PROBLEMS IN PROVIDING THERMAL CONTROL OF SPACECRAFT AND OTHER COMPLEX SYSTEMS

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This paper examines the main stages in operating an automated system for processing data from thermal experiments conducted in developing spacecraft, and the arrangement and planning of these experiments.

The contemporary level of experimental investigation of heat- and mass-transfer processes occurring in some systems, e.g., spacecraft, can be determined, to a considerable extent, by automating the processing and interpretation of results of observations in the design and experimental development of these sytems.

The reason for this is that automated systems have a number of advantages compared with the stage type of processing presently in widespread use. One advantage is saving time in processing the experimental information. In this case the results can be obtained in the required form practically immediately after the experiment is performed.

A second advantage is the possibility of conducting a large volume of tests under identical conditions, in a short time, which considerably increases the reliability of the results obtained. An important point also is that automatic processing increases the accuracy of the final results, compared with stage processing, since it removes an added source of error, that associated with intermediate "manual" processing.

The mathematical prescription of an automated system can be divided, arbitrarily, into two component parts, primary and secondary processing.

The mathematical prescription of primary processing consists of special algorithms (coding of experimental information, calibration of scales, editing, etc.) and algorithms for statistical analysis, a matter which receives special attention. The observational results recorded during the thermal experiment, as a rule, are data values of unsteady random processes. Analysis of these requires a different approach in each specific case. In conducting thermal tests one must also take into account that the number of data sets for a single test process may be severely limited in some cases.

Algorithms for statistical analysis have been developed for use in automated systems for processing thermal experimental data, and can be used to estimate the statistical characteristics of an unsteady random process from one or several data sets.

The mathematical prescription of primary processing in the form of system-related programs can be stored in the magnetic tape records of the automated system.

Secondary processing is associated with solving specific applied problems, in particular the direct and inverse heat-conduction problems.

During designs of efficient thermal protection systems and of some severely heated spacecraft units it is usual to emphasize theoretical prediction and experimental investigation of the thermal conditions. Here it is important to develop an efficient mathematical method for automated secondary processing of experimental information.

During the development of thermal systems the problem often arises of identifying the mathematical model used in the thermal design of the spacecraft. There is a problem in defining (or updating) the characteristics of the model from the observed results on the actual hardware. With the resulting corrected mathematical model one can more accurately predict the spacecraft thermal conditions in various flight regimes, in order to analyze the operational and functional conditions of individual units and systems. A reliable model increases the quality of the experimental development and achieves optimal planning of the experiment.

We are interested in examining the construction of programs to solve the problem of identification, relative to a model described by a system of nonlinear ordinary differential equations. In this case two approaches can be used to develop algorithms: the methods of mathematical programming and differential approximation.

It should also be noted that an important topic in formulating identification problems is analysis of the existence and uniqueness of a solution. With a correct analysis of problem description one can write down conditions and constraints which must be taken into account in carrying out the experimental investigations to develop the spacecraft.

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In experimental investigations associated with spacecraft design a strong emphasis is given to the study of unsteady heat-transfer processes. As the quality of the investigations improves it becomes important to analyze the efficiency of previously developed algorithms for solving inverse conduction problems (ICP) and to seek ways of creating new algorithms. For example, algorithms for establishing thermal boundary conditions, including the solution of ICP in two-dimensional formulation, have been developed and are being used with success.

With secondary data processing by algorithms one can considerably enlarge the circle of topics to be solved in experimental investigations, particularly to determine the region of efficient use of different types of heat flux sensors, estimate their structural degree of optimization, etc. For example, an algorithm for solving ICP, using temperature information at two points of a body, has allowed the efficient use of specially developed cooled calorimeters with which one can conduct diagnostics of plasma jets over a sufficient time period. The cooled sensors were used to determine the heat flux along a subsonic plasma jet, which made it possible to model an unsteady thermal load according to a given law.

It is well known that the process of thermal interaction of a solid body and a gas stream in test facilities with electric-arc heating of the working substance can be modeled by programmed variation of the electrical parameters of the heat source, by using a mixing chamber with monitoring of the cold gas mass flow rate, and by varying the distance between the body and the exit of a steady-state heater nozzle.

Having conducted heat flux diagnostics along the jet with the cooled calorimeters one can then use a method of moving the heater relative to the fixed model according to a given law.

When an electromechanical drive is used to move the heater it is possible to automate the process of defining the heat-transfer conditions by inserting a computer and appropriate synthesis and control units. In this case automation can considerably increase the efficiency of the entire system for modeling the heat transfer and the thermal experiment as a whole.

