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DETERMINATION OF THE HEAT FLUX ON THE SURFACE OF COMPOSITE MATERIALS UPON INTERACTION WITH HIGH-ENTHALPY GAS STREAM

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The article deals with the determination of heat fluxes on the surfaces of composite materials upon interaction with a gas stream of high enthalpy.

For the calculation of processes of heat and mass exchange occurring upon interaction of composite heat insulating materials with a gas stream, and for the evaluation of the efficiency of the material it is indispensable to know the boundary conditions on the surface, in particular the specific heat flux [1, 2]. It is difficult, and in many cases altogether impossible, to measure it directly because of the physicochemical transformations occurring on the surface of and inside the material. The problem of finding specific heat fluxes usually reduces to the solution of the inverse problem for the equation of nonsteady heat conduction on the basis of experimentally measured temperature fields in the material.

The present work involves the determination of the heat fluxes on the interface of the media by different methods on the basis of the experimental data in measurements of the surface temperature and of the temperature field within the bulk of the specimen of composite material.

The experiments were carried out in jets of air plasma of an electric-arc plasmatron ÉDP-104A and a vortex plasmochemical reactor (PCR) with the following parameters of the stream: enthalpy of the gas H_0 = 2-10 MJ/kg; Reynolds numbers Re = $(0.5\text{-}5)\cdot 10^3$, Ma $\leqq 0.3$. The gas temperature in the jet was determined by the method of relative intensities with a spectro-

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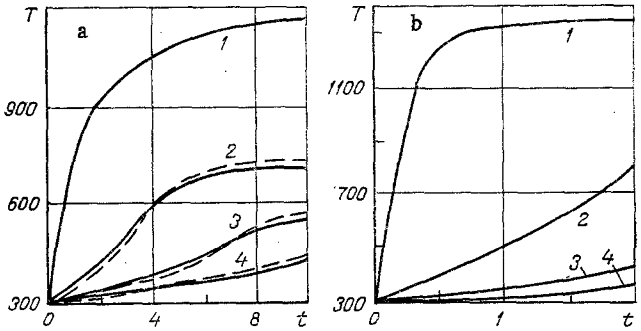

Fig. 1. Dependences of temperature on time at the points: 1) R = 0; 2) $R_1 = 1 \cdot 10^{-3}$ m; 3) $R_2 = 2 \cdot 10^{-3}$ m; 4) $R_3 = 3 \cdot 10^{-3}$ m; a) H_0 = 3.2 MJ/kg; b) H_0 = 6.2 MJ/kg; solid curves, experiment; dashed curves, calculation by the method (1)-(10).

graph ISP-30 [3], and also by a method presented in [4]. The method and results of diagnostics of a jet of air plasma are presented in more detail in [3, 5].

The heat insulating composite materials that were used were glass fiber reinforced plastics on the basis of epoxy binder [6]. For measuring the temperature field inside the glass fiber reinforced plastic and on its surface, four Chromel–Alumel microthermocouples with $5 \cdot 10^{-5}$ m diameter were pressed preliminarily into the specimens at the time of the heat treatment; they were placed 10^{-3} m from each other (the first one on the surface). The signals from the thermocouples and from the photoelectric pyrometer [7] were recorded by an oscillograph N-115. The results of measurements of the temperature in dependence on time at different points across the thickness of the specimens are presented in Fig. 1.

A number of ways are used for calculating heat exchange on the surface of composite materials failing under thermal effects.

