FEATURES OF HEATING A CERAMIC SURFACE BY CONCENTRATED SOURCES

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The process of heating and natural cooling of a structural ceramic surface during interaction with a plasma-arc filament is investigated. A change is shown in the intensity of radiation with time. A method is proposed for computing the true temperatures by their color values and results of a computation are presented. The dependence of the surface temperature on the energetic parameters of the arc filament is investigated. The effect of choking the heat flux in the transition layer during an abrupt temperature rise is clarified.

The possibility of obtaining a plane surface of structural materials by fusing it by concentrated heat sources is given a foundation in [1]. A gas-discharge plasma is most applicable for this purpose. The reliability and longevity of the decorative surfaces obtained were confirmed during experimental and full-scale investigations. Fragments of building walls treated by a plasma in 1974 and a structure faced with silicate brick with a fused surface in 1978 have not lost their decorative qualities up to now. These facts confirm the authenticity of the deductions in [1] about the possibility of applying plasma treatment of structural materials and constructions.

At the present time, enormous scientific material has been accumulated in the area of low-temperature plasma and its interaction with a solid substance. Quite important here are investigations of the phase transitions and their accompanying physicochemical processes during the interaction.

The apparatus is described in [2, 3] and methods are described for investigating the dynamics of heating and cooling a ceramic brick surface during interaction with an axisymmetric arc filament of a plasmotron PS-1. By using the spectrometer ISM-4 and a mirror-galvanometer oscillograph the radiation intensities were recorded of the fused surface of a ceramic specimen in four wavelengths of the infrared spectrum range according to whose ratios the surface color temperatures were obtained. They differ from the true temperatures by the magnitude of the logarithm of the ratio between the spectrum radiation coefficients $\ln(\varepsilon_{\gamma_1}/\varepsilon_{\lambda_2})$. Computation of the true temperature by means of the expression

$$T^{-1} - T_c^{-1} = \frac{\Lambda}{c_2} \ln \frac{\varepsilon_{\lambda 1}}{\varepsilon_{\lambda 2}} \tag{1}$$

is not complicated. However, the authors of [2] did not have data on the coefficient $\varepsilon(\lambda, T)$ available, and color temperatures were determined and investigated therein.

The question posed in this paper is the investigation of the change in the true temperatures during heating and natural cooling of a ceramic brick surface.

The clay used for its fabrication is distinctive in its composition within broad ranges which does not permit having sufficient information about the change in the spectrum radiation coefficient as a function of the wavelength and temperature. This makes the investigation of the object heating and cooling dynamics difficult.

The method of multicolor temperature based on solution of the system of equations

$$T^{-1} - T_{1,2}^{-1} = \frac{\Lambda}{c_2} \ln \frac{\varepsilon_{\lambda 1}}{\varepsilon_{\lambda 2}}, \tag{2}$$

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$$T^{-1} - T_{2,3}^{-1} = \frac{\Lambda}{c_2} \ln \frac{\varepsilon_{\lambda 2}}{\varepsilon_{\lambda 3}},$$
$$T^{-1} - T_{3,4}^{-1} = \frac{\Lambda}{c_2} \ln \frac{\varepsilon_{\lambda 3}}{\varepsilon_{\lambda 4}}, \quad (2)$$

does not satisfy the problem formulated since the number of unknowns exceeds the quantity of equations in the system.

The authors of [4] proposed introducing the additional equality

$$\varepsilon(\lambda, T) = \varepsilon_{\lambda 1} - \sum_{n=1}^{n} \frac{\varepsilon^{(n)}}{n!} \Delta\lambda^{n-1}, \quad (3)$$

that represents expansion of the function $\varepsilon(\lambda, T)$ in a Taylor series in the wavelength λ into the system (2), which simplifies the problem somewhat.

The method of multicolor temperature is used to solve the formulated problem in the paper by expanding the coefficient $\varepsilon(\lambda, T)$ and by adding a correction to its steepness expressed by the ratio between the difference of the reciprocal color temperatures and the difference of their corresponding wavelengths. This method, proposed in [5], permits taking account of the change in the coefficient $\varepsilon(\lambda, T)$ in both the wavelength and in the temperature dependence.

