SOME ASPECTS OF AUTOMATION OF DESIGN OF THERMAL PROTECTION SYSTEMS FOR SPACECRAFT

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This paper examines the structure of a system for designing thermal protection coatings.

The development of automated systems for designing spacecraft is being stimulated to a considerable extent by the widespread use of traditional methods of employing computers for complex numerical procedures, and by the availability of a new generation of computers equipped with a network of peripheral devices which allow efficient processing, systematization and storage of information, dialog operation with the computer, representation of information in graphical form, and operations with this information. The great speed of computers, the possibility of bringing different kinds of information to the designer, and the constant accumulation of new information are appreciably changing the content of specific stages of design and the designer's understanding of these.

The functioning of an automatic design system (ADS) as a whole and the peculiarities of its structure are determined to a considerable degree by the operation of the individual modules. In turn these experience a feedback influence which determines their composition and structure.

The structure examined below, the composition, and the relations between individual units of the thermal design module are not obligatory in the general case for the planned heat protection system for a specific type of spacecraft, although the individual principles of the modulus structure may have a common character [1].

We briefly consider some special features of the operating conditions of the equipment (for thermal testing) which have some influence on the modulus structure and composition.

Depending on the initial parameters of the spacecraft motion, the characteristics of the test facilities and the atmosphere, and the atmospheric entry plan, the thermal protection may vary appreciably, both qualitatively and quantitatively. For example, for earth atmospheric entry at speeds on the order of 11 km/sec and above the vehicle will receive both convective and radiative heat flux. At smaller (or larger) entry speeds the convective (or the radiative) heat flux will dominate.

Depending on the velocity along the trajectory we can identify the following basic velocity ranges for which we find typically special behavior of the incident stream gas: incompressible gas ($M \leqslant 0.7$ to 0.8), compressible gas ($M \leqslant 5$ for air), and the presence of chemical reactions in the gas (M is the Mach number).

It is known that in flow of a gas stream over a body there is a transition from a laminar to a turbulent boundary layer at a specific surface point described by a critical Reynolds number value. There will be a substantially different flow over the windward and leeward sides. In this case there are practically no relatively accurate methods for calculating the heat flux. The flow conditions and the nature of the heat flux distribution are also determined by the presence of discrete or distributed blowing of gas or liquid.

Thus, the heat-flux computation can involve the following programmed quantities:

the convective heat fluxes for hypersonic, supersonic, and transonic speeds and at low speeds (laminar boundary layer, windward vehicle surface);

the convective heat fluxes for hypersonic, supersonic, and transonic speeds and for low speed (turbulent boundary layer, windward vehicle surface);

the radiative heat fluxes in the presence of blowing;

the convective heat fluxes to the leeward vehicle surface.

This program for computing the heat flux to the surface of a specific spacecraft is not exhaustive and must be expanded and improved to allow for the special features of the heat protection system used.

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By analyzing the method of calculating the heat flux, we can identify three approaches towards construction of the mathematical models of the test process [2]:

1) the "exact" formulation of the problem, based on using the system of differential equations describing heat and mass transfer in the boundary layer and the shock layer;

2) the use of correlations;

3) the use of approximate heat fluxes, expressed as a function of the parameters of the trajectory, vehicle geometry, and flow regime.

The concept of an "exact" formulation is arbitrary since, on the one hand, the mathematical model describes the heat- and mass-transfer processes in sufficient detail, while, on the other hand, it uses a number of assumptions and hypotheses, e.g., that the flow field parameters are independent of the characteristics of the radiative field, that the chemical reactions are in equilibrium, etc. Introducing the various assumptions makes the model specialized and narrow, but the algorithm will take less computing time, which is important for an automated system.

The correlations and the approximations possess greater universality and less accuracy in the results obtained. However, they typically have the important feature of allowing a correlation based on more accurate calculations or experimental data. This must be taken into account and used in constructing the module.

Some comments should be made on calculation of thermal protection coatings. The presently known thermal protection coatings (TPC) can be classified into three groups:

1) passive, nondecomposing types (heat accumulating and radiative);

2) active, nondecomposing (porous, film-cooled, etc.);

3) protection based on decomposing materials.

