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HEATING OF A STRUCTURE BY A MOVING PLASMA SOURCE

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Formulas for evaluating the temperature in a concrete slab subjected to plasma decorative finishing are obtained. The temperature fields in the slab are calculated for a real unit with allowance for the special features of the technological process.

At present, the majority of the works on the action of concentrated energy fluxes on materials have been carried out for metals [1, 2]; much fewer of them are devoted to nonmetallic materials and, in particular, to plasma treatment of building products. For high-quality and efficient thermal treatment of building structures and products made of ceramic materials, a number of requirements are imposed on the plasma heater: proximity of the discharge to the product heated, sufficient width of the discharge (≥ 0.1 m), transverse blowing of the discharge directed toward the product, a low gas velocity in the flame, shielding, and return of the thermal radiation of the electric arcs to the discharge region. The structure of a multiarc plasmatron with graphite electrodes meets all the enumerated requirements to the greatest degree [4].

Figure 1 presents a diagram of the head of a plasmatron that consists of annular and rod-shaped electrodes, between which a plasma-generating gas is supplied via an annular gap.

The use of electric-arc heaters for the treatment of materials requires not only knowledge of their structural features and the conditions of discharge initiation and burning but also data on the thermal action of the plasma flame on the product treated.

The present investigation seeks to study the heating of a body (a concrete slab) by a mobile multiarc plasmatron.

In the work, consideration is given to a heat source of diameter $2r_0 = 0.1$ m that moves with a constant velocity $v = 0.3$ m/sec over the surface of a concrete slab of dimensions $L_x \times L_y \times L_z = 6 \times 1.2 \times 0.3$ m in the direction of its largest dimension.

To obtain the dependences in finite form, we adopted the following assumptions: the distribution of the intensity of the heat flux q in the plasma flame obeys a Gaussian law, due to the small thickness of the melted layer (to 0.5 mm) we disregard the heat of the phase change in the concrete, the heat losses by the slab surface by radiation and free convection are small, and the thermal conductivity ($\lambda = 1.4$ W/(m·K)) and the thermal diffusivity ($\chi = 0.8 \cdot 10^{-6}$ m^2/sec) are constant.

Let us evaluate the main time parameters of the process of thermal treatment:

$$t_x^{(1)} \approx 2r_0/v = 0.3 \text{ sec} ; \;\; t_z^{(1)} \approx (2 \div 3)\, t_x^{(1)} = \approx (0.7 \div 1.0) \text{ sec} ;$$

$$t_x^{(2)} \approx t_y^{(2)} \approx r_0^2/\chi = 3 \cdot 10^3 \text{ sec} ; \;\; t_v^{(1)} = L_x/v = 20 \text{ sec} ;$$

$$t_v^{(2)} \approx 700 \text{ sec} ; \;\; t_z^{(2)} = L_z^2/\chi = 10^5 \text{ sec} .$$

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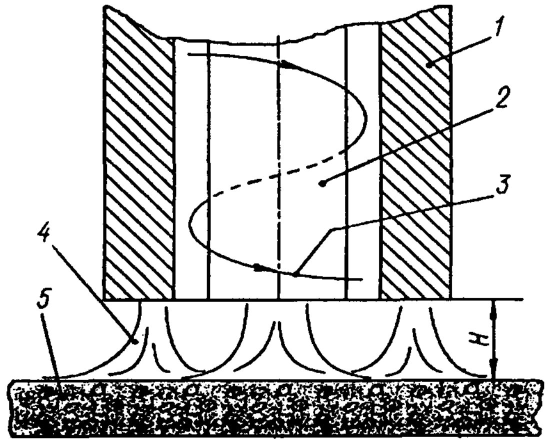

Fig. 1. Diagram of the plasmatron: 1) annular electrode, 2) rod-shaped electrode, 3) gas flow, 4) multiarc discharge, 5) concrete slab.

The results of comparing the indicated quantities suggest that the temperature field under the plasmatron is governed mainly by its velocity of motion and the heat removal into the depth of the slab. Thus, the problem of calculating the temperature is two-dimensional, in essence.

As a model, we take a "thick" slab, for which we will calculate the stationary temperature field produced by the mobile source without regard for the effect of the boundaries of the slab. It is appropriate to solve this problem in coordinates attached to the moving source. We have the following initial equation and boundary conditions:

$$v \frac{\partial T}{\partial x} + \chi \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) = 0 , \tag{1}$$

$$- \lambda \left(\frac{\partial T}{\partial z} \right)_{z=0} = q (x) , \quad T (\infty) = 0 . \tag{2}$$

The solution of this problem has the form [1]

$$T (x, z) = \int\limits_{-\infty}^{+\infty} G (\xi, x, z) \, q (\xi) \, d\xi , \tag{3}$$

where

$$G (\xi, x, z) = \frac{1}{\pi \lambda} K_0 \left(\frac{v \sqrt{(x - \xi)^2 + z^2}}{2\chi} \right) \exp \left(- \frac{(x - \xi) \, v}{2\chi} \right)$$

is the Green function of boundary-value problem (2).

In the general case, it is possible to calculate integral (3) only by numerical methods. From a practical point of view, we restrict ourselves to asymptotic evaluations. In particular, by virtue of the integrability of the functions $K_0(\xi)$ and $q(\xi)$, the absence of singularities of $q(\xi)$ on the real axis, and the high velocities v under consideration we can replace the calculation of integral (3) by its asymptotic equivalent, using the behavior of the function $K_0(\xi)$ at large arguments.

