UTILIZATION AND PROCESSING OF THERMOSENSOR INDICATIONS IN TEMPERATURE CONTROL IN COMPLEX OBJECTS

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Algorithms are considered for monitoring and control of thermal processes in specialized instrumentation.

Variable temperature regimes in an object containing multielement heat liberation and heat sink structures of various construction may be monitored by the indications of a series of temperature sensors. Analysis of the object's temperature regime allows accurate determination of temperature values, whose range might have been known beforehand only approximately.

With high technical requirements as to temperature drops needed to satisfy normal operating conditions, an organized control over the information proceeding from the temperature sensors makes it possible to prevent the development of malfunctions. Regulation must be accomplished on a real time scale, and decision-making and delay periods in the regulation process must not exceed the minimum interval for development of malfunctions. Thus, the first stage of data processing should include decoding of the incoming information, printout in graphic form, analysis and processing of control effects on auxiliary system temperature regulators (if such are included in the object), or making decisions on switch-on or switch-off of the heat-generating devices.

The following stages of the data processing are connected with analysis of instrument function and deviations occurring in the thermal processes and prediction of temperature regimes.

The temperature regime of complex objects may be described with sufficiently high accuracy by a system of thermal balance equations which are a particular case of the thermal-conductivity equations. The number of equations in the system corresponds to the number of segments into which the system is divided. Each segment is characterized by the condition that the temperatures of elements included therein may be taken as equal at any moment. The division process is governed by peculiarities of element function and structure, technical temperature-maintenance requirements, the character of thermosensor devices used, etc. The thermal-balance equation for any segment is written in the following form:

$$\frac{dT_i}{d\tau} = \frac{1}{(c_i G_i)}\Bigg\{q_{i\,\mathrm{ext}} + q_{i\,\mathrm{int}} + \sum_j^M \frac{\lambda_{ij}}{l_{ij}} F_{ij}(T_j - T_i) + C_0 \sum_j^N \varepsilon_{\mathrm{cor}\,ij} F_{ij}\left[\left(\frac{T_j}{100}\right)^4 - \left(\frac{T_i}{100}\right)^4\right] + \sum_j^P \alpha_{ij} F_{ij}(T_j - T_i)\Bigg\}. \tag{1}$$

It develops in practice that in the case of a complex object it is impossible to experimentally determine the coefficients of the thermophysical characteristics of the segments and the external thermal flux values appearing in the equation. Studies performed with test stands and temperature chambers do not allow complete modeling of the character of real thermal processes occurring in the object's functioning. Thus, some solution to this problem must be determined. It proves to be the case that it is possible to use temperature sensor indications to determine actual values of the thermophysical characteristics and the incident external heat fluxes of the segments.

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We write the thermal-balance relationship for contracting bodies or media in simplified form as follows:

$$Q = W_1 \Delta t_1 = W_2 \Delta t_2. \tag{2}$$

Methodological computation of thermal processes can be divided into two types — thermotechnical calculations of the first type and of the second type. In computations of the first type initial and final temperatures of both bodies are known and the problem reduces to determination of heat-transfer power. In calculations of the second type, values of thermal power Q and initial temperatures are used to determine final body temperatures.

In the case where we have available temperature-sensor information, the division of the body into segments is known, and it is known beforehand which of the thermal-balance equations are undefined; it is possible to solve the converse problem, i.e., to calculate the unknown parameters on the basis of thermotechnical computations of the first type. In the system of thermal-balance equations temperature curves obtained by processing of sensor indications allow the segment temperatures to be considered as known, while the thermophysical parameter values can then be found by converse-problem methods.

One of the most reliable methods, giving good results with a small number of variable parameters, is the method of least squares [1]. For example, if for the object studied it develops that the coefficients entering the i-th equation are unknown, the temperature curve of that segment can be recorded at a number of successive moments, with the condition that the number of these equations exceed the number of parameters studied. This system of equations is then taken as a system of conditional equations of the method of least squares,

$$\Gamma \cdot X = \Omega. \tag{3}$$

Minimization of squares of the conditional equations transforms them into a system of normal equations:

$$\Gamma' \cdot \Gamma \cdot X = \Gamma' \Omega, \tag{4}$$

where $\Gamma' \cdot \Gamma = B$ is a square matrix of dimensions $n \times n$, and

$$X = B^{-1} \cdot \Gamma' \cdot \Omega. \tag{5}$$

Actual calculation of a number of objects has revealed that variation of more than three parameters gives unreliable results independent of the number of conditional equations [2]. The problem lies in the fact that the absolute value of the determinant of the inverse matrix B^{-1} proves to be very large, and thus insignificant errors in Ω or Γ' produce significant distortions in the value X. In order to reduce error in Ω and Γ' to a minimum, it is also necessary that the thermosensor information be received without noise.