1. On the basis of mathematical models [1, 2, 8, 9] a new model of the process of heat and mass exchange in composite polymer materials (CPM) is suggested. Assume that the destruction in the CPM is due to the irreversible homogeneous chemical reaction of decomposition of the binder $A_r \to A_{gas}$, then the mathematical formulation of the problem is as follows:

$$\frac{d\rho_1}{dt} = \begin{cases} -B\rho_{1,0}\left(\frac{\rho_1 - \rho_r}{\rho_{1,0}}\right)^{\nu} \exp\left(-\frac{E}{RT}\right), & \rho_1 > \rho_r, \\ 0, & \rho_1 \leq \rho_r, \end{cases} \tag{1}$$

$$\frac{\partial \gamma\rho_2}{\partial t} + \frac{\partial}{\partial x}(\rho_2\gamma v) = \frac{d\rho_1}{dt}, \quad v = -\frac{K}{\mu}\frac{\partial P}{\partial x}, \tag{2}$$

$$g\frac{\partial T}{\partial t} + C_{P_2}\rho_2\gamma v\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) - Q\frac{d\rho_1}{dt}, \tag{3}$$

$$P = \frac{\rho_2 RT}{M_2}, \quad K = \frac{K_* \gamma^3}{(1-\gamma)^2}, \quad g = (1-\gamma)\rho_T C_P(T), \tag{4}$$

$$\mu \sim \sqrt{T}, \quad \gamma = 1 - \frac{\rho_1}{\rho_T}, \quad \lambda = \lambda(T), \tag{5}$$

$$T|_{t=0} = T_0, \quad \rho_j|_{t=0} = \rho_{j,0}, \quad j = 1, 2, \tag{6}$$

$$T|_{x=0} = T_w(t), \tag{7}$$

$$-\lambda\frac{\partial T}{\partial x}\bigg|_{x=L} = \alpha(T|_{x=L} - T_0), \tag{8}$$

$$P|_{x=0} = P_0, \tag{9}$$

$$v|_{x=0} = 0, \tag{10}$$

where $\lambda(T)$, $C_P(T)$ are known as functions of the temperature and ρ_T, generally speaking, is found experimentally.

Expressions (1)-(3) are equations of conservation of mass of the polymer binder and of the gaseous product of the pyrolysis reaction, the law of conservation of kinetic energy (d'Arcy's law) and of the energy of the biphase reacting medium, respectively. The first equation (4) is the thermal equation of state of the gaseous filtration products, and the value of permeability K was determined by the Kozeni–Karman formula [2].

It is assumed that the temperature $T_w(t)$ in (7) on the heated surface of the heat insulating material (HIM) is known from experiments. Relations (8)-(10) are the boundary conditions of the initial system of equations.

The system of equations (1)-(4) with the boundary conditions (6)-(10) was solved by the iteration-interpolation method [2]. The heat flux into the condensed phase (the K-phase) was found with an accuracy $O(\tau + h^2)$ by the formula

$$q_w = h\{T_w^{n+1}[2g_w + 3\tau(\lambda_w + \lambda_{w+1})/h^2 + \tau(f_{w+1} + 2f_w)(P_{w+1} - P_w)/h^2] + T_{w+1}^{n+1}[g_{w+1} - 3\tau(\lambda_{w+1} + \lambda_w)/h^2 - \\ - \tau(f_{w+1} + 2f_w)(P_{w+1} - P_w)/h^2] - g_{w+1}T_{w+1}^{(n)} - \tau R_{w+1} - 2(g_w T_w^{(n)} + \tau R_w)\}/6\tau, \tag{11}$$

$$f = C_{P_2} P_2 \gamma^{K/\mu}, \quad R = Q\frac{dP_1}{dt}.$$

To check the calculation program, test calculations were run. From the surface temperature known from experiments, the heat flux on a copper plate with thickness $L_M = 10^{-3}$ m ($C_{P_m} = 376$ J/kg·°K, $P_m = 8950$ kg/m³, $\lambda_M = 386$ W/m·°K) was restored by the formula

$$q_w = C_{P_M}\rho_M L_M \frac{dT}{dt}, \tag{12}$$

where dT/dt is known from experiments and numerically found by formula (11). The error of the result with $0 < t \leq 1$ does not exceed 0.1%. In addition, with other input data being equal, we carried out the calculation for different spatial steps $h = 2\cdot10^{-4}$ m and $h = 4\cdot10^{-4}$. The difference in maximum heat flux in the K-phase (t = 1 sec) and in temperature at a depth of $2\cdot10^{-3}$ m (t = 9 sec) is less than 5 and 0.2%, respectively.

