CERTAIN QUESTIONS ON THE INVESTIGATION OF THE THERMAL MODES OF FLYING VEHICLES DURING DESIGN AND EXPERIMENTAL CHECKOUT

B. M. Pankratov

UDC 533.6.011.6

Problems of a thermal investigation of a flying vehicle (FV) during its development and the domains of application of inverse problems of heat conduction during FV design and testing are considered.

General Formulation and Some Thermal Design Problems

A modern flying vehicle (FV) functions under complex thermal conditions characterized by both external and internal heat sources. The appearance of the FV, its fundamental characteristics, and the parameters of the heat-shielding system used can be determined by these conditions to a significant extent. Hence, a great deal of attention is paid to questions of the thermal design of the vehicles. Let us list some problems of investigating the heat- and mass-transfer processes in FV design and checkout: 1) the design of heat-shielding and regulating systems; 2) heat exchange in fuel tanks with cryogenic components and the selection of thermostating systems; 3) simulation of the operation of heat-shielding coatings (HSC) and of the thermal mode of structure operation.

The thermal mode of flying vehicles exerts great influence on the selection of the design parameters of fuel compartments. This influence becomes most significant when cryogenic fluids are used as fuels.

An investigation of the heat- and mass-transfer processes originating in a cryogenic fuel is based on the numerical solution of the motion equations of a nonisothermal viscous fluid in the Boussinesq approximation.

In our opinion, such an approach is most expedient, since it permits exposition and estimation of the most essential processes and mechanisms of heat and mass transfer without significant technical and economic difficulties which are characteristic for full-scale tests and simulation under ground-based conditions.

The main attention is paid in a numerical investigation to the structure of nonstationary freely convective fluid motion, temperature stratification of the fluid, and the parameters governing the evaporation process, the mass rate of evaporation, and the rate of evaporation.

The similarity criteria were selected in a form which permits easy estimation of the design parameters of the fuel compartments.

In a number of cases, one of the principal problems in FV design is the reliable protection of the internal compartments of the vehicle from heat loads originating because of intensive aerodynamic heating. The main purpose of the design analyses is to select a logical heat shield, its construction, materials, and the coating thicknesses needed at various points of the surface being shielded. In a rigorous formulation, an investigation of the thermal modes should be based on analyses including the combined solution of the heat- and mass-transfer processes in a gas–solid system taking into account the effects of rupture of the heat-shield material and injection of the rupture products into the boundary layer.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 29, No. 1, pp. 133-139, July, 1975. Original article submitted February 10, 1975.

It should be noted that at present there is a standard quasistationary formulation of this problem. However, under actual conditions, the FV is under an essentially nonstationary thermal effect. The "adjoint" problem of heat and mass transfer, which includes the system of nonstationary gas boundary-layer equations, an equation describing material rupture, and the heat-conduction equation for the HSC, must be solved to analyze the effect of nonstationarity on the main HSC design parameters. In a general formulation such a problem is quite complex and its solution is fraught with substantial difficulties associated with the limited possibilities of modern electronic computers.

Possible Ranges of Application of Inverse Problems of Heat Conduction

Inverse problems of heat conduction consist in seeking causes (heat loads, radiant and convective heat-exchange coefficients, thermophysical characteristics, etc.) according to a known consequence (temperatures at some points of the mock-up, model, or specimen being investigated). In principle, two cases of their application during FV design are possible. The first is the principle of thermal design and consists of determining the characteristics of the object being investigated, the parameters of its heat shield, etc., taking account of possible thermal effects. For example, the problem of selecting the number of layers in the coating structure and of the distribution of materials with the properties needed over it, by means of estimates of the change in the external heat loads and by known mathematical models of FV interaction with the surrounding medium, is posed. Such an analysis is based on examination of the weight and volume characteristics, the cost of the aggregates and systems, the requirements of FV operational reliability and efficiency, etc. Some design criteria governing the problem posed in developing an FV and its elements are hence usually introduced into the consideration.

Such complex design problems taking account of the thermal modes include the solution of various inverse problems, particularly, inverse problems of heat conduction. The main singularity of these problems is, as a rule, that their formulations admit of a set of solutions and some solution is finally selected according to some additional conditions.