The exact physical model of a nondecomposing TCP typically has temperature-dependent thermophysical parameters, contact resistance at a joint, and quite complex heat-transfer characteristics at the boundary surfaces. Approximate physical models are based on assumptions [3] regarding the dependence of the material thermophysical characteristics on temperature; on the nature of the contact between layers; on the layer thickness (finite or infinite); on the nature of the temperature field (three-dimensional, two-dimensional, or one-dimensional), etc.

Then the heating of the TPC is described by a system of nonlinear heat-conduction equations.

Comparing algorithms, e.g., for calculating the heating and breakdown of materials belonging to the different groups, we see that they are all a special case of a general heat-conduction equation with source and convective terms. However, the numerical details of each method will generally have special features, resulting from peculiarities of the breakdown mechanism. These peculiarities have an appreciable influence on the scheme for computing the temperature profile. In addition, the decomposing TPC may be part of one or more layers of TPC composites. The computation of such composites differs from that of monolayer coatings. And lastly, the library of applied programs for the ADS is built up on the basis of existing program capabilities, which are specialized and not of a universal nature.

This does not exclude the programs having some universality, but in a relatively narrow frame (e.g., for different materials with the same breakdown mechanism).

Calculations show that integral TPC characteristics (thickness of the ablated and heated layers, layer material, and number of layers) can be obtained with sufficient accuracy, so to speak, for engineering purposes, by using approximate physical models and computational methods.

For instance, the introduction of the concept of effective enthalpy appreciably simplifies both the physical model and the calculation of heating and breakdown. The same can be said of the use of various correlations approximating to the temperature field.

Analytical methods of calculating the heating of coatings are most attractive for purposes of choosing design parameters, since they allow considerable reduction in computing time when reduced accuracy is used. However, the validity of using a particular method must be based on an analysis of special features of the vehicle thermal load and the thermophysical characteristics of the individual TPC layers.

We now consider the content of individual blocks of the module and special features of their interrelationship (Fig. 1).

The original data are the quantities necessary to calculate the system parameters for any initial conditions. These can be divided into two groups.

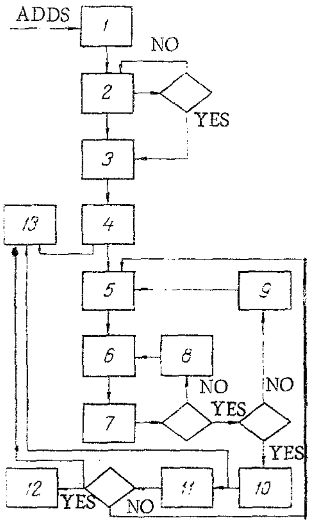

Fig. 1. Block diagram of the module for designing thermal protection coatings: 1) input of original and initial data; 2) composition of the module; 3) generation of the mesh of computational points; 4) heat fluxes; 5) assignment of TPC structure; 6) calculation of heating; 7) parameters of TPC; 8) generate new point; 9) generate new case; 10) form block of TPC parameters; 11) update thermal model; 12) mass of TPC; 13) approximation to computed results.

1. **Characteristics of the Structural Materials Used (Thermal Protection and Load-Bearing Elements).** These are determined from processing of flight and ground tests and are data in the form of tables or coefficients of approximation relations. Since these characteristics are steadily updated and their temperature range of application is expanded, the engineer must actively participate in inserting new values, and devices to represent these graphically or numerically must be set up in the lines connecting the ADS and the ADDS (automatic data definition system).

2. **The Numerical Coefficients in the Various Approximations and Constraints.** These constants fall into two subgroups: those stable relative to the initial conditions, and those correlated with the heat-load conditions. To the first group belong coefficients recommended for use over a relatively wide range of flight conditions. The second group contains values of the same coefficients, but obtained from approximating the results of exact calculations with the given initial conditions.

It should also be noted that formation of the blocks of first subgroup coefficients is a necessary preliminary phase in creating the ADS. For the specific type of vehicle and certain thermal protection systems the designer must carry out a certain volume of parametric investigations in a dialog mode with the computer, in order to determine the efficiency of the various approximations, assumptions, etc.

