USE OF ABLATION EXPERIMENTS TO DETERMINE HIGH-TEMPERATURE PROPERTIES OF FUSED QUARTZ

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By comparing the data of experiments with calculated heating and ablation, the authors have determined the viscosity and absorption coefficient of fused quartz at a temperature of about 2700°K.

In spite of the considerable number of sources in the literature on the properties of fuzed quartz, there has been a marked lack of data until now on the thermal conductivity, viscosity, and optical properties of this material and of quartz-based composite materials at temperatures above 2000°K. Because of the considerable difficulties in direct measurement of the properties at such temperatures, it is expedient for this purpose to use ablation experiments. This approach was first used in [1] to determine the thermal conductivity and the viscosity of fused quartz, based on a theoretical analysis of the ablation process, as applied to the experimental data of [2]. However, the results then obtained raise doubts from the viewpoint of contemporary ideas on the thermophysical properties of this material. In the present work we analyze possible reasons for this disagreement, and show results of a theoretical investigation of the ablation process in fused quartz, conducted using improved data on its thermophysical properties, allowing for partial transparency of the material with respect to thermal radiation.

Our statement of the problem of heating and ablation of fused quartz glass, as employed in the present analysis, differs from that in [1, 3] basically only in regard to added consideration of radiative heat transfer in the internal layers of the material. In our case, as was done in [4], to solve the radiative transfer equation we use one of the modifications of the moment method.

As an example, in this study we have analyzed the results of the same tests of [2] on ablation from optically transparent quartz in the jet of an electric arc facility, as was done in [1]. The test conditions, employed in the calculations, and the experimentally measured quasistationary parameters for ablation are as follows (the stagnation enthalpy of the gas stream in [2] was determined by calculation from the Fay–Riddell formula [5]): $r = 8.636$ mm; $p = 0.13$ bar; $h_{00} = 18.821$ MJ/kg; $\alpha_0 = 0.47$ kg/m^2·sec; $d = 2100$ m/sec; $T_w = 2700$°K; $G_\infty = 0.6236$ kg/m^2·sec; $\varepsilon_\Sigma = 0.1$.

The data used in the calculations on the specific heat and molecular thermal conductivity of fused quartz are shown in Fig. 1. The material density was taken to be 2250 kg/m^3 [1].

In regard to the viscosity of fused silicon dioxide, one should note the considerable scatter of the data of different authors (see, e.g., [13]). The most satisfactory approach in practice is to use, for the coefficients η_0 and A appearing in the relation

$$\eta = \eta_0^{-1} \exp(A/T), \text{ Pa·sec}, \tag{1}$$

values of the quantities recommended in [2]:

$$\ln \eta_0 = 22.315, \quad A = 68800 \text{ K}. \tag{2}$$

The refractive index of fused quartz was taken as 1.5, and the material surface was assumed to be specular. Experimental data on the absorption coefficient of fused quartz are mainly limited to a temperature of ~ 1700°K [14, 15]. Analysis of preliminary calculations indicates that propagating these data to the high-temperature region leads to a smaller calculated value of ε_Σ compared with the experimentally measured value, by about an

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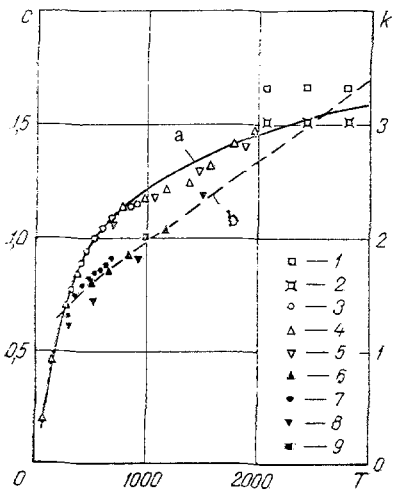

