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HIGH-TEMPERATURE RADIATIVE-CONVECTIVE HEAT EXCHANGE ON THE SURFACE OF GLASS-REINFORCED PLASTICS

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The results of experimental investigations of heat exchange on the surface of a thermal-protective material — glass-reinforced plastic — in the flows of high-temperature gases have been presented. It has been established that the influence of injection on the value of the heat flux does not exceed 10% in the range of variation of gas temperatures 300–2000 K and Reynolds numbers 350–9800.

Introduction. In analyzing heat exchange on the surface of polymer composite thermal-protective materials (for example, glass-reinforced plastics and carbon-filled plastics) in high-temperature gas flows, one mainly employs a theoretical apparatus presented as early as in [1, 2]. At the same time, the published results of experimental investigations of the regularities of heat exchange on the surface of thermal-protective materials undergoing substantial physicochemical transformations in intense heating are relatively few in number. This work seeks to experimentally investigate heat exchange on the surface of thermal-protective materials using glass-reinforced plastics as an example.

Procedure of Experimental Investigations. Experiments with specimens of glass-reinforced plastic and with those of indestructible materials into which heat-flux transducers were built have been conducted to determine the value of the heat flux to the surface of a thermal-protective material [3]. The basis for the procedure of experimental investigations is the method of an auxiliary wall [4] with a capacitive heat meter (calorimeter) whose diagram is shown in Fig. 1.

The sensitive element 1 of diameter 10 mm and thickness 1.2 mm was manufactured from red copper or brass. A Chromel-Alumel thermocouple 2 whose electrodes were brought out to the oscilloscope via the electrical insulating tube 3 was caulked-in at the center of the element at a depth of 0.5 mm from the surface heated. The element was fixed in the asbestos-cement holder 4. The employment of a good heat insulator — asbestos cement — led to a minimization of the heat loss by the calorimeter in measurements. Asbestos cement is also a good dielectric, which substantially reduces the measurement error due to the presence of external electric fields [5]. The holder was fixed in the metal casing 5, which was installed in any cross section of the specimen's surface (on which the heat flux was measured) with the use of a threaded connection. The copper plate employed in the heat-flux transducer was manufactured 1.2 mm thick and was rolled to the profile of the glass-reinforced-plastic tube. With a length of the circle of the internal tube channel of more than 93 mm, the inhomogeneities in the relief of the surface at the "transducer–tube" interface were less than 0.2 mm and did not introduce substantial errors into the readings of the transducer. We conducted special experiments with different scales of roughness at the boundary between the transducer and the lateral surface of the tube. With a change from 0.1 to 0.3 mm in the roughness height the variations in the value of the heat flux did not exceed 12%. Unlike the well-known procedure [6], we employed an air gap the heat loss in which amounted to less than 4% as the heat insulator of the surface unheated by the gas flow.

In the adiabatic regime, such a heat meter totally absorbs the heat flux incident on it. The temperature at each of its points is linearly dependent on time. Under the conditions of the conducted experiments, we measured the temperature $T(t)$ at a fixed point of the sensitive element. The adiabaticity condition failed and we computed the quantity

$$q_{\mathrm{e}}(t) = c\rho L \frac{\partial T}{\partial t} . \tag{1}$$

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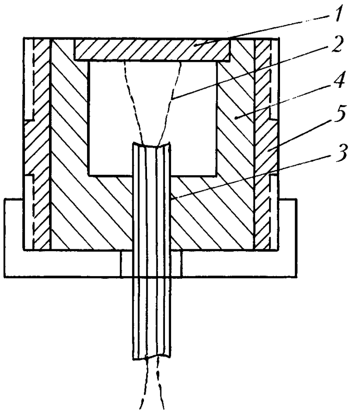


Fig. 1. Basic diagram of the capacitive heat meter (calorimeter).

as the measured heat flux $q_e(t)$.