For the thermophysical and thermokinetic parameters of HIM we used data of [8, 10].

2. As mathematical model of the calculation of the heat flux according to data of temperature measurement in the bulk of the specimen we used the nonlinear equation of heat conduction

$$\rho(T)C_p(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right] + F, \tag{13}$$

where $F = F(T, \partial T/\partial x)$. If the dependence of ρ, C_P, λ on the temperature is represented in the form $\lambda(T) = \lambda_0 + \varphi(T)$, $\rho(T)C_P(T) = \rho_0 C_{P_0} + \psi(T)$, where $\varphi(T)$ and $\psi(T)$ are continuous functions with continuous derivatives with respect to x from the first to the i-th derivative, inclusively, then Eq. (13) can be represented in the form

$$\rho_0 C_{P_0}\frac{\partial T}{\partial t} - \lambda_0\frac{\partial^2 T}{\partial x^2} = \frac{\partial}{\partial x}\left[\varphi(T)\frac{\partial T}{\partial x}\right] - \psi(T)\frac{\partial T}{\partial t} + F. \tag{14}$$

If we represent the right-hand side of Eq. (14) in the form of the sum of a power series in the vicinity of an arbitrary point in the region of change of the space coordinate x, then in accordance with [11], after i times differentiating Eq. (14) we obtain a differential equation of heat conduction of (i + 2)-nd order

$$\frac{\partial^{i+1}T}{\partial x^i \partial t} = a_0\frac{\partial^{i+2}T}{\partial x^{i+2}}. \tag{15}$$

To solve Eq. (15), we must have i + 2 boundary conditions which may be specified on the boundary surfaces of the body as well as at points within it. Therefore, with i >> 1 it may be assumed that the temperature field described by Eq. (15) practically coincides with the solution of Eq. (13). Surkov et al. [11] showed that with an insignificant loss of accuracy linear equations of third or fourth order may be used, and their solution does not pose any

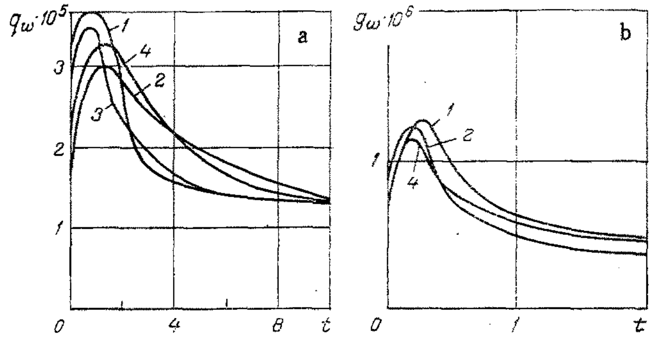

Fig. 2. Dependence of the heat flux on time: 1) formula (11); 2) formulas (18)-(19), $R_1 = 1 \cdot 10^{-3}$ m, $R_2 = 2 \cdot 10^{-3}$, $R_3 = 3 \cdot 10^{-3}$ m; 3) formulas (18)-(19), $R_1 = 0$, $R_2 = 1 \cdot 10^{-3}$ m, $R_3 = 2 \cdot 10^{-3}$ m; 4) formula (20); a) $H_0 = 3$ MJ/kg; b) $H_0 = 6.2$ MJ/kg.

difficulties. Therefore, when three thermocouples are inserted into the body, the system of equations to be solved has the following form:

$$\frac{\partial^2 \Theta}{\partial x \partial t} = a_0 \frac{\partial^3 \Theta}{\partial x^3} \quad (R_1 < x < R_3,\ t > 0), \tag{16}$$

$$\left.\begin{aligned} &\Theta|_{t=0} = 0 \quad (R_1 < x < R_3), \\ &\Theta|_{x=R_1} = \varphi_1(t) \quad (t > 0), \\ &\Theta|_{x_2=R_2} = \varphi_2(t) \quad (t > 0), \\ &\Theta|_{x=R_3} = \varphi_3(t) \quad (t > 0), \end{aligned}\right\} \tag{17}$$

where $\Theta(x, t) = T(x, t) - T_0$.