Fig. 1

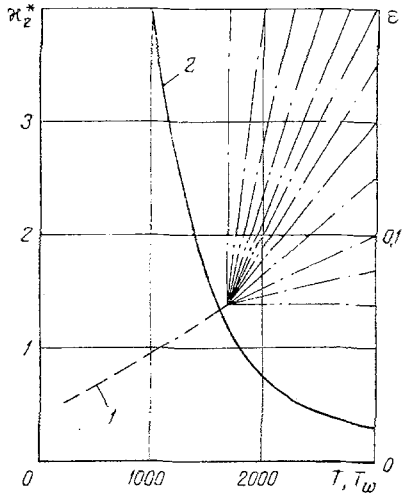

Fig. 2

Fig. 1. Literature values of the thermal conductivity of fused quartz (c is in kJ/kg; k is in W/m·K): 1-5) c; 6-9) k; 1) [6]; 2) [7]; 3, 7) [8]; 4) [9]; 5) [10]; 6) [11]; 8) 12; 9) [2]; a, b) used in calculating the dependence c(T) and k(T).

Fig. 2. Dependences $\kappa_2^*(T)$ and $\varepsilon(T_w)$ used in the calculations (κ_2^* is in m^{-1}; T is in °K): 1) $\kappa_2^*(T)$; 2) $\varepsilon(T_w)$.

order of magnitude. This is evidence of a decisive contribution of the high-temperature branch of the dependence $\kappa(\lambda, T)$ in determining the emissivity of the material, and indicates, that in principle, one could determine the high-temperature optical properties from results of experiments of the type analyzed. To solve this problem qualitatively, of course, one needs information on the spectral structure of the parameter ε_Σ for a number of values of temperature of the hot material surface. From analysis of a single group of experiments of this type one can only determine the level of the absorption coefficient for high temperatures. In pursuing this objective, in the calculations we used a very simple optical scheme for the material, characterized by a finite value κ^* of the absorption coefficient within the spectral interval 0.25-4.5 μm, and an infinitely large value outside this interval (the corresponding dependence $\varepsilon(T_w)$ is shown in Fig. 2). Up to a temperature of 1673°K in the calculations we used averaged data of [14, 15] (see Fig. 2), and the high-temperature branch of the dependence $\kappa^*(T)$ was assumed to have the form

$$\varkappa^*(T) = \varkappa_1^* + (\varkappa_2^* - \varkappa_1^*)(T - 1673)/1600, \quad \varkappa_1^* = \varkappa^*(1673) = 1.4 \text{ m}^{-1}, \quad \varkappa_2^* = \varkappa^*(3273), \quad T \geqslant 1673 \text{ K}, \qquad (3)$$

shown arbitrarily in Fig. 2 by the fan of broken lines corresponding to various values of the parameter κ_2^*.

As characteristics of the material to be determined by comparing the theoretical and experimental data on ablation from fused quartz, we consider the parameters η_0 and κ_2^*. For the coefficient A we used the same value as in Eq. (2).

A positive feature of these calculations is the high stability of the surface temperature T_w observed for quite a wide variation of the parameters η_0 and κ_2^*. The maximum scatter of its values did not exceed 1% (T_w = 2670-2700°K), and the agreement between theory and experiment here is entirely satisfactory.

Figure 3 shows the results of determining the coefficients η_0 and κ_2^* by comparing theoretical and experimental data on the quantities G_∞ and ε_Σ. As can be clearly seen (see the arrows), the experimentally measured values of emissivity correspond to values of the parameters κ_2^* and $\ln \eta_0$, equal to 157 m^{-1} and 22.25.

The value thus obtained for the absorption coefficient of fused quartz at high temperatures agrees satisfactorily with the experimental data of [16] (for example, at T = 2400°K, the value of κ^* calculated from Eq. (3) is 72 m^{-1}, and, according to [16], in the spectral range 0.4-1.0 μm the absorption coefficient varies in the range 370-4 m^{-1}, being 72 m^{-1} at λ = 0.55 μm), and the above data on the viscosity of the melt are quite close to the values recommended in [2].

