METHODS OF ANALYZING THE THERMAL CONDITIONS OF ENGINEERING SYSTEMS AND INVERSE HEAT- AND MASS-TRANSFER PROBLEMS

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UDC 629.782

Problems of thermal investigation in the course of designing and analyzing thermoprotective systems are considered.

Since the characteristics of engineering systems (ES) are basically determined by solvable goal-directed problems, the methods of analyzing their thermal conditions depend to a considerable extent on many constraints associated with possible extremal conditions of their functioning, the action of the external medium, the duration of operation, etc. These constraints ultimately not only result in significant complication of the mathematical model of the thermal problem, but also often require the development of new theoretical—experimental methods. To a certain extent, all this has stimulated the creaction of a series of new scientific fields, for example, thermal investigation of space transportation systems (STS) in the thermal design of engineering systems [1]. In the latter case, the most considerable constraints influencing the choice of STS thermal conditions are primarily the specific conditions of prolonged operation of the system in space, entry into dense atmospheric layers, the action of radiation from powerful motors and power units, etc.

The problem of synthesizing the optimal STS control with respect to the criteria of a minimum mass, minimum integral heat fluxes in the time of flight, a specified upper temperature limit for the structure, etc., may be formulated here; a complex functional may sometimes be used [1].

In the general case, the problem may be regarded as an inverse problem in an extremal formulation, i.e., from known conditions determining the STS thermal conditions, it is necessary to find the required causal characteristics satisfying these conditions and the efficiency criterion adopted [1].

A mathematical model of the transport system may be constructed on the basis of models of individual component parts (subsystems), structural elements, and the heat- and mass-transfer processes occurring in them. The choice, correction, and testing of the components of these models is widely based on experimental investigations and consequently inverse problems — problems of identifying given thermal systems or their thermal conditions, identifying and correcting the thermal models of the subsystems in test conditions and, subsequently, analysis of the results of thermal experiments and monitoring the characteristics in the course of analysis of the system itself.

Descent units (DU) are the most characteristic of the known STS in this respect. In analyzing the thermal conditions of DU entering dense layers of the planetary atmosphere, a significant role is played by the heat-shield system protecting components, instruments, and equipment from the action of the considerable thermal loads.

Experimental analysis of such systems is associated with the solution of a series of complex problems, one of which is the analysis of the interaction of high-enthalpy gas with heat-shield materials and the choice of the most effective materials [2].

In the general case, this problem is based on the solution of differential equations describing nonsteady heat and mass transfer in the gas—solid system.

The interaction of high-temperature gas fluxes with the surface of various bodies is very diverse. In the general case, it is necessary to consider the problem of interaction in a complex manner, solving the conjugate problem of processes in a gaseous boundary layer, a liquid film of melt (if it is present), and a heated layer of the DU solid shell (shield).

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 5, pp. 359-362, March, 1989. Original article submitted April 18, 1988.

The difficulty is that solid and liquid particles may be present in the gas flow, bubbles and solid particles in the liquid, and gaseous and liquid components in the solid.

Nevertheless, practical experience confirms the expediency of the conventional division of the whole interaction region into three zones separated by sufficiently clear boundaries, with different characteristic laws holding in each zone.

In general form, the problem presents considerable mathematical difficulties; therefore, it is usual to obtain the solution for each zone in final form as some function of the boundary conditions. By splicing these solutions together, particular practical recommendations for the choice of DU heat-shielding parameters may be obtained.

In studying such complex phenomena, a considerable role is played by experimental investigations, further increase in the efficiency of which undoubtedly depends on the use of modern mathematical methods at all stages of preparation, realization, and analysis of the results, as well as the use of modern engineering techniques.

Automated information-measurement complexes are now in wide use, for example, their applied mathematical software may be based on methods of solving inverse heat-transfer problems (IHP) in various formulations: determining the thermal boundary conditions, identifying heat- and mass-transfer problems, deriving the temperature fields, etc.

Note that deriving the thermal boundary conditions and temperature field in the material from experimental temperature data inside the sample, with analysis of the thermal processes occurring in composite heat-shielding materials breaking down on intense heating, is an extremely pressing problem.