The solution of this system by means of Laplace transformation [12] has the form

$$T(x, t) = T_0 + \varphi_1(t) + [\varphi_1(t) - \varphi_2(t)] \frac{(R_3 - x)(x_1 - R_1)}{(R_3 - R_2)(R_1 - R_2)} + [\varphi_1(t) - \varphi_3(t)] \frac{(x - R_1)(R_2 - x)}{(R_3 - R_2)(R_3 - R_1)} + [\varphi_1'(t) - \varphi_2'(t)] \times$$
$$\times \frac{(R_3 - x)(x - R_1)[(x - R_1)^2 + (R_3 - x)^2 - (R_1 - R_2)^2 - (R_3 - R_2)^2]}{24 a_0 (R_3 - R_2)(R_1 - R_2)} - [\varphi_1'(t) - \varphi_3'(t)] \times \tag{18}$$
$$\times \frac{(x - R_1)(R_2 - x)[(x - R_1)^2 + (R_2 - x)^2 - (R_3 - R_2)^2 - (R_3 - R_1)^2]}{24 a_0 (R_3 - R_2)(R_3 - R_1)}.$$

The heat flux is determined by the formula

$$q_w = -\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0}. \tag{19}$$

3. If the dependence of the surface temperature on the time is known from an experiment, then for the case of quasisteady flow around a semiinfinite body of revolution or a reacting plate, the heat flux can be determined from the solution of Abel's integral equation [2]. According to [13], if we divide the calculation interval (0, t) into N sufficiently small intervals τ and denote the discrete value of the measured surface temperature $T_w(s\tau) = T_w(ts) = T_s$, $s = 1, 2, \ldots, N$, we can obtain an approximate formula for calculating the heat flux:

$$q(N\tau) = \frac{\lambda}{\sqrt{\pi a \tau}} \sum_{s=1}^{N} (T_s - T_{s-1}) C_{N-s}, \quad C_m = 2(\sqrt{m+1} - \sqrt{m}). \tag{20}$$

Formula (20) is applicable when the condition Fo ≧ 0.1 is fulfilled. It follows from Fig. 1 that the theoretical temperature curves are in satisfactory agreement with the experimental curves; this indicates that the mathematical model (1)-(10) is adequate to the experiment. It can be seen that calculation by formulas (18)-(19) with the use of the temperature on the surface ($R_1 = 0$) is in sufficiently good agreement with the data of the numerical count of the problem (1)-(10). When for the calculation by formulas (18)-(19) only the inner thermocouples are used, and also in the calculation by formula (20), there is a difference of the heat flux as compared with the data of the calculation of the problem (1)-(10). The largest difference of these data is attained with small values of time. When t = 10 sec, the results of the calculations by different formulas practically coincide.

Figure 2b presents the results of calculations of the heat flux for the temperature fields shown in Fig. 1b. Here there is also quite good agreement between the calculations by model (1)-(10) and models (18)-(20). Maximum scatter of the data with t = 10 sec is 10% at most. The solution of the problem (1)-(10) without taking the reaction of pyrolysis of the polymer binder into account leads to a 12% reduction of the heat flux on the steady section (for t > 8 sec). An analysis of the results obtained showed that in the range of enthalpies of the incoming flow (2-10) MJ/kg the approximate methods of calculating the heat flux on the surface of glass fiber reinforced plastic may be used with an error of 10%. For more accurate calculations it is apparently expedient to solve the system of equations of a porous reacting body (1)-(10) using the thermophysical and thermokinetic constants characterizing the structure and the reactive properties of the material.

