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METROLOGICAL INTERRELATION FOR A GRADIENT-TYPE HEATMETER UNDER NON-STEADY-STATE CONDITIONS

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The article presents a method of determining the density of a non-steady-state thermal flux and the evaluation of its accuracy obtained by computer simulation.

The use of heatmeters type "auxiliary wall" for measuring non-steady-state heat fluxes is limited by their inertia. The cause of this is that the ordinary metrological interrelation (1) between the signal of the heatmeter and the density of the flux [1]

$$q = kl \tag{1}$$

is suitable only for measurements under steady-state conditions.

In the general case of measuring a non-steady-state thermal flux, it is necessary for establishing an interrelation between the density of the thermal flux and the signal of the heatmeter to solve the inverse boundary-value problem for the non-steady-state equation of thermal conductivity describing the process within the body of the heatmeter. One of the methods of solving the problem was described in [2] where it was shown that smoothing of the initial information with errors makes it possible to considerably reduce the errors in the calculated values of the density of the flux. To solve the problem of recovering the density of the thermal flux, the integral Laplace transform is used here, which makes it possible to easily find the solution in the image space and to ensure natural smoothing of the initial information. Inverse transformation is effected by the method of numerical inversion.

The problem of recovering the density of the thermal flux was solved in [3] with the aid of the Laplace transform. As a result of the application of analytical inversion of the transformation, expressions for the density of a non-steady-state thermal flux in the form of infinite series were obtained in a number of cases.

Assuming the temperature field in the heatmeter to be one-dimensional, the thermophysical characteristics and the initial temperature to be constant, we write the problem in Laplace transforms:

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$$\frac{d^2T(x,\ s)}{dx^2} - \frac{s}{a}T(x,\ s) = 0; \tag{2}$$

$$T(x,\ s)|_{x=l} - T(x,\ s)|_{x=0} = \Delta T(s); \tag{3}$$

$$T(x,\ s)|_{x=0} = T_1(s), \tag{4}$$

where $T(x,\ s) = \int_0^\infty t(x,\ \tau)\exp(-s\tau)\,d\tau$ is the Laplace transform of the temperature; $\Delta T(s) = \int_0^\infty \Delta t(\tau)\exp(-s\tau)\,d\tau$ is the Laplace transform of the difference between the temperatures on the surfaces of the heatmeter which is proportional to the signal.

The solution of Eq. (2) with the boundary conditions (3) and (4) has the form

$$T(x,\ s) = T_1(s)\,\mathrm{ch}\sqrt{\frac{s}{a}}\,x + \frac{\Delta T(s) + (1 - \mathrm{ch}\sqrt{s/a}\,l)\,T_1(s)}{\mathrm{sh}\sqrt{s/a}\,l}\quad \mathrm{sh}\sqrt{\frac{s}{a}}\,x.$$

From this we obtain an expression for the Laplace transform of the density of the thermal flux passing through the receiving surface of the heatmeter whose coordinate is $x = l$:

$$Q(s) = \lambda\sqrt{\frac{s}{a}}\,\frac{\mathrm{ch}\sqrt{s/a}\,l\Delta T(s) - (1 - \mathrm{ch}\sqrt{s/a}\,l)\,T_1(s)}{\mathrm{sh}\sqrt{s/a}\,l}\ . \tag{5}$$

When the initial temperature is an arbitrary function of the space coordinate, there are no fundamental difficulties in obtaining the dependence (5), but writing it in the general form is rather cumbersome.

To find the preimage of the density of the thermal flux (5), the method of numerical inversion of the Laplace transform with the aid of polynomials, orthogonal in the final interval [4], was used. If we choose biased Legendre polynomials as orthogonal polynomials, then the preimage of the density of the thermal flux is written in the form

$$q(\tau) = \sum_{k=1}^{n}(2k+1)\,a_k P_k^*(\exp(-\tau)), \tag{6}$$

where $a_k = \sum_{i=1}^{k}\alpha_i^{(k)}Q(i)$; $P_k^*(\exp(-\tau)) = \sum_{i=0}^{k}\alpha_i^{(k)}\exp(-\tau)$ are the biased Legendre polynomials; $\alpha_i^{(k)}$ are the coefficients of the polynomials; Q(i) are the values of Q(s) with integral s (1, 2, . . .).

A computer program was prepared which effects the conversion of the tabulated values of $\Delta t(\tau)$ and $t_1(\tau)$ into Laplace transforms by numerical integration, calculates the values of Q(s) by Eq. (5), and realizes the algorithm of numerical inversion. Adjustment of the program and investigation of the effect of various factors on the accuracy of the solution were carried out by computer simulation. For this purpose, the main program was provided with a procedural program, and thanks to this the following direct (in relation to the above-described) boundary-value problem for the equation of thermal conductivity with the boundary conditions was solved:

$$-\lambda\frac{\partial t(x,\ \tau)}{\partial x}\bigg|_{x=l} = q(\tau); \tag{7}$$

$$t(x,\ \tau)|_{x=0} = t_1(\tau). \tag{8}$$

The sought function here was the difference between the temperatures on the surfaces of the heatmeter which served as the initial information in the problem (2)-(4). The method of solution used in the subprogram was the finite-difference method, and the necessary accuracy of the solution was attained by subdivision of the difference grid.