Definition of the Composition of the Computational Program of the Module to Satisfy the Accuracy and Speed Requirements. Analysis of special features of the heat load in different sections of the entry trajectory shows that in general one must use a definite number of external heat-transfer models (computational algorithms), to ensure sufficient accuracy in calculating the heat fluxes. Here one should bear in mind, first, that the attainment of a specific accuracy in the heat-flux calculations is not an end in itself, and secondly, that the peculiarities of the heat load in individual sections of the flight may only have a slight influence on the final computed results, for example, because a section may be of relatively short duration. The same can be said concerning the heating models and, in general, regarding breakdown of the thermal protection coatings.

Taking into account what has been said, the problem of defining the composition of the computing program can be formulated as follows: From the available bank of programs, according to each special task, to find a sequence of programs which will solve the problem with the required accuracy while meeting the constraints on the computing time.

Thus, the problem to be considered at this stage is the search for the optimal composition of the computing program of the module, and this must be solved by methods of discrete programming. Here, because of the limited number of appropriate programs in the library, situations can arise where the problem has no solution. Then the requirement can be to minimize the error or the computing time, with a constraint, respectively, on the computing time or the solution accuracy, depending on which of the conditions is the limiting one.

Another approach is possible, that of developing new programs in the appropriate discipline. The designer must make the correct choice.

The core of the problem is to calculate the error in determining, e.g., the total coating thickness as a function of the error in the heat fluxes, the heating and breakdown models, and the method of computation. Taking into account the complexity of the problem as a whole to be solved, the determination of the error should evidently be based on approximate analytical or semianalytical methods for specific types of TPC and on the use of reference calculations. After the optimal module structure has been found it is fixed for a certain range of initial conditions, as long as the constraints are not violated.

The next stage in the computational scheme may be either calculation of the surface heat fluxes or the choice of the computational points. This uncertainty can be explained as follows. If we are choosing design parameters for TPC on vehicles for which the flow regimes are well known, and if these parameters are quite stable in nature with respect to variations in the vehicle parameters, one naturally limits thereafter the number of points on the surface for which the TPC parameters will be computed, and therefore, the second stage is the choice of computational points. But for vehicles of complex shape, with rather uncertain thermal load conditions, it is more expedient first to calculate the surface heat-flux (q) distribution, and to choose the computational points on the basis of this analysis.

Of these two steps we now consider the choice of computational points in somewhat more detail.

To calculate the TPC configuration and its specific and integral characteristics in the ideal case, the entire vehicle surface must be covered by the computational points. Clearly, this approach is rather time-consuming. It is more expedient to introduce points (or lines) on the surface defining boundaries in the nature of the heat-flux distribution, associated with transition of the laminar boundary layer to turbulent, with flow on the windward and leeward surfaces and at stagnation regions, with flow on a spherically blunted or a conical surface, etc. Within these zones, where there is typically a monotonic variation of q, and consequently of the TPC parameters, one must choose intermediate points for subsequent calculation of the surface distribution of the TPC parameters. If the designer designates the first group of points from analysis of the distribution of q, then for each zone the second group should be determined in general by solving the following optimization problem: to find intermediate points to ensure that, with the chosen function approximating the TPC parameters as a function of the coordinate, the deviations from the exact values will be allowable, and the constraints will be met at each point. This problem may even have simple solutions.

The calculation of the heating and breakdown of the TPC at each computational point for a known task complexity does not generate any problems in the automation plan. One feature in performing the computation is possible parallel calculation for several points. A more complex matter is the choice of the TPC parameters at the computational point. This task may be formulated as follows: to define the design parameters of the thermal protection system (e.g., the material, the order of locating the materials in the composite, the thicknesses of the layers) to achieve a minimum total mass, for known heat fluxes and known limits to their deviations. The complexity of the problem consists, first, in the need to use different methods of optimization (choice of structure and layer thicknesses) and, second, in the fact that the optimal parameters of the thermal protection can differ over the range $q \pm \Delta q$.

