A METHOD OF EXPERIMENTAL DETERMINATION OF THE PROFILES OF TEMPERATURE AND COMPOSITION OF A HIGH-TEMPERATURE GAS STREAM

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A method of determining the parameters of a high-temperature gas stream based on the phenomenon of removal of mass from a plate placed in the stream is discussed. The possibility of applying the method is shown on a particular example.

Gas streams with temperatures of up to 3000°K are used in a number of industrial devices (high-temperature combustion chambers and gas generators, heat exchangers, MHD generators, etc.). In investigating the working processes of such devices it is necessary to determine the profiles of temperature and composition of gas streams inside experimental models. Contact methods (using thermocouples) and optical methods (based on the reversal of lines of alkali metals) of temperature measurement [1] are usually used for this purpose, as well as the method of taking samples of the gas stream with their subsequent chemical analysis [2]. These methods possess a number of drawbacks hindering their practical application, especially when the profiles of temperature and composition have complicated configurations.

In this connection it seems promising to use a method based on the phenomenon of the decrease in the height of a rectangular plate made of a thermoplastic polymer and placed in a high-temperature gas stream for the experimental determination of the profiles of temperature and composition of the test stream [3]. The main advantages of such a method are the simplicity, efficiency, and reliability of the obtainment of information about the parameters of a high-temperature stream in a given cross section.

Let us consider the application of the proposed method on the particular example of the determination of the parameters of combustion products containing C, N, H, and O (content of free oxygen 0.03%) from the decrease in the height of a plate made of polymethyl methacrylate and not interacting chemically with the combustion products. The mechanism of destruction of the plate is determined both by processes taking place in the plate material and by processes of heat exchange between its surface and the gas stream, and it is complicated by the presence in the boundary layer of oncoming gas of an opposing flow of products of thermal decomposition of the plate. To describe this mechanism we write the following system of equations, using the results of [4-6]:

$$m(T_w) = \sqrt{\frac{B\rho\lambda R/E}{c(T_w - T_0) + Q/2}}\, T_w \exp[-E/(2RT_w)]; \tag{1}$$

$$q_0 = \left(\frac{\alpha}{c_p}\right)_0 (I_1 - I_w) = m\gamma(I_1 - I_w) + m\bar{c}(T_w - T_0) + mQ; \tag{2}$$

$$\left(\frac{\alpha}{c_p}\right)_0 = 0.763\mathrm{Pr}_w^{-0.6}(\eta_w\rho_w)^{0.1}(\eta_1\rho_1)^{0.4}\left(\frac{du}{dx}\right)^{0.5}; \tag{3}$$

$$\gamma = 0.67\left(\frac{\mu_1}{\mu_w}\right)^{0.25}; \tag{4}$$

$$h = \frac{m}{\rho}\tau. \tag{5}$$

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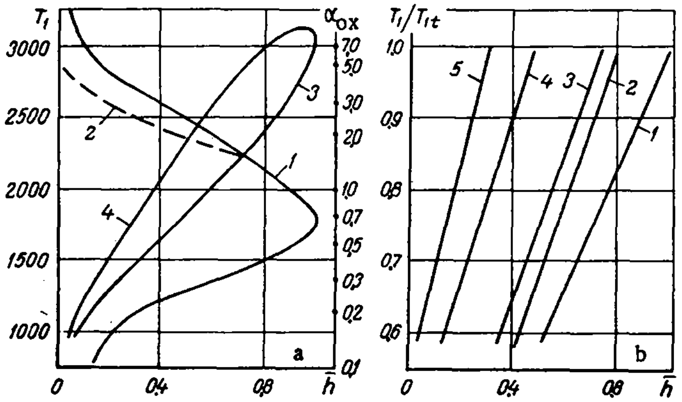

Fig. 1. Dependence of temperature T_1 and composition α_{ox} of a stream of combustion products on relative decrease $\bar{h}$ of plate height: a) equilibrium composition: 1) α_{ox}; 2) α_{ox} with allowance for nonequilibrium of processes in chamber; T_1 for: 3) $\alpha_{ox} < 0.7$; 4) $\alpha_{ox} > 0.7$; b) nonequilibrium composition for: 1) $\alpha_{ox} = 0.7$; 2) 0.5; 3) 1.5; 4) 0.3; 5) 5.0. $\bar{h}$ and α_{ox}: dimensionless quantities; T_1, °K.

Equation (1) connects the mass rate of removal of the plate material (from a unit area) with the temperature of its surface. This equation is valid for a quasisteady mode of destruction in the case of a one-dimensional heat distribution in the material of the plate, neglecting heat emission from its surface and the variability of the properties of the plate material during the heating period.