Values of the color temperatures $T_{1,2}$, $T_{2,3}$, and $T_{3,4}$ at the wavelengths 0.96, 1.19, 1.56, 2.37 μm were given from the results in [2]. It is established here that $T_{1,2} \gg T_{2,3} > T_{3,4}$ (for instance, their value was 2940, 2220, and 2050 K, respectively, 2 msec after disconnecting the arc discharge). It follows from an analysis of (1) in application to the temperatures obtained that the coefficient is a decreasing function of the wavelength. This is confirmed by the data in [6] for the oxides SiO_2, Al_2O_3, CaO, Fe_2O_3 that comprise the specimens being investigated. Moreover, it is established by analyzing these data that the relationship is actually $\varepsilon_{\lambda_4} = \varepsilon_{\lambda_1}/2$ in the 0.96...2.37 μm spectrum range, and differs just in the third place.

Taking the above into account, we obtain expressions for the coefficient $\varepsilon(\lambda, T)$:

$$\varepsilon_{\lambda 1}, \quad \varepsilon_{\lambda 2} = \varepsilon_{\lambda 1} - \Delta\varepsilon = \varepsilon_{\lambda 1} - \frac{\varepsilon'_{\lambda 1}}{1!}(\lambda_2 - \lambda_1) - \frac{\varepsilon''_{\lambda 1}}{2!}(\lambda_2 - \lambda_1)^2,$$
$$\varepsilon_{\lambda 3}, \quad \varepsilon_{\lambda 4} = \frac{\varepsilon_{\lambda 1}}{2}. \quad (4)$$

However, such a relationship does not reflect the change in $\varepsilon(\lambda, T)$ totally since in this case the dependence on the wavelength is just expressed. At the same time, the relationship between the color temperatures $T_{1,2} \gg T_{2,3} > T_{3,4}$ or $T_{1,2} < T_{2,3} > T_{3,4}$ indicates the redistribution of the change in $\varepsilon(\lambda, T)$ in the spectrum bands $\lambda_1 \ldots \lambda_2$ or $\lambda_3 \ldots \lambda_4$ associated with the flow of the physicochemical processes.

The change in radiation intensity of a fused layer with time during its cooling down is shown in Fig. 1. Here, as in the relationship of the color temperatures, the change in $\varepsilon(\lambda, T)$ is expressed implicitly. To take it into account by the method of an approximate computation [5] a correction to the steepness of the curve

$$\operatorname{tg} \varphi = \frac{T_m^{-1} - T_n^{-1}}{\lambda_n - \lambda_m} \quad (5)$$

should be introduced, which is numerically equal to the ratio between the reciprocal color temperatures and the difference in the corresponding wavelengths.

Taking all the substitutions into account, the system (2) takes the form

$$T^{-1} - T_{1,2}^{-1} = \frac{\Lambda}{c_2} \ln \left(\frac{\varepsilon_{\lambda_1}}{\varepsilon_{\lambda_1} - \Delta\varepsilon} - \operatorname{tg} \varphi_1 \right), \quad (6)$$

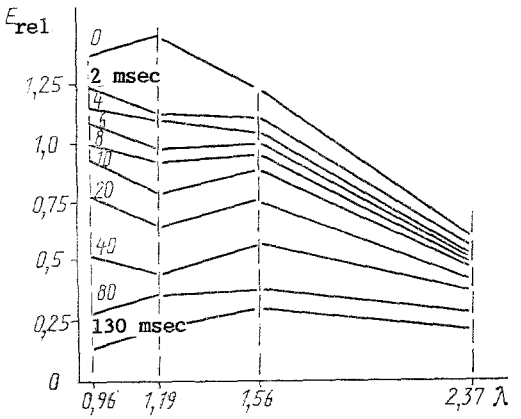

Fig. 1

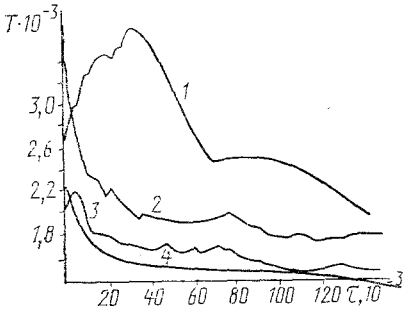

Fig. 2

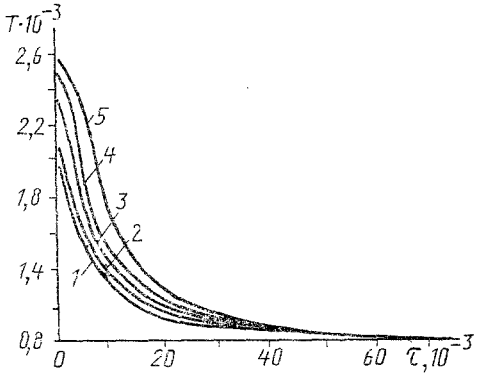

Fig. 3

Fig. 1. Change in the radiation intensity of a ceramic surface fused by plasma flux during the time from arc disconnection to 130 msec at the wavelengths 0.96, 1.19, 1.56 and 2.37 μm. λ, μm.