It is well known [7] that we can employ the following expression for the heat flux when $\mathrm{Bi} \le 1$:

$$q(t) = q_e(t) + \frac{\alpha_{\grave{o}}}{c\rho L} \int_0^t q_e(t)\, dt\,. \tag{2}$$

In this case the absolute error of measurement of the heat flux can be evaluated from the formula

$$\Delta q(t) = q(t) - q_e(t) = \frac{\alpha_h}{c\rho L} \int_0^t q_e(t)\, dt\,. \tag{3}$$

The transient characteristic of such a calorimeter is determined as

$$\Delta q(t) = q(t)\, K \exp(-t/\varepsilon)\,, \tag{4}$$

where

$$K = \frac{1 + (1 - x/L)\,\mathrm{Bi}}{1 + \mathrm{Bi}/3}\,;$$

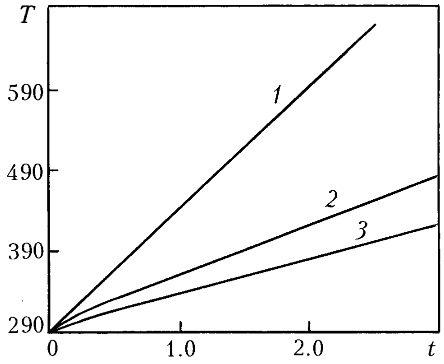
$$\varepsilon = \frac{L^2}{a}\left(\frac{1}{3} + \frac{1}{\mathrm{Bi}}\right). \tag{5}$$

The limiting time $t_{\max}$ for which the relative error $\delta q_e(t)$ does not exceed the prescribed value of δ_0 is

$$t_{\max} = t_{\min} \ln \frac{K}{1 - \delta_0}\,. \tag{6}$$

The quantities $t_{\max}$ and the exact values obtained by solution of the heat-conduction equation have been compared in [4]. It has been established ([4]) that expression (6) is in good agreement with the exact solution for $t > t_{\min}$. Consequently, it is most rational to employ such a calorimeter with the smallest prescribed relative error δ_0 in the time interval

$$t_{\min} < t < t_{\max}\,. \tag{7}$$



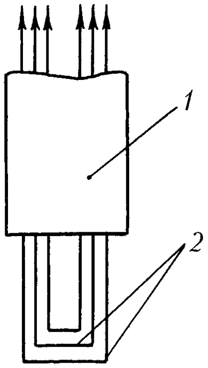


Fig. 2. Typical oscillogram of readings of the heat-flux transducers for three cross sections along the length of an asbestos-cement plate: 1) $x = 10^{-3}$; 2) $5 \cdot 10^{-3}$; 3) $9 \cdot 10^{-3}$ m. T, K; t, sec.

Fig. 3. Basic diagram of the probe for measuring the gas-flow temperature: 1) probe; 2) thermocouples.

If the calorimeter is in the horizontal plane, the influence of free convection is insignificant and the value of Bi is about 10^{-4}. Then the limiting time $t_{\max}$ for the calorimeter described above is equal to 2.0–2.5 sec when $\delta_0 = 0.1$.

Figure 2 gives a typical oscillogram of recording of the readings of the transducers installed in the asbestos-cement plate at three cross sections along its length. The initial portion of heating of the calorimeters $t_{\min}$ for a variable rate of heating is clearly defined; therefore, in processing experimental data, the value of $t_{\min}$ was subsequently taken from the oscillograms and did not exceed 1.5 sec. Accordingly, inequality (7) had the form $1.5 < t < 2.5$ sec for $L = 1.2 \cdot 10^{-3}$ m and $\delta_0 = 0.1$ for the calorimeter employed in the experiments.

In calculations of the value of the heat-exchange coefficient α from the experimental data on the cross sections (in which the calorimeters were installed) along the plate, we employed the formula [7]

$$\alpha(t) = -\rho c L \frac{d \ln (T_g - T_s)}{dt} . \tag{8}$$

for $\mathrm{Bi} \le 0.1$.

The above expression for α can be employed in accordance with the proposition of [7] only for small Bi, i.e., the values of the heat-transfer coefficient must not exceed $3 \cdot 10^3$ W/(m$^2 \cdot$K) for the copper calorimeters in question.