It is quite possible that, even with a monotonic variation of the heat fluxes, the optimal TPC structure at a single computational point will not correspond to that at a neighboring point. Here two solutions are possible: an optimal subdivision of the surface into zones, each having its own TPC structure, and choice of an optimal structure for individual surface zones. Thus, it seems necessary to introduce an additional step into the calculation, similar to the choice of the computational points, but qualitatively more complex. Once the steps examined have been performed, calculation of the mass of the thermal protection system does not represent any further complexity.

The individual features noted and the problems arising in setting up the computational program are valid when a single type of thermal protection system is used for the entire surface. A somewhat different case is the macroblock schematic for calculating the system, when different methods can be used for thermal protection of individual surfaces.

In conclusion we shall write down a number of requirements for the module being developed: it must satisfy the time and accuracy requirements; it should be adaptive to variations defined by the objectives and by the user, i.e., it should accept additions and allow expansion of its capabilities via insertion of existing computational programs and of programs which can be developed in the future; it should ensure complete control of the information passing between individual programs; it should allow intervention in the calculation process at any stage of the design; it should ensure storage of information from the previous step in the design, and development of the system at any stage in the design.

From the general requirements on the module one can write down a number of requirements for the programming capability with respect to each special topic: it must operate for a number of cases differing in degree of detail, and therefore, in the accuracy of the results and the computer time used; it must satisfy the accuracy in the final results while meeting the corresponding constraints; and it must be developed with allowance for possible replacement of some programs by others and for the addition of new programs.

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SOME QUESTIONS INVOLVED IN THE SOLUTION OF INVERSE PROBLEMS IN HEAT CONDUCTION AND AUTOMATED DATA PROCESSING IN THERMOPHYSICAL INVESTIGATIONS

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We consider the problem of constructing systems for the automated processing of thermophysical information and methods for the solution of inverse boundary-value problems in heat conduction.

I. The automation of information processing is today one of the most important methods for increasing the efficiency of scientific investigations and design work. This problem becomes a crucial one in thermophysical investigations closely connected with the production of new specimens of technology, particularly on the thermal design and experimental trials of modern aircraft and their component assemblies.

We can distinguish three main classes of problems in the thermal design of machines and assemblies which clearly require the automation of information processing:

a) the choice of design solutions and the optimization of the parameters of thermally stressed assemblies and systems for maintaining the thermal regime;

b) the choice and identification of mathematical models of the heat-exchange processes being investigated;

c) the processing of the results of experimental investigations and of thermal tests carried out on test stands and under natural conditions.

Although these problems differ from one another, they have important features in common from the viewpoint of formulating and realizing solutions. In the first place, most of them can be stated as extremum problems, and the same numerical optimization methods can be used effectively for their solution. In the second place, all three of these classes of problems are connected with the solution of direct and inverse heat-exchange problems of the same type. In the third place, they are usually nonlinear and require iterative corrections of the solutions as the desired quantities are optimized. As a rule, the problems require a great deal of work, and their solution by digital-computing methods consumes a large amount of machine time.

There are two obvious ways to reduce the amount of time spent on information processing – to devise efficient computation methods and to improve computer hardware. The automating of information-processing systems is a natural combination of these two lines of work. For the purposes of thermophysical research, this means automated systems of thermal design and automated processing of the data of thermal tests. The solution of problems in these two types of systems involves different types of logic, but the algorithmic modules in the software libraries used for them may be the same. The general requirements imposed on the computer hardware (speed of action, memory, service devices) and on the principles of construction of such systems (in particular, requirements imposed with respect to the active integration of the operator with the system) also are roughly the same.

From the foregoing we may draw a preliminary conclusion which is confirmed by a more complete analysis of the question: in many cases it is desirable to construct unified automated systems intended both for processing the data of the thermal experiment and for optimizing the design solutions and parameters of the thermally located assemblies and the thermal protection devices. The algorithm library in such an integrated system will contain general algorithms for solving direct and inverse problems in heat exchange, general procedures for iterative methods of optimization, etc. At the same

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