It should be noted that in experimental investigations of unsteady heat processes occurring in composite heat shield materials one must establish thermal boundary conditions and the temperature field in the material from the measured temperatures within the specimen.

The well-known error in formulating an ICP, which shows up as a strong sensitivity of the desired solution to errors in the input information, leads to a need to develop and introduce into engineering practice approximate control algorithms to reduce the instability of the results while preserving the required accuracy.

One promising approach to solving this problem is methods based on solving the problem of minimizing the deviation of the calculated temperature from the given, for a specific match between the number of iterations and the input information error. The inverse problem, represented by a system of differential equations, is interpreted as an optimal control problem. One must choose the optimal control (the heat flux or the temperature on the body boundary) in such a way as to minimize the target functional, which may be taken as the rms error. Here the functional gradient can be either computed by numerical differentiation or found by solving the boundary problem conjugate to the original heating problem. To obtain the conditions of the conjugate problem we must use the theory of optimal control of systems with distributed parameters. Numerical investigations of the efficiency of algorithms based on this approach, in solving nonlinear inverse problems, have shown that the methods are stable with regard to perturbations of the input information and that the final results are independent of the original approximation.

In calculating inverse boundary-value heat-conduction problems successful use is made of gradient methods for minimization with abbreviation of iterations in applying conditions for matching the minimized functional values and the experimental data errors. These methods can also be applied efficiently in automation of thermal experiment data processing. However, there is as yet no rigorous mathematical basis for applying them to solving incorrectly posed problems, particularly inverse heat-transfer boundary-value problems. We have shown it to be possible to construct control algorithms based on gradient methods, and specific algorithms have been proposed and proven. There is interest in control gradient algorithms to allow account to be taken of a priori information on the smoothness of the desired solution. In this case one can obtain more accurate solutions than with the algorithms used earlier, and also some means of increasing the rate of convergence of the methods when solving multiparametric heat-conduction problems.

During a thermal experiment it is usual to measure a large number of parameters describing the external conditions and the operation of the spacecraft structures: e.g., the distributions of enthalpy and pressure at the top edge of the boundary layer, of the convective and radiative heat fluxes, and of the body surface temperature; the temperature field in the body; the ablation of material at various points of the surface, etc.

The basic tasks of the thermal experiment are identification of the structure of the mathematical models and analysis of the actual heat-transfer processes in the test objects.

One way to increase the productivity and the efficiency of the experimental investigations is to apply contemporary mathematical methods at stages of the preparation, taking, and processing of the data, such as mathematical modeling, planning and interpretation of results, as well as to make the widest use of the latest technical advances.

Thermal investigations, particularly of naturally occurring phenomena, are extremely complex and involve great time and expense. Therefore, they require careful preparation and initially scientific justification and rational planning. In this connection one might mention the increasingly wide development of methods that allow not only processing of experimental data but also optimization in arranging the experiment.

Thus, the development of theory and general methods for problem solution and for planning many experiments is receiving considerably more attention than the development of applied methods for planning physical and particularly thermal experiments. In many respects this explains the complexity of mathematical description of unsteady heat- and mass-transfer processes.

The planning methods that are the most developed at present have a number of appreciable limitations, making it difficult to introduce them widely into thermal experiment practice. In our opinion there is a need for broad development of applied methods to allow an experiment to be planned in the presence of several controlled variables, of nonlinearity in the parametric modeling, and of timewise variation of the experimental conditions. Here it is promising to use a spline-type mathematical model and sequence methods of planning.

The creation of efficient methods of planning, control, and data processing of a thermal experiment, as has been done in contemporary computing systems, is one task of an automated system for conducting the experiment.

One of the main problems in thermal design of various spacecraft structural elements is a well-founded choice of thermal models. These models allow determination of the spacecraft thermal conditions, i.e., computation of the temperature fields in elements of the structure, heat exchange between the structure examined and the surrounding medium, etc.

A component element of a mathematical thermal model of a spacecraft is the problem of calculating temperature fields in the spacecraft structure. Different solutions to this problem stem from formalization of the thermal model. Thermal models which use the theory of graphs in their construction find wide use at present. Here the thermal model can be defined as a set of concentrated and distributed elements. This type of model can be represented in the form of a graph. Within the model the thermal conditions of lumped elements are described by heat-balance equations, and the state of distributed elements is described by the heat-conduction equations. Methods using some aspects of graph theory have been proposed to solve this kind of system of equations.

This approach to the construction of thermal models possesses a known degree of visualization, a definite universality, and convenience in applying computer techniques to the conduct of numerical experiments to investigate the thermal conditions of spacecraft and other technical systems.