NOTATION

t, time; x, space coordinate; τ, time step; h, space step; T, temperature; ρ, density; v, P, γ, M, speed, pressure, volume porosity, and molecular weight of gaseous products of the pyrolysis reaction: C_p, specific heat; λ, thermal conductivity; μ, dynamic viscosity; K, permeability; α, heat transfer coefficient; E, activation energy; B, preexponential factor; Q, thermal effect; ν, order of the pyrolysis reaction; L, thickness of the specimen; ρ_T, running density of the carcass of the solid residue; ρ_r, density of the coke residue; q_w, specific heat flux at the interface between the gaseous phase and the K-phase; a_0, thermal diffusivity of the material corresponding to the temperature T_0; F, source term determined by the pyrolysis of the polymer binder; $\varphi_1(t)$, $\varphi_2(t)$, and $\varphi_3(t)$, temperatures as functions of time ascertained experimentally at the points $x = R_1$, $x = R_2$, and $x = R_3$, respectively. Subscripts: *, characteristic magnitudes; w, parameters on the interface between the gaseous phase and the K-phase; 1, polymer binder; 2, gaseous products of the pyrolysis reaction; 0, initial value of magnitudes; M corresponds to the parameters of the copper plate; w + 1, to values at the depth h from the heated surface of a body; n + 1 and n, to the upper and lower layer, respectively, in time.

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COMPARISON OF THE RESULTS OF INTERFERENCE AND NUMERICAL DETERMINATIONS OF STREAM DENSITY IN A SEPARATION ZONE

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Density fields in the separation zone are determined from interferograms of supersonic turbulent flow over a body. A comparison is made with the results of numerical calculations by a combined scheme.

The problem of varying the aerodynamic characteristics of blunt bodies by extending heads of various shapes out on a needle [1] requires the study not only of integral quantities but also of the local parameters of the streamline flow. The structure for the case of the flow of a supersonic stream over a cylinder with a disk head, known from calculations and a qualitative analysis of shadow pictures, is shown in Fig. 1. The complexity of the flow occurring between the disk and the cylinder (frontal separation zone) resulted in an attempt at a combined experimental and numerical investigation of it, some results of which are presented in this article.

Interferometric investigations of axisymmetric inhomogeneities have been made on a ballistic course for more than 15 years. The procedure of such an experiment and the operational experience are given in [2]. The interferograms analyzed below were obtained on a diffraction displacement interferometer based on an IAB-451 shadow instrument [3, 4]. Gratings with a frequency of 75 lines/mm served as the light splitters; with the OGM-20 laser wavelength of 694.3 nm and the focal length of the objective of 1918 mm the displacement of the interfering wave fronts was 100 mm. The investigated inhomogeneity occupied an area of 60 × 100 mm in a meridional cross section.

The model of a body of cylindrical shape with a disk head extended on a needle (with a relative disk size $d/D = 0.233$ and a disk extension $\ell/D = 1.4$, where D is the cylinder diameter) was thrown at a velocity corresponding to a Mach number 2.35 on a ballistic installation at a pressure of 1 atm. In Fig. 2 we present a fragment of an interferogram of the stream in the frontal separation zone, obtained with the interferometer adjusted for bands of finite width.

In constructing the path-difference function from an interference pattern of the turbulent zone we used a priori information about the flow over the body under consideration. The direction of variation of the path difference near the extrema and of the lines of inflection of the wave surface of the probe light was established through the fact that the detached mixing layer of the frontal separation zone is a region of reduced density with respect to the compressed shock layer.

Let us clarify, in accordance with [5], how density pulsations within the turbulent region and pulsations of its boundaries are transferred to the interference pattern. The interference method is inferior to the Schlieren method in sensitivity to the transmission of pulsations. At the same time, pulsations of the boundary of a turbulent region (mixing layer,

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