EXPERIMENTAL INVESTIGATION OF THE EFFICIENCY OF GAS SCREENS AT A BURNING-OUT SURFACE WITH THE BLOWING OF A FOREIGN GAS

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The article gives the results of a systematic experimental investigation of the efficiency of a gas screen at a burning-out graphite surface organized in different manners and with the blowing of a foreign gas into the boundary layer. In the experiments, the Reynolds number was varied within the limits $R_{\triangle} \approx 1.2 \cdot 10^5 = 1.6 \cdot 10^6$, $R^* \approx 100-2000$, $R_Z = 2.3 \cdot 10^2 - 1.5 \cdot 10^4$; the enthalpy factor of the nonisothermicity in the initial cross section varied from $i_S/i_0 = 1$ with the tangential blowing of nitrogen to $i_S/i_0 \approx 34$ with the blowing of helium through the heated porous section.

Protection, using gas screens, of various structural elements from the action of high-temperature and chemically aggressive gas flows is effected, as a rule, under complex gasdynamic conditions. The problem of calculating the boundary layer under these conditions is complicated by the need to take account of the effect of the characteristics of various perturbing factors: nonisothermicity, blowing of a foreign gas, chemical reactions at the wall, etc. The present authors have investigated [1] the burning-out of graphite surfaces under conditions of homogeneous tangential blowing. It is shown in [1] that, in the case of a homogeneous turbulent boundary layer, the relative function of the heat and mass transfer has the same form as with burning-out without a screen

$$\Psi = \left(\frac{2}{\sqrt{\psi_1} + 1}\right)^2 \left(1 - \frac{b^*}{b_c}\right)^2, \qquad \psi_1 = \frac{i_w}{i_w^*}, \quad b^* = j_w / \rho_0 W_0 St_0 = b_1 \Psi \tag{1}$$

where ψ_1 is the enthalpy factor of the nonisothermicity; b_c is the critical blowing parameter.

In the case of homogeneous blowing, the effect of the screen is taken into consideration by the parameter of the permeability

$$b_1^* = 0.75 K_0 (1 - \theta) \tag{2}$$

where K_0 is the concentration of oxygen in the main flow; θ is the efficiency. There have been no experimental investigations of the effect of nonhomogeneous blowing on the rates of heat and mass transfer under the conditions of a screen. It is shown in [2] that, for the case of inhomogeneous blowing in a turbulent boundary layer, the relative function of heat and mass transfer has the form

$$\Psi = \frac{M_w^* T_0}{M_0 T_w^*} \left(\frac{2}{\sqrt{\psi_1} + 1}\right)^2 \left(1 - \frac{b^*}{b_c}\right)^2 \tag{3}$$

where M_0 and M_W^* are the molecular weights of the main flow and of the mixture of gases at an adiabatic non-reacting wall; T_0 and T_W^* are the temperatures of the main flow and of the adiabatic wall. Relationship (3) differs from relationship (1) by the factor $M_W^* T_0 / M_0 T_W^*$, taking account of the effect of the screen on the function Ψ and on the parameter of the displacement of the boundary layer b_c, which, with $\psi_1 > 1$,

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is determined by the expression

$$b_c = \frac{M_w{}^* T_0}{M_0 T_w{}^*}\left(\arccos\frac{2-\psi_1}{\psi_1}\right)^2$$

In the present work, to verify theoretical dependence (3), systematic experimental investigations were made of the efficiency of a gas screen at a burning-out graphite surface, with the blowing of a foreign gas. The experiments were carried out in a unit with the induction heating of a cylindrical graphite channel, a description of which, along with the experimental method, is given in [1, 3]. Burning-out was investigated with two schemes for the organization of the screen: a) blowing of an inert gas through a tangential slot; b) blowing of an inert gas through an initial porous section.

In the case of the tangential blowing of an inert gas, the working section, a schematic diagram of which is given [1], consisted of two coaxially mounted shaped nozzles, ensuring uniform velocity profiles of the air and the blown gas at the inlet to the graphite channel. The diameter of the outer nozzle was equal to the inside diameter of the graphite channel and was 41 mm; the diameter of the inside nozzle was 38.92 mm. The wall of the graphite channel with a thickness of 5-10 mm was heated up to a temperature $T_W = 1600$-$2000°$ K using a high-frequency unit. Air at a temperature of $T_0 \approx 290°$ K was fed into the experimental section through the inner nozzle; the blown gas (nitrogen, argon, or helium) at the same temperature was fed through a slot with a width of 2.08 mm, formed by the nozzles. The length of the graphite channel $l \approx 190$ mm. The density of the graphite samples tested varied from 1000 to 1925 kg/m^3. In the experiments made, the Reynolds numbers varied within the limits $R_\Delta \approx 1.2 \cdot 10^5$-$1.6 \cdot 10^6$, $R^* \approx 100$-2000, $R_S \approx 2.3 \cdot 10^2$-$1.5 \cdot 10^4$, which ensured turbulent flow conditions in the boundary layer. The experimental value of the rate of burning-out, the Stanton number, and the Reynolds numbers were determined by the relationships