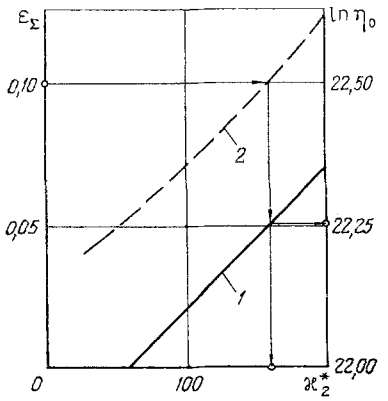

Fig. 3. Calculated dependences for $\ln \eta_0(\kappa_2^*)$ and $\varepsilon_\Sigma(\kappa_2^*)$, corresponding to a given material ablation rate (η_0, $N/m^2 \cdot sec$; κ_2^*, m^{-1}): 1) $\ln \eta_0(\kappa_2^*)$; 2) $\varepsilon_\Sigma(\kappa_2^*)$.

One should also note that the results of the present analysis confirm the fact established in [16] that there is a sharp fall in the transparency of fused quartz on increase of temperature in the high-temperature region.

One promising direction of investigations aimed at increasing the informativeness of experiments on mass transfer of the type considered here is to analyze the time t_{st} for the ablation process to reach quasisteady conditions. However, in analyzing the value of thermal conductivity obtained in [1], which achieves satisfactory agreement between theoretical and experimental values of t_{st}, one should note that values of k on the order of 12 W/m·K are of low probability in the light of the latest experimental data [11]. In turn, a difference in the values of thermal conductivity leads to a disagreement in the viscosity of the melt, as obtained in this work and in [1].

The results of our analysis of the experimental data of [2] on the parameter t_{st} show that the influence of internal radiative heat transfer in the material on the theoretical value of t_{st} is extremely small, and that in using the properties of the material as established above, the divergence between the calculated and experimental values of t_{st} becomes as large as about a factor of 2. The reason for this, as far as one can see, is that it is invalid to use, in the initial stage of heating of the material, the value of heat flux measured by a cooled copper calorimeter. The gas flow regime in the boundary layer when the tests of [2] were conducted is close to frozen, and in these conditions (e.g., see [17]), because of a difference in the degree of catalyticity of the surface, the heat fluxes supplied to the specimen of material and to the calorimeter can differ substantially. And, in turn, this is evidence that to improve the accuracy of the thermophysical properties of a material on the basis of an unsteady ablation experiment, one must first carefully study the specimen heating process in the initial stage of the experiment.

NOTATION

T, temperature; G_∞, mass rate of breakdown of the material; c, k, η, κ, specific heat, thermal conductivity, dynamic viscosity, and absorption coefficient of the material, respectively; α, heat-transfer coefficient; λ, wavelength of the radiation; h_{00}, stagnation enthalpy of the air stream; r, effective radius of the spherically blunted material surface; p, pressure in the boundary layer; τ_x, gradient of friction in the boundary layer in the vicinity of the stagnation point; d, coefficient of proportionality in the Reynolds analogy, equal to $\tau_{w,x} r/\alpha$; ε_Σ, ε, effective emissivity of the material surface, referenced, respectively, to the full spectral range, and to the spectral range of nontransparency of the material. The subscripts w and 0 refer to the heated and the nonpermeable surfaces of the material.

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INSTABILITY OF AQUEOUS SOLUTIONS OF POLYACRYLAMIDE IN A HYDRODYNAMIC FIELD

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This article discusses findings obtained regarding the effect of a hydrodynamic field on the reduced viscosity, effect of turbulent friction reduction, light scattering, double refraction, and optical density of aqueous solutions of hydrolyzed polyacrylamide.

The instability of polymer solutions during flow in a turbulent regime is an extremely undesirable phenomenon in regard to practical use of the solutions and is thus constantly a focus of investigators. To alleviate instability, it is necessary to determine the nature of the mechanisms responsible for it.

Several studies have examined the effect of different factors on lessening of the phenomenon of a reduction in hydrodynamic resistance as a function of the number of runs of a

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