The second case is typical for experimental studies of mock-ups and models, and the testing of FV aggregates and systems. The following three kinds of inverse heat-conduction problems (IHCP) can here be isolated: boundary IHCP, coefficient IHCP, and problems with inverse time. All these problems are incorrect in the classical (Hadamard) sense: there is no continuous dependence of the results on the input data.

The main domains of application of the inverse problems of heat conduction in carrying out the thermal design of an FV are:

1. Determination of the boundary thermal mode, i.e., recovery of the heat fluxes and body surface temperatures (the external thermal conditions of the surrounding medium can then be determined by means of these quantities). The case of nonstationary calorimetry by using special heat sensors is typical here. Since thermocouples or resistance thermometers are not often successful or for a whole series of reasons it is not expedient to mount a sensor on the wall being heated, then the inverse problem must be solved to obtain the boundary heat flux. The problem of constructing such sensors is closely associated with the method used to solve the inverse problem and its assumed application. Calorimetric sensors are used extensively in simulating the thermal modes on gasdynamic and radiation test stands, in testing liquid and solid propellant engines, etc.

2. In an experimental study of the rupture and entrainment of the heat-shield materials, and an investigation of their operational efficiency, the determination of the heat flux absorbed by the body by conduction is of interest. The change in this heat flux during the experiment can be determined by using an inverse problem whose initial data will be the temperatures measured at inner points of the specimen under investigation. Such a formulation of the experiment is needed in studying nonstationary heat processes of heat-shielding materials and heat-shield coatings. However, the solution of this problem is complicated substantially by the effects of mass entrainment from the surface and bulk of the body, by thermal decomposition of the material and other phenomena from which ablation of the heat-shield material is comprised.

3. Inverse heat-conduction problems are used in studying combustion and heat-transmission processes in solid-fuel rocket motors, for instance, in an experimental checkout of the igniter, in the investigation of transients, particularly during start-up, and regulation and deflection of the motors.

4. Inverse heat-conduction problems can be used effectively for an experimental determination of the thermal-contact resistors and the film resistors in a multilayered heat shield, for instance.

5. The problem quite often occurs of reproducing the temperature fields corresponding to the continuation of the solution of the heat-conduction equation from a smaller to a larger domain (also the inverse heat-conduction problem). Closely connected with such a problem is the problem of the thermal strength of various heat-shield materials when the temperature gradients must be simulated during the experiment and the temperature field must be determined. At the same time, the initial informability of such investigations is difficult to raise and often reduces to just indirect temperature measurements at a sufficiently large distance from the external heated surfaces of the model.

6. The problem of organizing closed systems of equations, for example, in plasma or radiant heating apparatuses, results almost inevitably in the need to have an algorithm of the solution of the inverse heat-conduction problem.

7. Finally, an investigation of nonstationary heat exchange in an external gas medium–solid system (i.e., taking account of the body influence on the heat-transmission process) can be constructed by IHCP methods. A theoretical formulation of conjugate problems for a whole set and interrelation between the different parameters often turns out to be quite complex (does not occur for the largest electronic computers) and contains a whole series of assumptions difficult to confirm. Under these conditions the inverse heat-conduction problems are one of the principal methods for studying the effects of thermal nonstationarity.

8. Determination of the thermophysical characteristics of the bodies under nonstationary heating conditions, the determination of the intensities of the internal heat and mass evolution in the heat-shield materials during their destruction, all of these are the purpose of the coefficients of the inverse heat-conduction problem.

9. The radiant heat-exchange coefficients (absorption, reflection, radiation) can also be determined parametrically. Their identification is accomplished in thermal tests by means of temperature measurements at appropriate points of the construction, for example, during FV mock-up tests in the thermal pressure chamber.

10. Boundary-value problems with inverse time, i.e., when the solution within the domain is sought for by means of known values of the solution at the terminal time and on the side surface of the domain under consideration, are of theoretical and practical interest. Such problems can be related to some full-scale machine tests.

This list can be continued even further. But even this list is probably sufficient to indicate the place which methods of solving inverse heat-conduction problems do, or can, occupy as methods of processing and interpreting experimental results. Let us note that planning the thermal experiments and tests is closely related to the three mentioned kinds of inverse heat-conduction problems.