Fig. 2. Change in the color temperatures $T_{1,2}$ (1), $T_{2,3}$ (2), $T_{3,4}$ (3) and the computed true temperature T (4) under natural cooling. T, K; τ, sec.

Fig. 3. Dependence of the true temperature T on the discharge power and the cooling dynamics of a fused surface: 1) U = 185 V, I = 300 A; 2) 185 and 350; 3) 190 and 400; 4) 190 and 450; 5) 185 and 500.

$$T^{-1} - T_{2,3}^{-1} = \frac{\Lambda}{c_2} \ln\left(\frac{\varepsilon_{\lambda_1} - \Delta\varepsilon}{\varepsilon_{\lambda_3}} - \operatorname{tg}\varphi_2\right),$$
$$T^{-1} - T_{3,4}^{-1} = \frac{\Lambda}{c_2} \ln\left(\frac{2\varepsilon_{\lambda_3}}{\varepsilon_{\lambda_1}} - \operatorname{tg}\varphi_3\right) \qquad (6)$$

and permits performing a computation of the true temperature with up to 4% error.

It is established from the computation results that the maximal surface temperature recorded at the time of disconnecting the discharge depends on the discharge power and reaches 1900 K for a power of N = 50 kW, 2000 K for N = 60 kW, and 2200 K for N = 80 kW. The results obtained are in agreement with the results of a temperature computation in [7] according to the expression

$$\Theta = \frac{T_s - T_h}{T_s - T_0}. \qquad (7)$$

The relative excess temperature was found as a function of the Fourier number for different values of this number Fo from tables in [7].

On the basis of structural investigations performed in [1, 8] and data on the clay constitution [9], the heating and cooling dynamics for a ceramic specimen could be traced during its interaction with a plasma flux.

The behavior of the color and true temperatures of a fused surface after disconnection of a 100 kW power arc is shown in Fig. 2 from the results of the computation performed. The heating time, governed by the velocity of specimen motion relative to the arc filament at a 3-mm distance from its axis, was 10^{-2} sec. For a T_h = 9000 K [2] plasma temperature in this zone, the heating rate reached $5 \cdot 10^4$ K/sec, which is commensurate with a thermal shock.

Short-time heating of the surface causes it to melt an insignificant depth (up to $3 \cdot 10^{-4}$ m). The melt here is a porous inhomogeneous glass phase containing quartz and feldspar fused to a different degree depending on the grain size and melting point. Heat transfer between the plasma and the specimen is magnified because of convection in the liquid phase. The temperature gradient in the plasma boundary layer reaches $(6\text{-}7) \cdot 10^3$ K/mm. Evaporation of the melt and entrainment of the liquid phase are observed in parallel with this. The corroding action of the plasma on the layer being fused and the intensification of the gas liberation from its pores in the form of bubbles is explained by this. The processes of thermal dissociation and lowering of the melt viscosity contribute to their coarsening.

In addition, an abrupt reduction in the specimen heat conduction coefficient is assumed because of the rise in its temperature in the heating transient zone [10-12] at a rate reaching $3 \cdot 10^3$ W/m·K·sec, i.e., choking of the thermal flux deep in the specimen is observed, which protects it from deep heating and destruction. This can explain the fact that the specimen temperature at a 1-mm depth reaches the maximum at 400 K just 10-12 sec after beginning of the heating.

It is characteristic that the heating rate prior to the appearance of the melt diminishes by almost two orders when using low-temperature (up to 3000 K) sources (gas burner flame) for the heating, which contributes to deep through-heating and spoilage of the ceramic structure.

The fused surface temperature recorded at the time of arc disconnection can be considered maximal during the fusion process by taking account of the temperature inertia and the time of plasma dissociation. The most intensive cooling under natural conditions is observed in the first 10 msec (Fig. 3) since heat elimination in this time occurs because of convection, heat transmission, and radiation. As the temperature becomes lower the role of radiation is reduced and the cooling intensity is correspondingly reduced. The fused layer reaches the normal temperature after 7...8 min, which permits it to be packed safely.

The transition zone from the coating to a base of depth 20...60 μm is not expressed clearly and has darker tinge as compared with the base, as is explained by amorphization of the converted clayey component, the phase transitions, and the iron oxide transformations.