Equation (2) determines the condition of heat balance at the surface being destroyed, under the assumption that the rate of removal of plate material equals the flow rate of the gaseous components being injected into the boundary layer, chemical interaction between the gaseous components and the oncoming stream is absent, and the injection effect is treated in a linear approximation.

Equation (3) determines the generalized coefficient of heat transfer between the oncoming subsonic stream and the plate in the vicinity of the leading critical point in the case of an impermeable surface as a function of the parameters of the gas stream and the geometrical size and temperature of the plate surface, while Eq. (4) is an approximate dependence for the injection coefficient.

The decrease in the plate height (5) is determined by the rate of removal of material and by the time the plate is in the stream.

In solving the system of equations (1)-(5) we took the thermophysical properties of polymethyl methacrylate in accordance with [7] and the thermodynamic and thermophysical properties of the combustion products from the data of [8]. The calculation was made for the following conditions, allowing us to close the system of equations: the composition and temperature of the combustion products correspond to the equilibrium values; the composition of the combustion products does not change inside the boundary layer at the plate; the flow density is distributed uniformly over the stream cross section.

The system of equations (1)-(5) was solved numerically in the range of maximum removal rates of (2.6-5.2) mm/sec. The results of the calculation showed that in this range one can, with an accuracy no worse than 1%, replace the removal rate by the relative value of the decrease in the linear dimensions of the plate. This allows one to considerably simplify the treatment of the experimental results, using graphic functions obtained from the calculated results and presented in Fig. 1a.

In the case when the temperature of the combustion products in the local volume under consideration does not correspond to the equilibrium temperature for the given composition, the rate of removal of plate material decreases both due to the decrease in enthalpy (and temperature) of the oncoming stream and due to a decrease in the general coefficient of heat

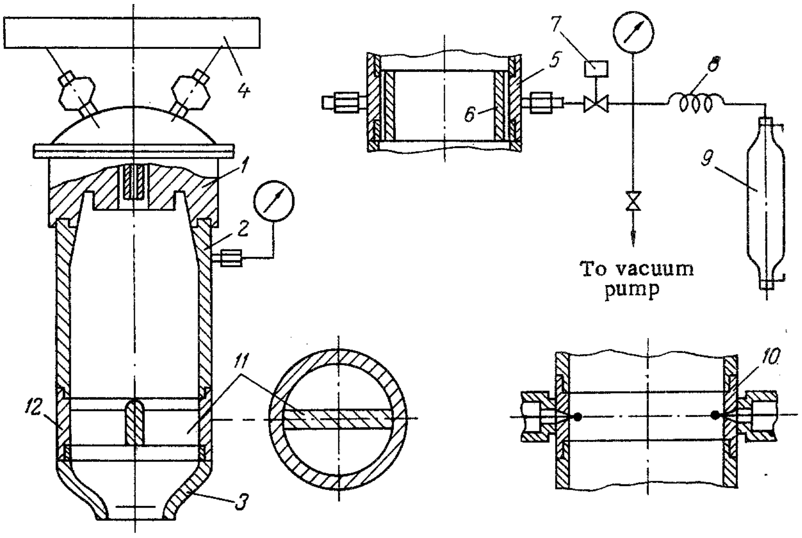

Fig. 2. Diagram of experimental installation.

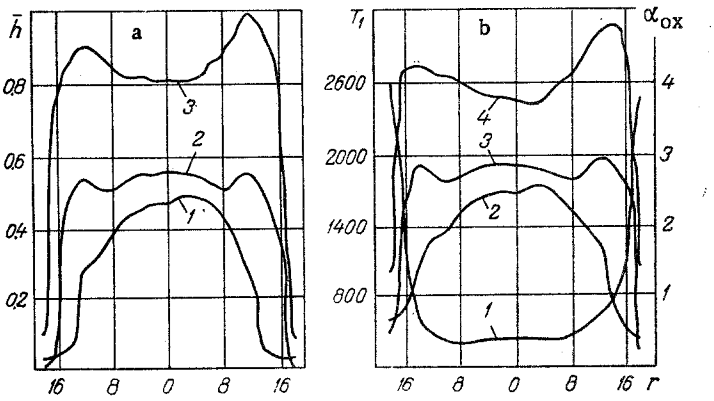

Fig. 3. Experimental profiles of the relative decrease $\bar{h}$ in plate height (a) and temperature T_1 and composition α_{ox} of combustion products (b) over radius r: for a: 1) l_{re} =0.4 m; 2) 0.6; 3) 1.5; for b: 1) α_{ox}; T_1 at: 2) l_{re} =0.4 m; 3) 0.6; 4) 1.5. r, mm.

transfer. The results of a calculation of the relative decrease in plate height as a function of the degree of decrease in the temperature of the combustion products are presented in Fig. 1b.