A very promising and universal approach to the solution of various types of IHP is based on iterative methods [3]. In this case, the IHP is formulated as an optimal-control problem, in which the desired control functions or parameters are chosen from the condition of a minimum of the mean square discrepancy.

The iterative sequence for finding the IHP solution is constructed using gradient methods of minimization, in combination with interruption of the search according to the discrepancy principle, i.e., from matching of the level of the functional to be minimized with the integral error of the experimental data. The gradient of the functional may be calculated by numerical differentiation and on the basis of the solution of the problem for the conjugate variable. Existing data confirm the high efficiency of the numerical algorithms based on this approach in solving both boundary and coefficient IHP.

The region of application of iterative methods is constantly expanding. In particular, an algorithm has been proposed for parametric identification of mathematical models describing the nonsteady heat transfer in the interaction of decomposing heat-shield materials with a gas flow. The desired characteristics here are the functional parameters of the heat-balance equation at a decomposing surface, for example, the integral emissivity as a function of the surface temperature and the thermal effect of the physicochemical transformations of the material as a function of the rate of mass loss of the DU heat shield. In the general case, this problem has no unique solution. Therefore, combined analysis of the data of several experiments with different thermal loads is expedient.

Identifying particular characteristics of mathematical models is an urgent problem not only for passive heat-shield systems but also for active systems, such as porous heat-shield thermoprotection systems with gaseous coolant. The efficiency of such systems is determined not only by the change in character of heat transfer at the external surface with coolant injection in the boundary layer, but also by the internal heat transfer when the coolant filtering to the external surface removes heat from the porous frame. The most reliable information on the local heat-transfer coefficients and the internal heat-transfer coefficients in the porous body is obtained experimentally at present.

In view of the intensity of heat-transfer processes in the boundary layer, the algorithm for deriving the thermal boundary conditions at the external surface of the porous body from experimental data on the temperature of the porous frame – i.e., from the solution of the inverse problem – takes on particular importance. In this case, the boundary IHP is formulated for the system of equations describing nonsteady heat transfer in a porous body with induced filtration of the gaseous coolant.

Another important application of the inverse-problem apparatus is the combined determination of the internal heat-transfer coefficient and the effective thermal conductivity of the porous frame. However, in this case, sufficiently rigorous constraints on the existence and uniqueness of solution of the corresponding inverse problem are in effect.

Practical application of iterative algorithms for the solution of boundary and coefficient IHP shows that their efficiency, and consequently the accuracy and reliability of the results obtained, depends to a considerable extent on the experimental conditions and the scheme for temperature measurement: the number and coordinates of the temperature sensors.

In many thermophysical investigations, the experimental conditions, thermophysical properties of the materials and geometric dimensions of the samples are predetermined or are characteristics to be established. Therefore, practically the only step influencing the accuracy of solution of IHP is the choice of a rational number of temperature sensors and their locations. The minimum number of measurements, and in some cases their location relative to the heated surface, are determined here by the conditions of existence and uniqueness of the solution. At the same time, the use of additional sensors increases the reliability and confidence level of the results of analyzing the experimental data.

In connection with this, the problem of planning the experiments may be formulated; this entails choosing the measurement plan (the vector of coordinates of the points of temperature measurement and their number) ensuring the maximum accuracy in determining the desired characteristics and the greatest efficiency (convergence, stability, etc.) of the algorithms used for IHP solution.

Various functionals of the characteristics of the normalized information matrix [4], reflecting the sensitivity of the given thermal system at the measurement points to small changes in the desired quantities, may be used as the criteria for choice of the measurement plan. Since the elements of the information matrix depend on the true values of these quantities, it is possible to speak of the construction of locally optimal plans using a priori information on the vector of the desired quantities.

This problem of optimal planning of the measurements may also be reduced to solving the corresponding extremal problem.

The choice of an optimal measurement plan is expediently complemented by analysis of the sensitivity of the planning criteria to possible versions of the vector of coordinates of the temperature-measurement points for elucidating the region of possible sensor locations and also estimates of the possible losses of accuracy due to indeterminacy in the sensor coordinates in analyzing the experimental data. Thus, the development of an apparatus for solving inverse problems for the identification of the characteristics of mathematical models of heat and mass transfer in heat-shielding systems, in combination with methods of experiment planning, permit further increase in the efficiency of experimental investigations.

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