In solving methodological examples, different regularities of the change in heat flux (7) were specified: monotonic, impulse, harmonic, and one obtained by superposition of these. The period of the harmonics and the length of the impulses varied between 0.01 and 100 sec, and their amplitude between 1 and 10^4 W/m^2. On the basis of these data and as a result of the work of the subprogram, the difference between the temperatures on the surfaces was determined; the maximum values of the difference varied between 0.001 and 10°K. If

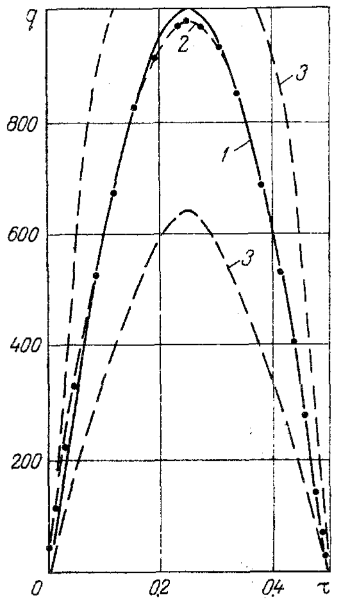

Fig. 1. Results of the recovery of the density of the thermal flux q, W/m², in dependence on the time τ, sec: 1) specified values of the density of the thermal flux; 2) change in density recovered by the method of numerical inversion using the initial data with an error μ = 0.05; 3) limits of the domain of the density of the thermal flux recovered by the method of [2].

it is used as boundary condition of (3), the second boundary condition (4) is specified on the basis of (8), and as a result of the operation of the main program we obtain an approximation to the specified density of the thermal flux (7). If the effect of the accuracy of the solution of the direct problem on the final result is eliminated, then the difference between the calculated values of the density of the thermal flux and the specified value is determined entirely by the error of the method of numerical inversion. As a result of the solution of the methodological examples it was established that when in the expansion (6) 15 terms are retained, the error in the recovery of the density of the thermal flux with different regularities of its change does not exceed 1%. An exception are only the functions of change in density whose derivatives have points of discontinuities of the first kind; in the vicinity of these points the maximum error attains 3%.

An advantage of the method of Laplace transforms in solving problems of the recovery of the density of a thermal flux is also the fact that when the initial information is transformed, it is also naturally smoothed. When other methods of solution are used, additional smoothing is indispensable, and the selection of the method of effecting it is not connected with the method of solving the problem; it is therefore largely arbitrary.

Figure 1 compares the results of recovery of the density of the thermal flux by the method of numerical inversion and by the method described in [2]. It can be seen that the distortion of the difference between the temperatures on the surfaces with the aid of a program for generating random numbers δ_i, normally distributed and with zero mathematical expectation and dispersion μ:

$$\Delta t_\delta(\tau_i) = \Delta t(\tau_i) + \mu\delta_i\Delta t(\tau_i),$$

and the simulated experimental errors have practically no effect on the results of recovery of the density of the thermal flux by the method of numerical inversion, whereas the same distortion in the method of [2] makes the calculation results (without additional smoothing) unusable for practical application.

On the basis of all this it may be concluded that the method of numerical inversion of the Laplace transform is efficient in establishing an interrelation between the signals of a gradient-type heatmeter and the density of a non-steady-state thermal flux.

NOTATION

q, density of thermal flux; τ, time; t_1, temperature of the rear surface of the heatmeter; Δt, temperature gradient over the thickness of the heatmeter; λ, a, thermal conductivity and thermal diffusivity, respectively; l, thickness of the heatmeter; x, space coordinate; Q(s), ΔT(s), $T_1(s)$, Laplace transforms of the thermal flux, of the temperature gradient, and of the temperature of the rear side of the heatmeter, respectively; s, parameter for the Laplace transform.

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INVESTIGATION OF RADIATION SCATTERING BY SULFURIC ACID DROPS*

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A study was made of the scattering of radiation by polydispersed drops of sulfuric acid, with gamma and log-normal distributions of the drops according to size. Scattering functions, attenuation coefficients, and backscattering coefficients were calculated.

Radiative transfer plays an important role in the development of thermal and other dynamic processes on atmospheric planets, ultimately determining their thermodynamic state. For earth, the thermodynamic state of the atmosphere and its dynamics affect global climate and, thus, environmental conditions for human life. The problem of the climate on the earth has become important in recent years since, given the present state of science, technology, and industry, man's activities may be affecting the climate on a global as well as local scale. The earth's atmosphere is being continually fouled by industrial wastes on an enormous scale, comparable to natural contamination of the atmosphere from volcanoes, dust storms, and hurricanes. Incomplete combustion of fossil fuels leads to pollution of the atmosphere with carbon dioxide, sulfur dioxide, etc. and to a qualitative change in the composition of the atmosphere. All this has a significant effect on processes of radiative transfer in the atmosphere and on global climate.

Many atmospheric processes are determined by solar radiation, along with thermal radiation from the heated earth.

Study of the radiative state of the atmosphere is being given much attention in an international program of investigations of global atmospheric processes (PIGAP); study of the atmospheres of other planets by means of spacecraft has also become important.

In connection with the rapid growth of industry and proliferation of hazardous wastes, the problem of protecting the atmosphere from pollution has become more acute in recent decades and can be solved only by cooperation on a global scale, involving the efforts of many nations. Calculations show that the following tonnages of natural and industrial pollutants are received by the atmosphere every year [1]: carbon dioxide $7 \cdot 10^{10}$ and $1.5 \cdot 10^{10}$; SO_2 $1.4 \cdot 10^8$ and $7.3 \cdot 10^7$; natural H_2S sulfates $1.3\text{-}2 \cdot 10^8$, industrial H_2S sulfates $1.3\text{-}2 \cdot 10^8$

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