The proposed method was tested in a determination of the parameters of combustion products in a model gas generator. For this we created an experimental installation, a diagram of which is given in Fig. 2. Its principal elements were a gas generator with a sprayer head 1, an interchangeable cylindrical combustion chamber 2, and a nozzle 3; a fuel-supply system 4; a system for taking samples of combustion products from the boundary layer, consisting of an insert 5 and a bushing 6 separating the boundary from the core of the stream, an electrical valve 7, a coil 8 for cooling the sample, and a pipette 9 for taking the sample; a system for measuring the temperatures with Chromel—Alumel thermocouples, for the placement of which an insert 10 was used. An insert 12, interchangeable with the inserts 5 and 10, was used to install the plate of polymethyl methacrylate 11 in the stream of combustion products. In the course of the experiments we determined the values of the flow-rate complex and of the coefficient of completeness of the flow-rate complex, which characterize the completeness of fuel combustion [9]. The experiments were conducted with different reduced lengths l_{re} of the combustion chamber, which, as is known, characterizes the time of stay of the fuel and the completeness of its combustion in the gas generator.

Practically complete fuel combustion was assured with a reduced length of the combustion chamber of the model generator on the order of 1.5 m. This made it possible to determine the experimental profiles of the temperature and composition of the combustion products using the curves presented in Fig. 1a.

TABLE 1. Comparison of Experimental Results Obtained by the Proposed Method with Results Obtained by Known Methods

l_{re}, m	T_1, °K		α_{ox}		φ_β	
	1	2	1	3	4	5
0.4	—	—	—	4.15	0.72	0.74
0.6	—	—	—	4.3	0.82	0.86
1.5	1000	1290	3.8	4.8	0.93	0.95

An estimate showed that the rms travel of individual moles of combustion products due to turbulent diffusion does not exceed 2.5 mm for this reduced length, which is explained by the relatively low level of turbulence in the combustion chamber (ε = 5-10% [10]). In this connection it can be assumed that the profile of the excess oxidant ratio remains practically constant at the scale of the combustion chamber (r_c = 18 mm). This allowed us to obtain the temperature profiles for smaller reduced lengths of the combustion chambers and incomplete heat release in them, using the curves of Fig. 1b.

Experimentally determined profiles of the relative decrease in the heights of plates placed in combustion chambers of different lengths are shown in Fig. 3a as an example, while profiles of temperature and of the excess oxidant ratio obtained by the expounded method are presented in Fig. 3b.

In Table 1 we present the results of a determination of the temperature and composition of the combustion products in the boundary layer as the "coolest" and relatively easily subjected to experimental investigation, obtained using the method suggested in the present report (col. 1), as well as the results of a measurement of the temperature with thermocouples (col. 2) and a determination of the composition using chemical analysis (col. 3). A comparison shows the satisfactory agreement of these results. The profiles of the temperature $T_1(r)$ and of the excess oxidant ratio α_{ox} allow one to estimate the coefficient of completeness of the flow-rate complex (col. 4) and compare it with that determined experimentally from the flow rate of the components and the pressure in the combustion chamber of the model gas generator (col. 5). The results of such a comparison, presented in the table, are also in satisfactory agreement.

From these experimental data it is seen that the given method can be used to obtain operational information on the profiles of temperature and composition of complicated configuration in the form of continuous functions of the coordinate of the high-temperature stream.

NOTATION

B, preexponential factor in equation for the reaction rate constant of the thermal decomposition of the plate material; E and Q, activation energy and thermal effect of the reaction; R, universal gas constant; I, enthalpy; ρ, λ, and c, density, coefficient of thermal conductivity, and heat capacity of plate material; T_w and T_0, surface temperature and initial temperature of plate; m, mass rate of removal of plate material from a unit surface; q_0, specific heat flux; $(\alpha/c_p)_0$, generalized coefficient of heat transfer in the case of an impermeable surface; Pr, Prandtl number; η, coefficient of dynamic viscosity; μ_1 and μ_w, molecular weights of oncoming stream and of the product of decomposition of plate material, respectively; u, velocity; $\bar{h} = h/h_{max}$, relative decrease in plate height; h and h_{max}, current (at a given radius) and maximum values of decrease in plate height; l_{re}, reduced length of combustion chamber; r, radius; α_{ox}, excess oxidant ratio; ε, degree of turbulence; φ_β, coefficient of completeness of flow-rate complex. Indices 1 and w mean that the stream parameters are taken either at the temperature T_1 of the oncoming stream or at the plate surface temperature T_w; t, theoretical (equilibrium) value of parameter.

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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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