Formulation of Experimental Investigations on Nonstationary Rupture and Heating of Heat-Shield Coatings

The usual simplifying approach to the investigation of heat transfer between a gas and solid is to separate the general problem artificially into two parts, an outer problem and an inner problem. The outer problem is to determine the heat fluxes to the body under the assumption of a quasistationary heating mode. The inner problem is to analyze the body heating under known thermal boundary conditions.

Strictly speaking, such an approach does not correspond to the physics of the heat-exchange process between a solid and the surrounding medium, since the active role of the solid is not taken into account. Only the quantities characterizing the external problem enter into the criterial equation, for instance,

$$\mathrm{Nu} = \mathrm{Nu}\left(\mathrm{Re},\ \mathrm{Pr},\ M,\ \frac{T_w}{T_\infty}\right).$$

A continuous change in the temperature and velocity fields in the boundary layer occurs in nonstationary heating. This change not only depends on the intensity of the change in the free-stream parameters but also on the thermophysical characteristics and linear dimensions of the body, which govern the heat release within the body. For an entrainable heat-shield material the phenomenon mentioned is complicated by nonstationary progress of processes associated with material entrainment. A complex or several complexes taking account of the active role of the body in the heat-exchange process,

$$\mathrm{Nu} = \mathrm{Nu}\left(\mathrm{Re},\ \mathrm{Pr},\ M,\ \frac{T_w}{T_\infty},\ k_1,\ k_2,\ \ldots,\ k_m\right),$$

must be included in the criterial equation for nonstationary heat transfer. Let us show that the influence of nonstationarity on heat transfer can be taken into account by the following variables:

$$\frac{\partial T_w(\tau)}{\partial \tau};\ \frac{\partial^2 T_w(\tau)}{\partial \tau^2}.$$

In many cases, only the first derivative of the temperature can be taken into account as a first approximation. The criterial equation then becomes

$$\mathrm{Nu} = \mathrm{Nu}\left(\mathrm{Re}_\delta,\ M_\delta,\ \mathrm{Pr},\ \mathrm{Le},\ \frac{T_w}{T_\delta},\ k_T\right),$$

$$k_T = \frac{b^2}{a}\cdot\frac{dT_w}{d\tau}\cdot\frac{1}{T_\delta - T_w}.$$

Determination of the simulation domains where the hypothesis of quasistationarity of the heat-exchange process is satisfied can be estimated by means of the following criterion:

$$k = \frac{\mathrm{Nu}}{\mathrm{Nu}_0} = f(k_T).$$

As a rule, experiments to study the operation of a heat-shield material are conducted under stationary conditions at present. Indeed, the heat shield functions in nonstationary modes and it is important to model just such modes on experimental apparatus.

Thermal and dynamical similarity can be assured in the quasistationary case by means of the heat flux $q_W(\tau)$, the enthalpy $i_\delta(\tau)$, and the pressure $p_\delta(\tau)$ on the boundary layer limit. Time changes in these parameters should correspond to a given phase of the FV trajectory.

The interrelationship between these quantities,

$$q_w \sim \frac{i_\delta}{\sqrt{p_\delta}},$$

must be taken into account in realizing the required laws of variation of i_δ and q_W.

In turn, the enthalpy and pressure are mutually related by means of the fundamental characteristics of an experimental gasdynamic apparatus (such characteristics are ordinarily the power and the mass flow rate). Regulation of the required operating parameters of the apparatus should be accomplished automatically in conformity with a given program.

As our investigations show, nonstationary effects can be significant and must be taken into account in producing heat-shielding systems. Experiments have been conducted on estimating the nonstationary heat fluxes during interaction of a solid with a high-temperature gas in a plasma apparatus. Processing the data was accomplished by using methods based on solving the inverse heat-conduction problem.

A plasma apparatus, intended to investigate the nonstationary operating modes of heat-shield materials, was used to produce a complex for thermal simulation with an automated data-processing system. The mathematical assurance of the automated system is constructed on the basis of algorithms of the solution of the inverse heat-conduction problem. This complex permits solution of the following fundamental problems of an experimental investigation of heat-shield coating operation.

1. Estimation of the limits of applicability of quasistationary theory.

2. Selection and checkout of the required laws of variation of the simulation parameters.

3. Investigation of nonstationary heating and entrainment of the heat-shield coating under quasistationary external heat fluxes.