The temperature of the gas flow was measured with probes (Fig. 3). The time constant of the thermocouples of these probes did not exceed 0.1 sec.

We evaluated the error of measurement of the temperature due to the heat loss by the radiant heat exchange of the flow with the ambient medium, for which purpose we employed the expression [8]

$$\Delta T = \frac{\sigma \varepsilon_T}{\alpha} (T_h^4 - T_w^4) . \tag{9}$$

The temperature of the gas flow with account for (9) was determined from the formula

$$T_g = T_h + \Delta T . \tag{10}$$

We determined the quantities α and T_g by the successive approximation method with the use of (8)–(10) and the measured values of the temperature of the heat absorber (carbon rod). The procedure described above was used for calculation (from the data of calorimetric measurements) of the values of the heat fluxes and the heat-transfer coefficients for the polymer materials studied in the period of heating until the temperature of the beginning of decomposition of the binder was attained (as long as the composite acted as an inert material).

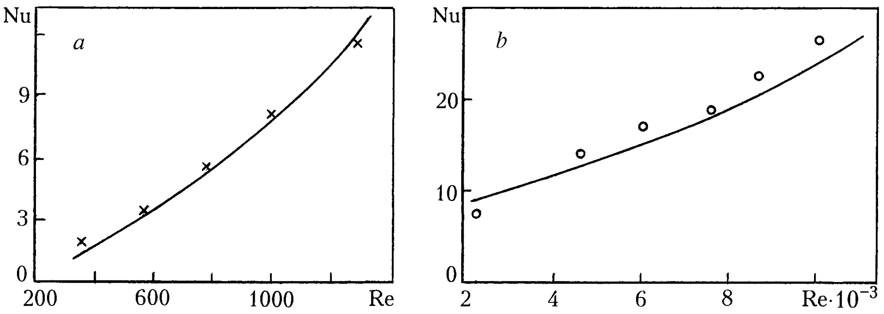


Fig. 4. Results of experimental investigations of heat exchange in the case of tube flow of a gas for the laminar (a) and turbulent (b) regimes of flow.

In the course of the experiments, we used a propane–oxygen burner to produce high-enthalpy flows. This device enabled us to vary the radiative component of the heat flux by changing the proportions of the fuel and the oxidant in the flame. Thus, by increasing the proportion of the fuel in the mixture, one can vary the flame temperature and accordingly the radiative component of the total flux in a certain range. The radiant component of the heat flux was determined experimentally with the use of the calorimeter described above. For this purpose, the surface of the sensitive element was covered with an optically transparent material — quartz glass — to exclude the influence of the convective heat flux on the transducer's readings. The emission spectrum of the propane–oxygen flame lies in the visible and near-infrared regions (1.5–2 μm). Therefore, as the experiments have shown, one can employ not only quartz glass but also ordinary glass to determine the radiant component of the heat flux.

In the course of the experiments, the radiant component and the total flux were determined successively with the use of transducers covered with quartz glass and without it. A comparison of the measured values of these fluxes has shown that the contribution of the radiative component does not exceed 15% with a change from 10^5 to $4 \cdot 10^5$ W/m^2 in q_e.

Results of the Experiments and Their Discussion. Experimental investigations of high-temperature heat exchange in heating of glass-reinforced plastic by a gas flow were carried out in two steps. In the first step, they were carried out with specimens manufactured from materials that are not destroyed under experimental conditions, i.e., from metals. The heat-flux transducers were installed in the specimens in the form of steel tubes of length 0.3 m and inside diameter 0.03 m; the interior surface of the tubes was heated by a high-temperature heat flux.

One end of the tube was located at a distance of two diameters from the exit section of the nozzle of a high-temperature generator. The heat-flux transducers were installed at different distances from the front end of the tube. The gas velocity in the cross sections corresponding to certain transducers was calculated from the rate of flow of the gas at the tube inlet.

We also employed air-plasma-based gas generators in the experiments. The character of flow in the tube depended on the type of gas generator. The experiments have shown that the propane-oxygen flame is characterized by a laminar regime of tube flow, whereas the air plasma is characterized by a turbulent regime.

