THERMAL MODELS IN THERMAL DESIGN

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UDC 532.24.02

Various approaches to the design of models for heat-engineering systems are discussed, and the regions of best application are indicated.

A large part is played in thermophysics research by heat calculations on technical systems, since these enable one to determine the working conditions and to define the design parameters. This is particularly important in relation to computer-aided design systems, which are intended to accelerate design and improve design performance.

One of the major aspects of computer-aided design systems in this field is the use of methods in which the design parameters can be refined. A specific feature of problems in this area is that the calculations are laborious and complicated.

A major step is provided by the proper choice of a model, which precedes detailed analysis of the thermophysical processes. This meets two major purposes. Firstly, it serves to define the processes occurring in the system and the relative contributions of the various processes to the thermal situation, which indicates which processes dominate the state of the system and the accuracy required in defining the characteristics. Secondly, it indicates which components govern the thermal conditions and enables one to identify the thermal links between these components, as well as the specifications for the input data.

Models relate to various levels in accordance with the accuracy and completeness of the input description and the area of application.

In a first-level model, the thermal state of each component is described by an ordinary heat-balance equation, while the coupling coefficients (heat-transfer coefficients) unambiguously determine the mode and rate of heat transfer with the environment and with the other components:

$$c_{m_i}\frac{dT_i}{dt}=\sum_{j=1}^{N}[k_{ij}(T_j-T_i)+q_{v_i},\quad i\neq j;\quad i,\ j=\overline{1,N}. \tag{1}$$

The conductivity coefficients k_{ij} in (1) characterize the heat transfer by convection, radiation, and conduction between elements i and j.

First-level models play an important part in defining design parameters; a major purpose of using a model is to define integral estimators for the thermophysical characteristics, with an indication of the limits to their application.

A relatively simple mathematical technique is used at this level. Ordinary differential equations describe the time course of the thermal states of the components, and various numerical methods are available, while standard programs have been written for some of these that have been incorporated into computer software. However, there are many different thermal links between components, and some of these are nonlinear, so computational complexity may arise in implementing the algorithms, although these are not of an essential character.

In some instances (e.g., for electronic equipment), one can consider the system as a set of individual components whose heat-transfer parameters are given. Dul'nev's school has developed an efficient method of solving such problems, which involves simplifying the thermal model. For example, the thermal state of any element is examined by means of a model consisting of N equations, which is then replaced by a model with two equations, the first of which describes the thermal state of the relevant element and the second describes the thermal state of some effective body representing all the other elements. An important feature of such a simplified model is that an analytic solution can be obtained.

Considerable significance is attached to the interactions between components in some engineering devices (form factors, surface characteristics, etc.); in that case it is best to use an initial model composed of N elements and to pay particular attention to the heat interactions.

Virtually all models at this level have a direct bearing on design work, which means that they can be used as components of more complex models in designing.

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 2, pp. 231-234, August, 1980. Original article submitted January 2, 1980.

0022-0841/80/3902-0845$07.50

We now consider second-level models. The nonstationary conditions in each component are described by energy equations, which represent the thermal states of lumped components, namely the equations for the nonstationary heat balance together with the equations for distributed components, which in general are multiparameter heat-conduction equations

$$c_{m_\alpha}\frac{\partial T_\alpha}{\partial t}=\sum_{j=1}^{N}\lambda(\mathbf{r}_j,\ T)\left.\frac{\partial T}{\partial n_j}\right|_{\mathbf{r}_j\in(\Gamma_j\cap D_\alpha)}+q_{v_\alpha}(T,\ t),$$

$$\alpha=\overline{1,N_\alpha};$$

$$c_m(\mathbf{r}_j,\ T)\left.\frac{\partial T}{\partial t}\right|_{\mathbf{r}_j\in(\Gamma_j\cap\Gamma_i)}=$$

$$=\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\lambda(\mathbf{r}_j,\ T)\left.\frac{\partial T}{\partial n_j}\right|_{\mathbf{r}_j\in(\Gamma_j\cap\Gamma_i)}+(q_{\mathrm{co}})_{i,j}\right],$$

$$i\neq j,\quad(\Gamma_j\cap\Gamma_i)\subset\Gamma_{\mathrm{int}}\subset D_j,\ \forall i,\ j\in\{\overline{1,N}\};\tag{2}$$

$$\lambda(\mathbf{r}_j,\ T)\left.\frac{\partial T}{\partial n_j}\right|_{\mathbf{r}_j\in(\Gamma_j\cap\Gamma_{\mathrm{ext}})}=q_{\mathrm{ext}\ j},\quad j=\overline{1,N}.$$

The coupling between the components involves all forms of transfer. Correct formalization of the thermal links is an important aspect of model formulation, since the accuracy in describing the couplings largely determines the accuracy of the model as a whole. To avoid excessive complexity, the couplings are usually represented as functions, which are derived from theory or experiment.

In some instances, simulation involves correct allowance for the thermal states of heat carriers (gases and liquids). The conditions in these are usually described by energy equations involving convective transport, phase transitions, etc. The simulation of these processes can be complicated.

