plasmatrons in a high-temperature air flow [6].

3. The most substantial influence on the reliability of the computational models is exerted by allowance for the injection effect, the effect of reduction in the convective heat flux when the gaseous products of destruction of heat-shielding materials are injected into the boundary layer of the incident flow.

From this viewpoint, an effort to evaluate the limiting energy efficiency of different classes of heat-shielding materials at very high temperatures (attainable in today's plasma units) is of great interest.

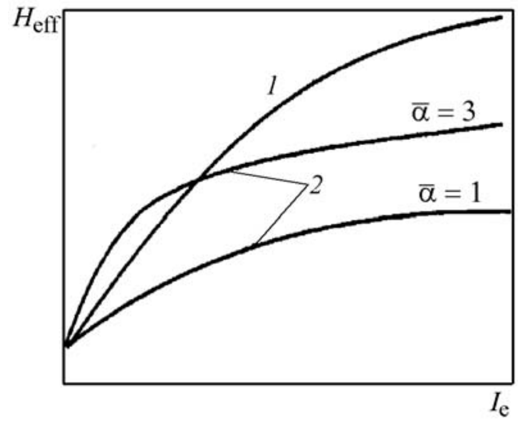

Fig. 6. Influence of the flow regime (laminar (1) or turbulent (2)) in the boundary layer on the effective enthalpy of destruction. H_{eff}. H_{eff} and I_e, MJ/kg.

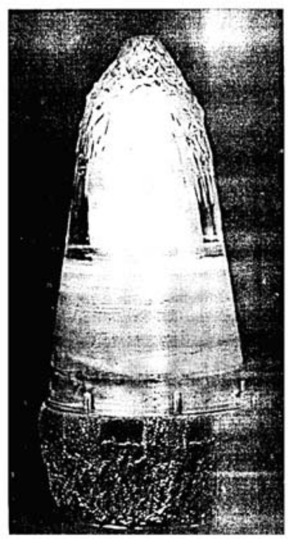

Fig. 7. Appearance of the model of a full-scale product after testing on a large-scale thermal gasdynamic test bed.

Figure 5 gives a generalization of the obtained results, where $\overline{G}_\Sigma = G_\Sigma/(\alpha/c_P)_0$; here $(\alpha/c_P)_0 = q/(I_e - I)$ is the heat-exchange coefficient on an impermeable surface (without injection of the destruction products). This result, among many others, served as a theoretical basis for substantiation of the discovery registered under No. 298 in 2005 (with a priority of December 16, 1975) [7].

4. The heat flux at the leading critical point of a specimen blunt in a hemisphere is dependent on the pressure P and the specimen's radius R_N. In the laminar regime of flow in the boundary layer, we have

$$q_L \sim \sqrt{\frac{P}{R_N}}\,(I_e - I)\,, \tag{1}$$

in the turbulent regime, we have

$$q_t \sim (P)^{0.8} R_N^{-0.2} (I_e - I)\,.$$

It follows that the heat-flux ratio (q_t/q_L) grows with the parameter $\sqrt[3]{PR_N}$. Such a situation could not but have an effect on the scale of ground testing and on the possibility of extending effective enthalpies H_{eff} (1) measured experimentally to flight conditions.

Figure 6 diagrammatically shows the influence of the laminar-to-turbulent transition of boundary-layer flow on the effective enthalpy of destruction of heat-shielding materials H_{eff}. The influence of the pressure P and of the dimension of the body in flow R_N is demonstrated by the value of the parameter $\overline{\alpha} = (q_t/q_L)$.

A search for the methods of extending the scope of the test-bed basis for testing heat-shielding materials finally brought gasdynamic units whose thermal capacity exceeds 2000 MW into being. A picture of the model manufactured from polymethylmethacrylate (Plexiglas) after testing in a high-temperature gas flow in this bed is presented in Fig. 7.

5. Solution of numerous problems arising required a system approach and development of physical and mathematical models of different classes of heat-shielding materials. Wide interaction between fundamental and applied investigations was of critical importance in this formulation of the problem. Today it is difficult to understate the role played by Academician A. V. Luikov for establishing contacts between scientists both in this country and abroad. The book "Thermal Protection" (Yu. V. Polezhaev and F. B. Yurevich, 1976) was written and published, on his initiative, in Énergiya Press.

In his preface to the book, A. V. Luikov wrote: "Taking into account that requirements imposed on thermal protection in power-generating units and space equipment have become similar recently, it is of interest to acquaint heat engineers and designers of station and industrial power engineering with the latest modes of thermal protection, with the basic regularities of heat and mass transfer in heat-shielding materials, and with the methods of investigation of the heat-shielding properties of materials."

A. V. Luikov died 36 years ago. But it is only 50 years ago that the problem of thermal protection was first formulated. Comparing these two figures, one can come to the conclusion that A. V. Luikov was at the forefront of research on this problem and the very first to search for its solution. He found himself among the pioneers of high-temperature thermal physics and its current success. It is due to this that we hold the memory of him sacred.

NOTATION

c_P, specific heat at constant pressure; G_Σ, total mass loss by the material; H_{eff}, effective enthalpy of destruction of the tested material; I, enthalpy; I_e, stagnation enthalpy; q, specific heat load; Q_w, integral heat load; T_{eq}, equilibrium temperature; T_m, melting temperature of the material of the outside casing of the descent module; P, pressure; R_N, specimen's radius; V, velocity of the descent module; α, heat-exchange coefficient; ε, emissivity of the material; v_∞, linear destruction rate; ρ, material's density; σ, material's strength; τ, time. Subscripts: eff, effective; w, surface; eq, equilibrium; e, stagnation, deceleration; N, specimen number; L, laminar; t, turbulent; m, melting; $^{-}$, dimensionless quantity.

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