Depending on the character of the connecting circuitry and the conditions under which the object functions, in many cases it is impossible to avoid the appearance of random noise in the sensor indications. There exist several methods for smoothing discrete information and eliminating noise. The most convenient and most simply explained is smoothing by expansion in a Fourier series. Comparison of this method with others revealed no special advantages.

This method represents the random noise δ-function as a divergent Fourier series, and so the coefficients of this Fourier expansion of the noise are all of the same value. Simple reception of discrete information characterizing a smooth function can be identified with an odd function whose Fourier coefficients b_n decrease as $1/n^3$. Such a function can be written as a Fourier series in sines:

$$g(x) = b_1 \sin \frac{\pi}{a} x + b_2 \sin \frac{2\pi}{a} x + \ldots + \tag{6}$$

The coefficients b_K are determined from the condition that at the moment of arrival of information from the thermal sensors the function g(x) must correspond to that information.

The Fourier coefficients of the temperature function must decay as $1/n^3$ and, after some value b_m can be taken equal to zero. On the other hand, the coefficients of the δ-function Fourier series remain unchanged in value. Consequently, after a number m the coefficients of the expansion of the function constructed from the thermal-sensor information will be practically constant. It is obvious that they may be discarded. A major complexity of this method is the search for a boundary frequency. Good results in thermal-sensor information processing were given by the following algorithm:

$$\sum_{n=1}^{P_1} b_n^2 > 10 \sum_{n=P_1+1}^{P_1+5} b_n^2; \quad \sum_{n=2}^{P_3=P_2+1} b_n^2 > 10 \sum_{n=P_3+1}^{P_3+5} b_n^2;$$
$$\sum_{n=1}^{P_2=P_1+1} b_n^2 > 5 \sum_{n=P_2+1}^{P_2+5} b_n^2; \quad \sum_{n=2}^{P_4=P_3+1} b_n^2 > 5 \sum_{n=P_4+1}^{P_4+5} b_n^2. \tag{7}$$

Use of the information-smoothing method aids in determining reliable values of the thermophysical parameters. Converse-problem methods are especially convenient in cases where during use of the apparatus thermodynamic parameters of its component parts change (basically due to chemical reactions and incidence of foreign objects) and combustion and contamination (due to oxidation and formation of scale) of the contacting surfaces occur.

After the values of the unknown thermophysical parameters are established, the thermal regimes of complex objects can then be predicted by thermotechnical computations of the second type.

These procedures for thermal-sensor data processing permit monitoring of an object's thermal regime, determination of thermophysical parameters of its elements, and analysis of factors concerned with the surrounding medium in the functioning of serial objects.

NOTATION

T_i, temperature of i-th segment; T_j, temperature of j-th segment, with which the i-th segment is in thermal contact; τ, time; c_i, specific heat of i-th segment; G_i, weight; $q_{i\,ext}$, $q_{i\,int}$, external and internal thermal fluxes; λ_{ij}, coefficient of thermal conductivity of joint between i-th and j-th segments; l_{ij}, joint length; F_{ij}, thermal interaction area between segments i and j. C_0, Stefan–Boltzmann equation constant; $\varepsilon_{cor\,ij}$, corrected mutual radiation coefficient; α_{ij}, coefficient of heat transfer between i-th segment and liquid; M, N, P, number of segments with which i-th segment is in one or another form of thermal contact; $Q = kH\Theta$, quantity of heat transferred from cooling body to warming body; $W_1 = c_{p1}G_1$; $W_2 = c_{p2}G_2$, water equivalents; $\Theta = t_1 - t_2$; Δt_1, Δt_2, temperature changes in first and second bodies; Γ, n by m matrix, $m > n$; X, column of unknown parameters; Ω, column of free terms; Γ', transposed matrix Γ, a, time interval for data accumulation from i-th sensor; h, interval between successive data transmissions, $x = 0, h, 2h \ldots nh = a$.

LITERATURE CITED

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