To represent experimental data in the form of generalized dependences of the type of [9] we selected the expression [10]

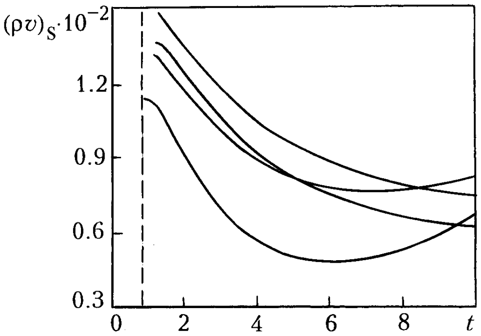
$$\mathrm{Nu} = 0.332\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.3} \tag{11}$$

for the laminar flow and the expression

$$\mathrm{Nu} = 0.022\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\left(1 + \frac{k-1}{2}\,\mathrm{M}^2\right)^{0.42} \tag{12}$$

for the turbulent flow.

Under experimental conditions, the Prandtl number was equal to 0.64 for the propane–oxygen flame and to 0.78 for the air-plasma jet. The Re numbers changed in the experiments from 350 to 1500 for the flame and from



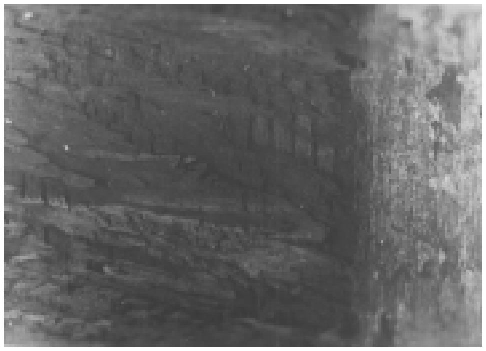


Fig. 5. Experimental dependences of the mass rate of injection on the time for four different investigated glass-reinforced plastics (the dashed curve corresponds to the time of the beginning of the loss in the specimens' mass). $(\rho v)_s$, kg/(m^2·sec), t, sec.

Fig. 6. Typical fragment of the glass-reinforced-plastic specimen after the experiment.

2100 to 9800 for the plasma. The temperature of the flame changed from 1700 to 2800 K, whereas the temperature of the plasma changed from 2700 to 3300 K. The experimental results were processed in accordance with general recommendations [11]. For a reliability of 0.95, the confidence intervals of determination of the basic functions sought did not exceed 9% for a number of experiments for each level of variation of the factors of no less than seven.

Dependences (11) and (12) were employed for computation of the heat-transfer coefficients α. Figure 4 gives results of the experiments in the case of flow over the tube surface for the laminar and turbulent regimes of flow. The results of these experiments were basic for determination of the value of the heat flux to the surface of a polymer composite material — glass-reinforced plastic — on whose surface and thin near-surface layer a number of physicochemical transformations occur [1, 12]. Injection of the gaseous products of the thermal decomposition of the polymer binder into the wall region is known [13] to be one of the most significant resulting processes exerting a direct influence on heat exchange.

