PROBLEMS OF HEAT AND MASS TRANSFER IN THE INTERACTION OF GAS FLOWS WITH THE SURFACE OF BODIES*

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Questions regarding the solution of different problems of heat and mass transfer during the design of heat protection systems are examined.

Studies of the interaction of high-temperature and high-velocity gas flows with the surfaces of various bodies are presently becoming more important in connection with the fact that many areas of science and technology could not fruitfully develop without a thorough knowledge of the essence and principles of such interactions.

These problems have in turn fostered the vigorous development in recent years of an independent direction of scientific inquiry into heat and mass transfer — theories of thermal protection and, in the field of designing thermally loaded systems and power plants, thermal design. Much new empirical work has also been done.

Proceeding on the basis of fundamental postulates of the classical theory of heat conduction, studies of heat and mass transfer in the interaction of gas flows with the surface of bodies have in turn expanded the boundaries of the classical theory. This expansion owes primarily to the examination of problems of heat transfer, not only in uniform or stable media, but also in multicomponent, reinforced, decomposing, and chemically active materials undergoing a broad range of phase transformations during heating. Expansion of the classical theory is also the result of elaboration of the foundations of mass transfer in porous materials with a variable structure, i.e., mass transfer which is mainly the result of heating. Its intensity is in turn determined not only by the total quantity of heat supplied, but also by the heating rate [1-6].

Problems of the interaction of high enthalpy gas flows with thermally protective materials are scientifically important primarily because they are boundary-value problems in many areas of science, such as aerodynamics and solid-state physics, gas dynamics and thermodynamics, chemistry and thermophysics, strength of materials, and materials science. Also, the range of high and ultrahigh temperatures and the variety of interacting processes occurring over finite time intervals is undoubtedly an interesting field of study for investigators working in different but related areas. The need to develop these areas of science and technology has led to the rapid growth of computer mathematics, special branches of physics, etc.

Finally, it is difficult to offer in one work a more or less full account of all of the basic problems of the interaction of high-temperature and high-velocity gas flows with the surfaces of materials. As already noted, relatively little has been done in this direction. However, there are even fewer theoretical and experimental works generalizing significant basic studies in this area. The reasons for this situation include not only the extreme complexity of the phenomena in question and the difficulty of further, deeper, and more detailed analysis of them, but even the difficulty of performing studies of them and, in some instances, the impossibility or lack of knowledge of how to directly measure most of the parameters determining the phenomena.

In recent years there have appeared many monographs devoted to many of the heat and mass transfer problems being discussed here: on the theory of thermal protection, the thermal

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design of equipment and systems, methods of inverse problems, etc. Thus, certain prerequisites have been met for systematizing accumulated knowledge and findings regarding important theoretical principles of heat and mass transfer in the interaction of high-temperature gas flows with materials [1-6].

The interaction of a hot gas with a thermally protective material involves the occurrence of numerous mutually dependent processes. Theoretical studies of this problem must generally be based on the solution of a system of differential equations describing nonsteady heat and mass transfer in the gas—body system. These equations include equations describing external gas dynamics, convective and radiative heat transfer to the body, mass transfer in a reactive, multicomponent gas mixture, heating of the body, and the kinetics, destruction, and motion of materials of the body in the solid, liquid, and gaseous states. The solution of this problem in such a complex, conjugate formulation (conditions of the fourth kind must be satisfied at the corresponding interfaces between the gaseous, liquid, and solid phases both on the surface and inside the body), with allowance for the nonuniformity of the processes, currently presents exceptional difficulties from a mathematical and computational point of view. Furthermore, the initial physical model of the given phenomenon has not yet been fully investigated, and the transfer coefficients for some processes have not been reliably validated [7].

Under these conditions, it often proves difficult to a priori evaluate the effect of individual processes and parameters on the final results and to validly make simplifying assumptions. Thus, in studying such complicated phenomena as the nonsteady destruction and heating of a thermally protective coating, the role of experiment becomes more important. Indeed, experimentation may be the main tool for solving many heat problems. However, as noted, in many cases experimental studies also fail to correctly answer the stated questions. To a certain extent, this has to do with the difficulties of distinguishing the effect of the necessary factor in the complex system of interacting processes, as well as with methodological errors of measurement. However, the main reason probably lies in the methodology of both the conduct of the experiment and the analysis of the results.

Often the methods used to set up an experiment or interpret the resulting data are based on assumptions which might, upon careful examination, be seen to significantly distort the findings even if the investigation were correctly done in a technical sense. To simplify the algorithms for analyzing the empirical data, the experiment is also simplified considerably (usually at the expense of completeness and accuracy of the model). For example, a steady-state experiment may be substituted for a nonsteady experiment, the time of the experiment may be limited, hypotheses which are difficult to verify may be used, etc.

Now, when powerful computers and automatic data collection and analysis systems can be employed to analyze empirical data, in many cases it is necessary to take a new approach to the methodology of performing thermal experiments. Study of the complex mechanism of nonsteady heat transfer requires not only a detailed and technically correct experimental plan, but also fundamental changes in the methodological and computational parts of the investigation.

