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APPLICATION OF PULSED HEAT BALANCE METHOD FOR DETERMINING THE CHARACTERISTICS OF CONSTRUCTION MATERIALS

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Abstract. The possibility for applying the pulsed heat balance method was considered to determine thermal and physical characteristics of different construction materials. The determination methods of characteristic points at temperature curve and correlations were offered to calculate values of thermal and physical characteristics of construction materials among them there are materials with protective and hardsurfacing overlays including anisotropic materials.

1 Introduction

Variation of thermal and physical characteristics (TPC) of construction materials during exploitation leads to significant changes in heat flows in manufacturing equipment, pipeline systems and other parts of the different objects. The presence of thermal stress fatigue effect, which leads to significant changes in TPC of construction materials (in some instances, up to two-fold), generates a need for determining TPC. Traditional experimental calorimetric methods for TPC determination [1] require a long period to prepare and conduct the experiment. For multilayer materials including construction materials with hardsurfacing and protective overlays, which are gaining greater acceptance, as well as for materials with high heat conduction and/or shallow thickness, the traditional methods have significant errors in TPC determination which reach tens of percent of the actual TPC value.

The pulse thermal method can be applied to determine quickly the TPC of construction materials. The pulse thermal method of "flare" of TPC determination, which was suggested by Parker [2], has widespread occurrence, currently. The method is based on using a thermal pulse (of laser, xenon lamp and other) which is supplied to the surface of an object under study to develop a temperature gradient in it. Temperature variation in time at reverse or front side of studying object (in relation to supplied pulse) is fixed by temperature element and used to calculate TPC.

According to the existing classification, the determination methods of TPC of different materials are divided by stationary and non-stationary. Moreover, non-stationary methods take a special place as more informative. Further, non-stationary methods include purely non-stationary methods which use initial unordered stage of heating (cooling) process and methods based on a steady regime of heating or cooling [3]. Whereby, the method of "flare", developing intensively at the present, is relegated to non-stationary [2].

A question was raised as to whether this method purely non-stationary or not, is not only a methodological question: the inclusion of the method in the category of purely non-stationary one predetermines the necessity to find the initial condition corrections in the identification of TPC.

Modifications of pulse thermal method, especially double-sided method and single-sided pulse thermal method in which the temperature is measured on the same surface of the material to which the heat flow is directed from the heat source, allow accelerating significantly the process of TPC determination and decreasing its errors. This method allows us to determine TPC of multilayer materials, their applying enhances significantly the characteristics of construction materials.

The determination of TPC of different materials is an essence of the coefficient inverse problem of heat conduction. To solve such problem, the thermometering results of an object under study provided from from a material with unknown properties are the initial data.

Because an inverse problem of heat conduction refers to incorrect problems in mathematical physics, this brings up the questions related to regularization of solutions. The method of reverse of direct heat conduction problem solving is one of the effective methods to solve the inverse heat conduction problem. It gives simple calculation dependences for TPC which allow obtaining effective measure systems. If such a solution is obtained in the form of analytical expression, when one applies the temperature values measured in the experiment to the left side of the expression and solves the problem of relatively desired TPC, then we can deduce the required algorithm for calculating the values of the characteristic. The most simple calculation dependences were found for the heat conduction direct problem solution abridged to the first member that is for regular temperature regime [3]. Whereby, fixation of the moment of temperature regime regularization remains the only problem.

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2 Study technique

TPC determination was performed by measuring the duration of time intervals from the final time of heat pulse to the moments corresponding to characteristic points of temperature curve which describes the temperature variety of studied object surface. After determination of appropriate time intervals, we either calculated the values of TPC or performed additional operations, in particular, we determined the integration step of temperature curve characterizing the variation of surface temperature after becoming the moment of temperature regime regularization and then we calculated values of TPC. Among other factors, the values of TPC were calculated by the following formulas for the noisefree method of "stepwise integration" [4]:

$$a = \frac{L^2}{\pi^2 \Delta\tau} \ln \frac{I_2 - I_1}{I_3 - I_2} \tag{1}$$

$$\gamma = \frac{Q\Delta\tau(2I_2 - I_1 - I_3)}{L(I_2^2 - I_1 I_3)} \tag{2}$$

$$\lambda = a\gamma \tag{3}$$

where a – temperature conductivity coefficient of material under study;
L – material thickness;
$\Delta\tau$ – integration step of temperature curve, $\Delta\tau = 0{,}1\Delta t$, $\Delta t = t^* - t_0$,
t^* – time point of the beginning of temperature regime regularization;
t_0 – time point of the termination of heat pulse;

$$I_1 = \int_{t^*}^{t_1} T dt \qquad I_2 = \int_{t_1}^{t_2} T dt \qquad I_3 = \int_{t_2}^{t_3} T dt \tag{4}$$

T – overtemperature of material surface;
γ – volumetric heat capacity of material;
Q – quantity of absorbed energy;
λ – heat conduction coefficient of material.

We determined the time point $t_{12} = 0{,}25 L_1^2 / a_1$ of the beginning of information processing for overtemperature of the surface of the material under study, which is necessary for calculation of compatible (effective) TPC λ_{12}, γ_{12}, a_{12} for surfaces and basic construction materials by "stepwise integration" method. This was defined for construction materials with hardsurfacing and protective overlays after determining TPC of surfaces from condition $F_0 \geq 0{,}25$; $F_0 = a_1 t / L_1^2$, where a_1 is a temperature conductivity coefficient of covering material, t is a time interval from the termination of heat pulse to the current time, L_1 is a surface thickness. Then we obtained the values of TPC of basic construction material by the following correlations:

$$\lambda_2 = \frac{m}{\dfrac{1}{\lambda_{12}} - \dfrac{1-m}{\lambda_1}} \tag{5}$$

$$\gamma_2 = \frac{\gamma_{12} - (1-m)\gamma_1}{m} \tag{6}$$

$$a_2 = \frac{\lambda_2}{\gamma_2} \tag{7}$$

where $m = L_2 / (L_1 + L_2)$, L_2 is a thickness of basic construction material.