The surface fused during plasma interaction acquires a decorative form while the porous structure does not spoil the mechanical properties. The contact zone, represented by the smooth transition from the coating to the base with a constant smooth diminution in the amorphousized surface, contributes to the good adhesion and strength of the decorative layer.

The results of the investigations performed afford a possibility of selecting technological parameters of the plasma treatment process for structural ceramics in order to obtain a facial surface of decorative and protecting coatings thereon. Equipment and a fabrication technology have been developed on their basis for facial brick that is utilized successfully in industry.

NOTATION

T, $T_{1,2}$, $T_{2,3}$, $T_{3,4}$, true and color temperatures; λ, wavelength; c_2, radiation constant; Λ, equivalent wavelength; $\varepsilon(\lambda, T)$, spectrum radiation coefficient; ε_{λ_1}, ε_{λ_2}, ε_{λ_3}, ε_{λ_4}, spectrum radiation coefficients at the wavelengths λ_1, λ_2, λ_3, λ_4; Θ, relative excess temperature; T_s, temperature of the heated surface; T_0, initial surface temperature; T_h, temperature at a given distance from the surface; and Fo, Fourier number.

LITERATURE CITED

1. L. I. Kiselevskii, S. G. Korotkevich, A. K. Shipai, et al., Dokl. Akad. Nauk BSSR, 19, No. 5, 403-406 (1975).
2. A. I. Zolotovskii, V. D. Shimanovich, and A. K. Shipai, Inzh. Fiz. Zh., 42, No. 4, 604-608 (1982).
3. L. I. Kiselevskii, V. D. Shimanovich, A. K. Shipai, et al., Vestsi Akad. Nauk BSSR, Ser. Fiz.-Tekh. Navuk, No. 2, 82-86 (1986).
4. V. D. Shimanovich, B. M. Solov'ev, A. K. Shipai, et al., Proc. 4th All-Union Conf. on Physics and Generators of a Low-Temperature Plasma [in Russian], Alma-Ata (1970), pp. 209-213.
5. A. K. Shipai, Evolutionary Problems of Energy Transfer in Inhomogeneous Media [in Russian], Minsk (1982), pp. 134-139.
6. A. E. Sheindlin (ed.), Radiative Properties of Solids Materials (Handbook) [in Russian], Moscow (1974).
7. A. V. Lykov, Theory of Heat Conduction [in Russian], Moscow (1967).
8. N. I. Lipnitskaya, V. D. Shimanovich, A. K. Shipai, and T. N. Osipova, Abstracts of Reports, "Intensification of Technological Production Processes of Structural Materials and Improvement of Their Quality" [in Russian], Minsk (1979), pp. 104-108.
9. S. S. Brel', B. K. Demidovich, O. U. Bud'ko, et al., Abstracts of Reports, "Intensification of Technolgoical Production Processes of Structural Materials and Improvement of Their Quality" [in Russian], Minsk (1979), pp. 46-52.
10. I. K. Kikoin (ed.), Tables of Physical Quantities [in Russian], Moscow (1976).
11. I. E. Campbell (ed.), High Temperature Engineering [Russian translation], Moscow (1968).
12. V. S. Chirkin, Thermophysical Properties of Nuclear Physics Materials [in Russian], Moscow (1968).

NONISOTHERMAL MOTION OF A RAREFIED GAS IN A SHORT PLANAR CHANNEL OVER A WIDE RANGE OF KNUDSEN NUMBER

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Results are presented from a calculation of two-dimensional nonisothermal motion of a rarefied gas in a short planar channel. Calculations were performed for two different temperature distributions along the channel wall. Kinetic coefficients are calculated and the Onsager relationships are verified. Thermomolecular pressure difference indices are found.

A brief overview of studies on motion of rarefied gases in finite length channels was presented in [1], whence it follows that practically all studies in that field have been limited to consideration of isothermal gas flow. Until the present nonisothermal flow has been considered only in an infinite channel. Thus, the study of nonisothermal gas flows in finite channels is of practical interest.

We will consider a planar channel of length ℓ, height a, and infinite in the z-direction, as shown in Fig. 1, joining two infinite vessels containing one and the same gas. At sufficient removal from the channel within the vessels the gas is maintained under equilibrium conditions at pressures P_1 and P_2 and temperatures T_1 and T_2. The equilibrium distribution functions have absolute Maxwell forms:

$$f_i = \frac{P_i}{kT_i}\left(\frac{m}{2\pi kT_i}\right)^{3/2}\exp\left(-\frac{mv^2}{2kT_i}\right), \quad i = 1, 2. \tag{1}$$

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