It is particularly complicated to understand and quantitatively represent nonsteady effects of the interaction of high-temperature gas flows with a solid if the latter is destroyed during the heating. This problem should be considered as still inadequately investigated. The difficulties in studying it are obvious and are in large part due to the lack of effective methods of modeling transient regimes, interpreting the empirical data, and generalizing the results.

In studying such complex phenomena as the nonsteady interaction of a thermally protective material with a hot gas flow while the material is undergoing disintegration, experiment often becomes the main tool for solving the problem.

A modern, large-scale heat experiment involves large expenditures, not to mention the costs of developing, making, erecting, and adjusting the experimental complexes. Thus, in our opinion, it is very important to increase the amount of information gained from such studies and improve the reliability of the results. It is necessary to find methods of analyzing and interpreting the experimental data which will make it possible to extract the maximum amount of information on the investigated phenomenon given certain standards for the accuracy of the systems used to measure, record, and interpret the experimental results.

In many cases, the programs for nonsteady thermal experiments may be based on methods of solving inverse heat-transfer problems (determination of the thermal boundary conditions, identification of heat and mass transfer processes, establishment of "external" temperature fields, etc.).

In contrast to direct problems of calculating heat and mass transfer processes, inverse problems are imperfectly formulated in the classical sense (small changes in the recorded functionals correspond to large changes in the sought solutions). This main feature of inverse problems makes their solution more difficult and requires the development of special methods of obtaining stable results without on the whole disturbing the adequacy of the mathematical models with regard to their description of the actual processes [8-10].

In the general case, along with the parameters of the incoming gas, factors affecting the heat flow to the wall are the catalytic activity of its material, chemical reaction with the components of the gas flow, the injection of gaseous decomposition products, and the presence of a condensed phase in the flow. The quantity of heat flowing to the surface of the body also depends on the flow regime in the boundary layer.

The possibility of solving some heat and mass transfer problems may also be limited to a significant degree by the absence of data, essential for the computations, on the kinetics of homogeneous reactions inside the boundary layer and heterogeneous reactions on the surface. Generally, in the case of a turbulent boundary layer, additional problems arise in connection with the nonclosure of the equations of a multicomponent turbulent boundary layer with chemical reactions.

The presence of particles in the flow and their contact with the wall may lead to a significant increase in the heat-transfer coefficient compared to a pure gas. Determination of heat and mass transfer in two-phase flows is complicated by the diversity of the acting factors (high particle inertia, turbulence, the action of buoyancy and thermophoretic forces, etc.). Despite the several large-scale studies that have been considered, the theory of heat and mass transfer in two-phase media is still far from complete.

One of the more complex heat and mass transfer problems has to do with the mechanical destruction of thermally protective and erosion-resistant materials in hot gas flows. This can be attributed to the chemicomechanical pitting of structurally nonuniform filled and porous materials which accompanies their disintegration in chemically active gas flows, as well as to complexity of physically interpreting the different factors attendant to the process of thermal degradation of thermally protective materials based on organic binders. The latter may lead to mechanical disintegration of the coking layer under conditions of intensive thermal and mechanical action by the gas flow.

In regard to vehicles travelling at high speeds in planetary atmospheres in excess of the first or second escape velocities, the choice of characteristics for the thermal protection is of decided interest. In this case, thermally protective coatings on such vehicles are subject to the action of powerful radiant fluxes on individual sections of their flight path [11]. Here, important questions requiring their own solution and preceding analysis of the efficiency of a given system of thermal protection are calculation of the radiant fluxes in nonearth atmospheres, the distribution of the radiant fluxes over the surface of the body, and the effect of injection (blowing) on the magnitude of the boundary-layer flow.

To determine the basic design parameters of such equipment, the system of equations describing the phenomenon of nonsteady heat and mass transfer in a gas–body (vehicle) system must be supplemented by the equation of the dynamics of motion of the vehicle and mass and other relations characterizing the design features of the vehicle.

Thus, the formulation and solution of the inverse heat-transfer problems may be obvious. Meanwhile, such problems can be used at nearly all stages of design and testing of the vehicle and its equipment and systems, the characteristics of which in large measure depend on limitations connected with the effect of thermal loads.

Optimum thermal design is based on the mathematical thermal model of the vehicle or its systems and an extreme object function. The model should connect the sought design parameters with the external and internal heat flows acting on the vehicle. Thus, a problem of optimum thermal design can be regarded as an inverse heat-transfer problem in an extreme formulation, i.e., a problem involving the use of known conditions defining the thermal state of a system to find the parameters required to satisfy this state and the chosen criterion of optimality of the system.

The test heat-engineering calculations performed at the preliminary design stage generally involve direct heat-transfer problems, since here one seeks to determine the thermal state of the system from known governing characteristics.

Thus, solution of the problems discussed above will help make it possible to evaluate their effectiveness in examining basic problems of heat and mass transfer in the interaction of gas flows with the surface of bodies.

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