As a result, for a Gaussian heat source, we obtain the asymptotic value of the temperature in the far zone ($x > 2r_0$ and $z \neq 0$)

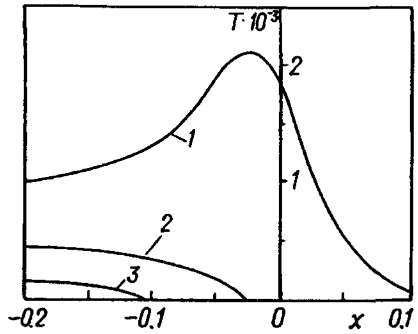

Fig. 2. Temperature field in a concrete slab ($Q = 50$ kW; $v = 0.3$ m/sec): 1) $z = 0$, 2) 1.25 mm, 3) 2.5. T, °C; x, m.

$$T(x, z) = \frac{Q}{\pi \lambda r_0} \sqrt{\left(\frac{\chi}{v}\right)} \frac{\exp\left(-\frac{v}{2\chi}(x + \sqrt{x^2 + z^2})\right)}{(x^2 + z^2)^{1/4}}, \tag{4}$$

and find the temperature profile on the treated surface ($z = 0$)

$$T(x, 0) = \frac{q_0 r_0}{\lambda} \sqrt{\left(\left(\frac{\chi}{v r_0}\right) H_{-1/2}\left(\frac{x}{r_0}\right) \exp\left(-\left(\frac{x}{r_0}\right)^2\right)\right)}. \tag{5}$$

Here, the relation of the power to the intensity $Q = \pi r_0^2 q_0$ for a Gaussian source is used.

In expression (5), the product $H_{-1/2}(x/r_0) \exp(-(x/r_0)^2)$ attains the maximum $2/\sqrt{e}$, which yields the value

$$T_{\max} = \frac{2}{\sqrt{e}} \frac{q_0 r_0}{\lambda} \sqrt{\left(\frac{\chi}{v r_0}\right)}. \tag{6}$$

for the maximum attainable temperature on the surface. Hence we can easily obtain the value of the minimum power transferred by the plasmatron to the slab that is required for the beginning of surface fusion:

$$Q_{\min} = \frac{\pi \sqrt{e}}{2} \lambda r_0 T_m \sqrt{\left(\frac{v r_0}{\chi}\right)}. \tag{7}$$

For the above parameters of the material with $T_m \approx 1700$°C, the minimum power is $Q_{\min} \approx 40$ kW.

From Fig. 2 it can be seen that the maximum of the temperature $T_{\max}$ in a thermocycle shifts rapidly to the region of negative values of x as z increases. Expression (4) enables us to find the position of the maximum of the temperature as well. We determine $x_{\max}$ approximately by the formula $x_{\max} = -vz^2/2\chi$, which on substitution into (4) yields the asymptotic law of decrease in the maximum temperature

$$T_{\max}(z) = \frac{1}{\pi} \sqrt{\left(\frac{2}{e}\right)} \frac{Q\chi}{r_0 v \lambda} \frac{1}{z}. \tag{8}$$

According to a calculation by (8), at depths $z \geq 4$ mm the maximum temperature is lower than 150°C (for an initial temperature $T_0 = 20$°C). Allowing for the short stay of the material at this temperature, we can assume that the mechanical properties of the slab treated are not impaired.

In conclusion, we dwell on some technological features of the process of plasma treatment of building slabs. Because of the nonuniform distribution of the heat-flux density along the radius of the flame the slab is thermally treated with overlap so that the thickness of the melted layer remains approximately the same and equal to 0.5 mm. With this fusion, the temperature in the slab can be evaluated using the principle of superposition of temperature fields. Thus, with an overlap that is equal to the half-width of the flame r_0, the fusion increases the temperature of the middle of a neighboring (yet to be fused) track to $\sim T_{\max} e^{-1} \approx (600-700)^{\circ}C$. By the time the plasmatron returns to fuse this track (in 20 sec) the surface temperature will decrease to $\sim \sqrt{r_0/L_x}\, T_{\max} e^{-1} \approx (60-70)^{\circ}C$, while in 5 sec it will decrease just to 160°C.

In other words, the smaller the time of the reciprocating motion of the plasmatron, the higher the temperature of the material by the time of fusion and the greater the overheating of the structure. Experiment shows that peeling of the fused concrete occurs most frequently at the edges of the slab where the return time of the plasmatron is minimum. To increase the time of reciprocating motion, overshoot of the plasmatron onto stationary technological slabs is provided for in [4].

NOTATION

x, y, and z, coordinates of a point in the slab; r_0, radius of the heat source; L_x, L_y, and L_z, length, width, and thickness of the slab, respectively; $q(x, y) = q_0 \exp(-(x^2 + y^2)/r_0^2)$, heat-flux density; $t_{(x)}^{(1)}$, time of the temperature increase on the surface; $t_z^{(1)}$, time of cooling due to heat removal into the depth of the slab; $t_x^{(2)}$ and $t_y^{(2)}$, times of cooling due to redistribution of heat over the slab surface; $t_v^{(1)}$, time of a single pass over the slab; $t_v^{(2)}$, complete cycle of thermal treatment; $t_z^{(2)}$, time of complete equalization of the temperature throughout the entire volume of the slab; v, velocity of plasmatron motion; Q, heat flux (power) from the flame into the slab; $H_{-1/2}(x/r_0)$, Hermite function of half-integer order; T, temperature; T_m, melting point; K_0, McDonald function of zero order; q_0, density of the heat flux on the axis of the plasma source; e, base of natural logarithms.

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