Experiments have been conducted with glass-reinforced-plastic specimens in the form of tubes identical to steel tubes in dimension. The velocity of mass removal $(\rho v)_s$, averaged over the specimen length and characterizing the intensity of injection into the wall region, was additionally determined in these experiments [13]. This quantity was determined by the gravimetric method [14]. Results of experimental investigations for four glass-reinforced plastics differing in the grades of reinforcing fibers and binders are presented in Fig. 5. Experiments with a group of materials of the same kind have been conducted to evaluate the intensity of flow rate of the gaseous products of thermal decomposition of different binders. The range of variation of the quantity $(\rho v)_s$ for each instant of experimental time has been singled out and the identical character of the dependence of the velocity of mass removal on time has been established for four different glass-reinforced plastics. It should be noted that the inspection of the specimens after the experiments and observation in the process of the experiments allowed the conclusion on the absence of any signs of thermomechanical destruction (analogous to [12]) of the materials investigated in the covered range of variation of the parameters. Therefore, the process of destruction of the investigated typical glass-reinforced plastics can be assumed to be purely thermochemical. We did not perform a special analysis of the features of the mechanism of removal of mass of each material, since the differences in removal velocities were insignificant (at least, for three materials) and these differences were most likely attributed to the purely thermochemical features of the processes of thermal decomposition of the binder. And their analysis requires special investigation of another character. Furthermore, the results of the experiments (Fig. 5) show that at times longer than 8 sec, the difference in the velocities of removal of mass for the four materials becomes comparable to the experimental error and it is impossible to analyze the reasons for the differences in these velocities. Figure 6 is a photograph of a typical fragment of a specimen after the experiment in an air-plasma flow for 8 sec; in the photograph, it is seen that the front of thermal decomposition of the glass-reinforced plastic has penetrated to a fairly large depth substantially exceeding the glass-fiber thickness over this period. The fibers of both direct and transverse winding [20] are open, since the decomposition of the binder at a depth equal to

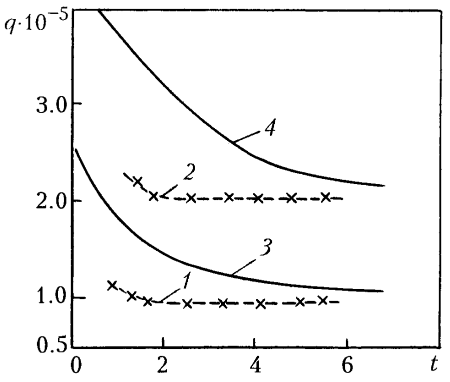


Fig. 7. Experimental and calculated dependences of the values of the heat flux of the glass-reinforced plastic investigated: 1 and 2) experiment; 3 and 4) calculation; 1 and 3) $x = 9{\cdot}10^{-3}$; 2 and 4) 10^{-3} m. q, W/m^2; t, sec.

the glass-fiber thickness has been completed. Furthermore, traces of fusion and deformation of the fibers are clearly seen. Since the fusion temperature of the glass fibers is much lower than the temperature of the air plasma, the duration of the experiment is fairly long, and the thermal conductivities of the glass-reinforced plastics are relatively small [20], the layer of material near the surface is heated to temperatures exceeding the temperature of fusion of glass filaments. The fibers fused are deformed under the action of the friction stresses of the plasma flow passing in parallel to the heated surface. The traces of these local deformations are seen in the photograph. The relief of the composite surface, which is inhomogeneous over the area (shown in the photograph) is, apparently, determined by the inhomogeneity of the initial structure of the glass-reinforced plastic (by the presence of the fibers of direct and transverse winding the space between which is filled with the binder in the initial state). The results obtained (Fig. 6) allow the conclusion that in the experiments conducted, the glass-reinforced plastic undergoes substantial physicochemical transformations.

Figure 7 gives experimental data on the value of the heat flux to the glass-reinforced-plastic surface; the data have been obtained under conditions identical to those of the experiments with steel tubes for two cross sections of a specimen along the length.

We evaluated the influence of the nonstationarity of the process of heat exchange on the value of the heat flux measured in the experiment by comparing the experimental values of q_e and the results of numerical solution of the heat-conduction equation for glass-reinforced plastic under thermal-action conditions adequate to the experiment. We employed a mathematical model totally adequate to [15] and the finite-difference method [16] showing a good performance in solution of fairly complicated problems of heat transfer in composite materials (for example, [17, 18]).

Figure 7 also gives results of a comparison of the experimental and calculated values of q for the glass-reinforced plastic investigated. Satisfactory (within 20% at times longer than 4 sec) agreement is seen between the numerical calculations and the experimental data. The heat flux to the composite surface decreases with time due to the growth in the surface temperature, asymptotically approaching a stationary value. Variations in the experimental and calculated values of q can be due to both certain errors of the experiment and errors in the tabular values of the thermophysical characteristics of the glass-reinforced plastic. Based on the comparison of the results in Fig. 7 we can draw the conclusion that the reliability of the calorimetric method of determination of the value of the heat flux to the glass-reinforced-plastic surface employed in the experiments in question is good.