4. Study of unsteady heating and entrainment modes of the heat-shield coating in the domain of nonstationary external heat transmission.

Electronic Computers in Conduction of a Thermal Experiment

In the majority of cases, thermal tests are conducted under essentially nonstationary conditions. The nonstationary thermal mode can hence be produced specially, for example, by a programmed change in the test-stand control parameters or can occur without their dependence on nominal operating modes. Simulation of the given time laws of variation of the quantities governing the heat-transmission process is an important problem at present and is gradually starting to be used in investigations of different heat-shield systems.

The deviation of heat modes from the nominal (even constant) can be related to nonstationary phenomena of solid body heat exchange (heat shields, elements of the construction, etc.) to the oncoming gas stream. Because of reconstruction of the temperature profile in the boundary layer due to the different intensity of heat elimination in the body with time, the boundary conditions on the outer body surface will vary according to laws different from those computed for the quasistationary case.

Taking the above elucidation into account, the results of a thermal experiment must be processed taking into account the time change in the governing parameters. Such an approach requires a change in the whole methodological part of the experimental investigations, since the methodology developed for stationary thermal modes is mostly inapplicable to investigations of nonstationary processes. The problem of obtaining the output parameters of the experiment is complicated substantially and can be solved effectively only by using modern electronic computers.

The process of obtaining data of interest to the researcher carrying out a thermal experiment can be separated into two major independent sections:

1. Primary processing of the readings of a different kind of sensor (temperature, pressure, current intensity, etc.).

2. Secondary processing, obtaining the output parameters of the experiments.

Primary processing includes obtaining the statistical characteristics of the quantities being measured, the recovery of the functions and their first derivatives by means of the experimental information which always contains the errors associated with the imperfection of the measuring and recording devices, obtaining simple analytical expressions approximating the sensor readings, etc.

Secondary processing is understood to be obtaining the output parameters of the experiment by means of results obtained after the primary processing. This is primarily obtaining the thermal boundary conditions on the surface of the object under investigation around which the high-enthalpy gas flows, determination of the thermophysical characteristics of the specimen material, the heat- and mass-exchange parameters in the gas—body system, etc. All the questions of secondary processing of results of the experiment are closely connected with the solution of inverse (boundary and coefficient) problems of heat conduction in linear and nonlinear formulations. In the general case, the problem is complicated in an investigation of the heat and mass exchange by the presence of a moving boundary on the specimen or the model.

Each of the problems listed above for processing the experimental data is associated with carrying out a large number of similar and tedious computations which causes great expenditures in obtaining the final results. This refers especially to the secondary processing problems whose calculational algorithms of the solution are based on using iterations, where one iteration is a solution of the boundary-value problem for the heat-conduction equation in some formulation.

Such problems do not permit obtaining results completely "by hand." Even using modern electronic digital computers, each problem requires a sufficiently large quantity of machine time.

Formulation of individual problems on an electronic digital computer partially solves the general problem of processing the data of a nonstationary experiment. However, the great deal of work in preparing the input information for each particular problem does not afford the possibility of obtaining the output parameters of the problem sufficiently operationally.

A single means to cut down the total processing cycle is complete automation of the process. Such automation is achieved because of the combined use of analog and digital electronic computers. The signal from the sensor goes to the electronic digital computer through an analog-code converter. The information obtained is later used for primary and secondary processing.

Besides the complex technical realization, such an automated data-processing system requires algorithmization of all individual problems and, moreover, the creation of a control program-dispatcher whose functions are to combine particular algorithms into a single whole and to carry out the computations in the sequence needed. An automated system opens broad opportunities for the experimental investigation of thermal processes. Different storages (magnetic drums, tapes, disks) permit storage of numerous information to obtain multiform statistical characteristics and correlation dependences between the separate parameters.

Besides rapidly obtaining the results of the experiment, which is quite urgent at the modern level of development, such an approach to the problem of processing the data of an experiment permits elimination of the known subjectivity during obtaining the final results.

NOTATION

Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number, M, Mach number; T_W, wall temperature; T_∞, stream temperature; k, some coefficients; τ, time; q_W, specific heat flux; i, enthalpy; p, pressure.