For one-sided pulse heat balance method the time moment of the beginning of temperature regime regularization was determined by "gliding tangency" method [5]. In this method the finding of time point of temperature regime regularization reduces to detecting the time point when the function equals zero:

$$F = T + k\Delta t T^{!}\, 1 \tag{8}$$

where k – constant coefficient,

Δt – time interval from the moment of the termination of heat pulse to the current moment,
$T^!$ – first-order derivative from overtemperature of material surface in time.

In a case of front monitoring at a section of temperature regime regularization, the forward solution of heat conduction for the material under study reduces to the correlation

$$T = \frac{Q}{\gamma L}[1 + 2k_1 \exp(-\pi^2 at / L^2)]\,, \tag{9}$$

where L – material thickness,
k_1 – constant coefficient determined from the initial conditions,
and TPC values of material are defined by formulas:

$$a = -L^2 \frac{\ln F}{\pi^2 \Delta\tau} \tag{10}$$

$$\gamma = \frac{Q(1-F)}{LD} \tag{11}$$

where F, D are the functionals which are measured on the base of overtemperature of construction material surface at intervals $\Delta\tau$ after the time point of the beginning of temperature regime regularization.

If there are such conditions when the structure and properties of studying materials are indeterminate, a need in the simultaneous definition of TPC values and surface thickness of studying construction material arises. The infeasibility of the simultaneous definition of above parameters has a dual nature: theoretical and experimental. Experimental problems closely related to theoretical ones because there are no algorithms of the simultaneous definition of target values. Theoretical problems are caused by the fact that the target values are included in the solution of differential equations of heat exchange in the form of multipliers and it is difficult to divide them. Experimental problems, which should be solved in the presence of completed algorithms, lie in the determination instruments for TPC because high-speed measurement tools of construction material surface temperature are necessary.

The proposed approach to solve the problem for anisotropic materials is based on applying the one-sided thermal pulse method and it is as follows. For construction materials with temperature conductivity a, the axial component a_x can be determined by the formula [6]:

$$a_x = -\frac{L^2 \ln F}{\Delta\tau\pi^2} 1 \tag{12}$$

$$F = \frac{\sum_{k=1}^{n} T^k \sum_{k=1}^{n} T^{k-1} - n\sum_{k=1}^{n} T^k T^{k-1}}{(\sum_{k=1}^{n} T^{k-1})^2 - n\sum_{k=1}^{n} (T^{k-1})^2} \tag{13}$$

where T^k – temperature measured at the moment of t_k in the center of the spot of heating;
n – temperature dimensions performed at the same point in increments in time $\Delta\tau$.

The radial component of temperature conductivity coefficient a_r can be defined by the correlation [6]:

$$a_r = \frac{\dfrac{T_i^k - T_i^{k-1}}{\Delta t}}{\dfrac{T_{i+1}^k - T_i^{k-1}}{2r_i \Delta r} + \dfrac{T_{i+1}^k - 2T_i^k + T_{i-1}^k}{(\Delta r)^2}} \tag{14}$$

In the equation (2) the parameter T_i^k is a temperature measured at the moment of t_k on the surface of studying material in the points $r=r_i$. The time Δt and spatial Δr intervals are determined by the correlations:

$$\Delta t = t_k - t_{k-1} = t_{k+1} - t_k\,,\ \ \Delta r = r_{i+1} - r_i \tag{15}$$

Data on the accuracy of the considered method are presented in the works [6, 7].

For homogeneous isotropic materials $a_x=a_r=a$, we obtain the system of two equations (1, 2) with two unknowns – temperature conductivity a and material thickness L. Solving this system, we obtain:

$$a = \frac{\dfrac{T_i^k - T_i^{k-1}}{\Delta t}}{\dfrac{T_{i+1}^k - T_i^{k-1}}{2r_i \Delta r} + \dfrac{T_{i+1}^k - 2T_i^k + T_{i-1}^k}{(\Delta r)^2}} \tag{16}$$

$$L = (-a\frac{\Delta\tau\pi^2}{\ln F})^{0,5}. \tag{17}$$

The formulated problem can be solved for one-sheeted material and material with insulating and protective overlay. In the consequence, there is a possibility for determining the thickness and temperature conductivity of coverage and modified surface layers of various construction materials, as well as to identify the depth of the defects (cracks, delaminations and others, that is nonuniformity of characteristics) in studying materials. Limitation of temporary nature resulting from the correlation of the constant of measured system time t_d and characteristic period of the studying object can be depicted with the correlation $4t_d < 4{,}43 \cdot 10^{-3} L^2/a$.

The limitations come out from the forms and sizes of research objects are the supplementary conditions. For example, for research objects in the form of infinite plate the correlation $L<0{,}3R_i$ should be realized; in the form of a disk of radius R - $L<0{,}3R_i$ and $L<0{,}6R$ (R_i is a radius of the spot of heating) [5].

3 Conclusion

Therefore, we suggested the determination methods for TPC which expand the scope of practical application of pulse heat balance method. The results of determining the values of TPC, with the help of the considered methods can be used in the calculation of parameters of heat fluxes, and the diagnosis of thermal stress fatigue of construction materials. By changing the values of TPC it can be inferred by heat aging of construction materials, hardsurfacing and protective overlays, and density of different defects in crystal structures of construction materials.

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