It is not usual to employ complete simulation of these processes at this level, but instead one uses fairly simple relations, which provide adequate accuracy in deriving integral evaluations.

A major problem in using models at this level lies in developing algorithms for solving the multiparameter conduction equations (for the distributed elements) and the heat-balance equations (for the lumped elements). Further, one has to consider the external heat load, the various internal sources, the heat conditions in the coolants, etc.

Therefore, models at the second level are suitable for reasonably complete investigation of engineering systems, i.e., they can be used in designing systems with allowance for fairly detailed processes and also in performing theoretical studies provided that the accuracy of the models is sufficient.

Functions are used for the thermal couplings in models of the first and second levels. These functions usually have an experimental basis. If the experimental basis is not rigorous, additional experimental or theoretical studies must be performed. Experiment plays the main part in the identification of suitable levels, particularly in the development of new systems, i.e., where not much experimental information is available.

Third-level models differ from those in the second level in that the mathematical description of the thermophysical processes reflects the physical essence as closely as possible. On the other hand, individual processes may be combined within the framework of a single model.

This approach is extremely laborious, particularly as regards computing implementation. Therefore, third-level models are at present used to simulate detailed thermophysical processes in order to test out principles on the physics of the phenomena. An example is provided by theoretical study on convection, multiphase flows in coolants, etc. A second line is concerned with research on thermophysical processes designed to provide quantitative characteristics or correlations between the basic parameters. Such relationships can then be utilized in models of the first and second levels in calculating the thermal couplings, the heat-transfer coefficients, etc.

The models at the three levels are related as follows. The first and second levels are clearly of design character, i.e., they can be used directly in software. On the other hand, third-level models are best used in check calculations. However, the third level can also be used for design purposes in simulating thermophysical processes for which experimental information is lacking.

A model at any of these levels should be open, i.e., the mathematical formalization should allow one to incorporate additional units that either describe different processes or else refine the couplings between elements. Also, the mathematical techniques and the logic of the couplings should provide, if necessary, for combining models at the different levels in application to any particular system.

NOTATION

T, temperature; **r**, spatial coordinate; n, normal; t, time; λ, thermal conductivity; ρ, density; c_p, specific heat; c_m, mass heat capacity of a lumped element; k_{ij}, conductivity between elements i and j of model; q_v, source function; q_{ext}, heat flux from the surroundings to the element; q_{co}, heat flux characterizing thermal interaction of elements; D_j, space region corresponding to element j of model; Γ_j, boundary of D_j; Γ_{ext} and Γ_{int}, sets of external and internal boundaries; N and N_α, numbers of distributed and lumped elements; subscripts: i, j, model element; α, lumped element.

CONCEPTUAL ALGORITHMS FOR ANALYSIS OF EXPERIMENTAL DATA

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UDC 536.24.083

A study is made of process simulation in inverse situations. Some problems arising in this approach are discussed, and a study is made of the choice of solution form, as well as of solution technique.

An important aspect of computer assistance in thermophysical research is to design algorithms for interpreting results; inverse treatments are often involved [1, 2]. In the treatment of experimental data, one often has to determine the causes of an observed effect, and inverse treatments provide a basis for analysis, which involves concepts in the interpretation of data. In practice, one often has the necessary information on the object in the form of models for conservation laws. Incorporation of a model into an analysis algorithm provides for more profound study of the structure and relevant factors. The corresponding algorithms may therefore be called conceptual, since the analysis is performed by inverse simulation. Simulation involves transfer from a general functional description to some particular description, which distinguishes this approach from other ways of solving inverse problems. In other words, conceptual algorithms presuppose the solution of more general problems, in which the formalization applies to the model and not to the initial data. The result is a model for an experiment that can provide characteristics of the process that are not accessible to direct observation, including the dynamic behavior of the object and so on.

We now consider ways of designing conceptual algorithms. We assume that we have chosen a model

$$L_a u = f, \tag{1}$$

and some observations are given

$$u^\delta = \bar{u} + \varepsilon$$

with a known value for the norm of the deviation from the true value:

$$\|u^\delta - \bar{u}\| \leqslant \delta. \tag{2}$$

In the choice of the model of (1) it is assumed that there exists a solution $u \in U$ that is unique in some metrical space U and that is continuously dependent on the initial data $a \in H$ and $f \in F$.

The model of (1) is the result of formalizing the process, so some of the parameters may be unknown or may differ from the actual object parameters. If appropriate a priori estimation is difficult, these parameters may be included in a vector a. Then the conceptual processing amounts to simultaneous determination of the state function $u \in U$ that satisfies the model throughout the relevant region of the independent variables together with the unknown parameters in metrical space H, which is the space of vector a. The latter requires additional information, where condition (2) is used.

In the construction of such a solution, it may happen that the result is not unique or that the solution is unstable. In the first case it is then necessary to establish a one-to-one correspondence between the desired quantities and the given

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 2, pp. 236-241, August, 1980. Original article submitted January 2, 1980.

0022-0841/80/3902-0847$07.50