$$j = \frac{\delta\rho}{\tau}, \quad \mathrm{St} = \frac{j_c}{\rho_0 W_0 b_1{}^*}, \quad R_\Delta = \frac{\rho_0 w_0 \Delta}{\mu_0},$$

$$R_s = \frac{\rho_s w_s S}{\mu_s}, \qquad R^* = \frac{(1+b_1{}^*)\int\limits_0^x j_c\,dx}{g\mu_0 b_1{}^*}$$

where δ is the thickness of the burning-out layer; ρ is the density of the graphite; τ is the burning-out time; Δ is the length of the channel reckoned from the cross section where the burning-out started. In the analysis of the experimental results, the enthalpy, the heat capacity, and the molecular weight of the mixture of gases were determined from the relationships

$$j_\Sigma = \sum_i^n K_i, \quad c_{p_\Sigma} = \sum_i^n c_p K_i, \quad \frac{1}{M_\Sigma} = \sum_i^n \frac{K_i}{M_i}$$

where K_i is the weight concentration of the i-th component of the gas; c_{pi}, M_i are the heat capacity and the molecular weight. The viscosity of the mixture of gases was determined using the Wilke formula.

Three series of experiments were made with blowing through a tangential slot and three series of experiments with the blowing of nitrogen, argon, or helium through an initial porous section. The aim of the experiment was to investigate the effect of each factor separately (the parameter of permeability, the molecular weight of the blown gas, the temperature and enthalpy factors, the nonisothermicity) and their combined effect on the rate of burning-out of the graphite surface.

With blowing through a tangential slot, the temperatures of the blown gas and the main flow were equal, $T_0 \approx T_S \approx 290°$ K. The temperature factor determined from the temperature of the wall under adiabatic conditions with a screen was equal to unity, $T_0/T_W{}^* = T_0/T_S = 1$. This permitted isolating the effect of the individual factors on the rate of burning-out.

In the first series of experiments with a screen of inert gas, an investigation was made of the burning-out of a graphite surface in a flow of air, with the tangential blowing of nitrogen, i.e., $M_0 = M_S$. Under the conditions of these experiments, in comparison to experiments without a screen [3], the rate of burning-out varied along the length of the channel in accordance with the change in the permeability parameter (2). The relative factor Ψ retained the same form as without a screen (1). An analysis of these experiments is given in [1]. In the second and third series of experiments, argon or helium with a temperature $T_S \approx T_0 \approx 290°$ K were blown into the stream of air through a tangential slot. The condition $T_0/T_W{}^* \approx T_0/T_S \approx 1$ was satisfied, but the molecular weight of the mixture of gases at the adiabatic nonreacting wall $M_W{}^*$ varied along the length of the channel, due to turbulent mixing of the blown gas with the flow of air.

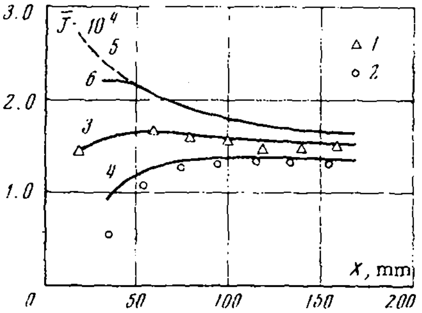

Fig. 1

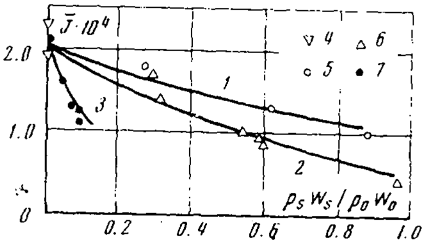

Fig. 2

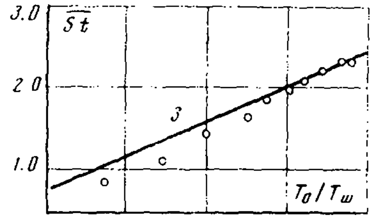

Fig. 3

As the calculations show, the heat capacity and the molecular weight of the gases at the wall varied only slightly as a result of the burning-out of the surface. Therefore, in the experiments the factor of nonisothermicity $\psi_1 = i_w/i_w{}^*$ retained a constant value along the length of the channel and, in value, corresponded to the case of burning-out in a flow of pure air $\psi_1 = 7$–9.

Figure 1 gives the results of experiments on the rate of burning-out $\bar{J} = j_c/\rho_0 W_0$ of a graphite surface in a flow of air with the blowing of helium through a tangential slot. The mass flow rate of the air was $\rho_0 W_0 = 150$ kg/(m$^2\cdot$sec). Experimental points 1 were obtained with a blowing parameter $\rho_s W_s/\rho_0 W_0 = 0.041$, points 2 with a blowing parameter $\rho_s W_s/\rho_0 W_0 = 0.073$.