It is well known that the injection of the gaseous products of thermal decomposition, evaporation, or sublimation of thermal-protective materials into the wall region leads, as a rule, to a substantial reduction in the value of the total heat flux to the heated surface [1]. Analogous regularities also manifest themselves, for example, in destruction of meteoroids in the earth's atmosphere [19]. Therefore, we have performed a special analysis of the influence of the gaseous products of the glass-reinforced plastics investigated in the surface layer of the external high-temperature flow on the value of the heat flux to the heated surface.

The calculations of the injection parameters for the entire range of variation of the Re and Pr numbers, which was attained in the experiments conducted, have shown that the quantity β does not exceed 0.15.

Employing the well-known [2] expression for the dependence of the relative heat flux to the surface of the heated channel $q/q_0 = 1 - 0.67\beta$, based on the results obtained we can infer that the injection of the gaseous products of the thermal decomposition of the polymer binder of glass-reinforced plastics reduces the value of the heat flux to the surface by no more than 10%.

We note that some of the results presented have been obtained for regimes corresponding to heat exchange in the case of fires [20]. Consequently, we can also draw a conclusion on the possibility of employing expressions (11) and (12) in analysis of heat exchange under the action of high-temperature gas flows on polymer composite materials under the conditions of fires.

It should be emphasized that both the thermophysical and thermokinetic characteristics not only of polymer composites but also of many other thermal-protective materials are determined with errors no less than 12% [21], as a rule, in connection with the special properties of the structure and technology of manufacture of composites and thermal-protective materials. For these reasons, the scale of influence of injection on the intensity of heat exchange in the case of flow about decomposing glass-reinforced plastics is comparable to the scale of the errors of determination of the basic characteristics of materials required for calculation of the process of decomposition and accordingly injection. Consequently, it will be legitimate to employ heat-exchange models of the type (11) and (12), obtained for conditions of the absence of injection, in analyzing the processes of heat-exchange on the surface of glass-reinforced plastics.

CONCLUSIONS

We have experimentally investigated heat exchange on the surface of typical thermal-protection materials — glass-reinforced plastics — in the flows of high-temperature chemically active gases, passing in parallel to the heated surface. The experimental data obtained characterize not only heat exchange on the surface of glass-reinforced plastics undergoing intense physicochemical transformations in high-temperature heating. They can also be employed in further development and evaluation tests of the models [1, 15] widely used in modeling of heat and mass transfer in glass-reinforced plastics at high temperatures.

Also, the results of the work show that the heat-exchange models formulated in [9, 10] satisfactorily describe heat transfer under the conditions of moderate injection from the heated surface.

NOTATION

L, thickness of element, m; c, specific heat, J/(kg·K); ρ, density, kg/m^3; t, time, sec; α_T, coefficient of heat transfer on the rear side of the measuring element with an air gap, W/(m^2·K); x, depth of embedment of the thermocouples, m; T, temperature, K; T_g, gas-flow temperature, K; T_s, calorimetric temperature, K; Bi, Nu, Re, Pr, and M, Biot, Nusselt, Reynolds, Prandtl, and Mach numbers respectively; k, adiabatic exponent; δ, Stefan–Boltzmann constant, W/(m^2·K^4); ε_T, emissivity factor of the carbon rod; T_h, heat-absorber temperature, K; T_w, wall temperature, K; q, heat flux, W/m^2; a, thermal diffusivity, m^2/sec; $(\rho v)_\mathrm{s}$, velocity of mass removal from the glass-reinforced-plastic surface, kg/(m^2·sec); β, injection parameter; q_0, heat flux to the indestructible surface, W/m^2; α, coefficient of heat transfer on the heated surface, W/(m^2·K); δ_0, prescribed value of the relative error of determination of the heat flux. Subscripts: e, experiment, 0, initial; min, minimum; max, maximum; h, heat (thermal); g, gas; w, wall; s, surface.

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