As is shown in [1], in the presence of a screen of inert gas, the rate of burning-out of a graphite surface can be determined using the formula

$$j_c / \rho_0 W_0 = 2.9\cdot10^{-2} b_1{}^* R_\Delta^{-0.2} S^{-0.6} \Psi^{0.8} (\mu_w/\mu_0)^{0.2} \tag{4}$$

where S is the Schmidt number; μ_w, μ_0 are the viscosities at the wall and in the main flow. The relative function of the mass transfer Ψ was calculated using formula (3) which, for the case under consideration, has the form

$$\Psi = \frac{M_w{}^*}{M_0}\left(\frac{2}{\sqrt{\psi_1}+1}\right)^2 \tag{5}$$

Figure 1 gives curves 3 and 4, calculated using formulas (4) and (5). Curves 5 and 6 were calculated using these same formulas, respectively, for the conditions of experiments 3 and 4, but without taking account of the molecular weight $M_w{}^*/M_0$ in formula (5). These curves lie considerably higher than the experimental points, i.e., the presence of the screen must be taken into account in the relative laws of heat and mass transfer.

The effect of the molecular weight of the blown gas on the rate of burning-out can be seen on Fig. 2, which shows the dependence of the rate of burning-out $\bar{J} = j_c/\rho_0 W_0$ on the relative blowing of argon (4, 5), nitrogen (6), and helium (7). Curves 1, 2, and 3 represent calculation using formulas (4) and (5) for argon, nitrogen, and helium. As can be seen from the figure, with identical mass flow rates of the blown gas and other conditions being equal ($S = 2.08$ mm, $\Delta = 60$ mm, $T_w = 2000°$ K, $\rho_0 W_0 = 150$ kg/(m$^2\cdot$sec), the rate of burning-out is lower with the blowing of a lighter gas.

In the experimental investigation of the rate of burning-out of a graphite surface under the conditions of a gas screen beyond the section of porous blowing, the inner nozzle was removed and air with a temperature $T_0 = 290°$ K was fed into the channel (the primary flow). The secondary flow of inert gas was blown into the boundary layer through a porous section with a width $S = 40$ mm, made of porous graphite PG-50 with a porosity of 50%. The remaining part of the working section was made of dense graphite V-1. During an experiment the dense and porous sections were heated simultaneously, which made it possible to vary the heat content of the blown gas.

The first series of experiments was aimed at verifying, under the conditions of a screen, the effect of the temperature factor $T_0/T_w{}^*$ on the rate of burning-out of a graphite surface. The experiments were made with the blowing of nitrogen through a porous section in which the condition $M_w{}^*/M_0 = M_s/M_0 = 1$ was

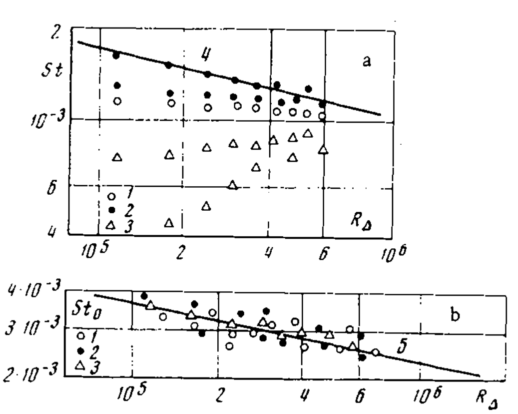

Fig. 4

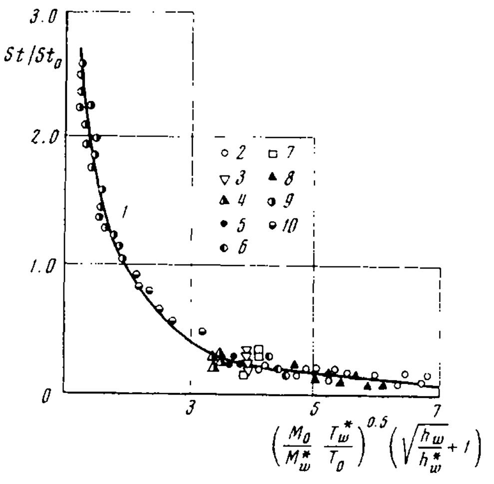

Fig. 5

satisfied. In distinction from the case of blowing through a slot, the nitrogen passing through the porous graphite was heated and its temperature varied within the limits 1510° K < T_S < 1970° K (i_S/i_0 = 6–8.5). Downstream beyond the section of porous blowing, the temperature of the wall corresponding to adiabatic conditions T_W^* varied along the length. Figure 3 gives experimental data, worked up in the form of the dependence of the relative Stanton number $\overline{St} = St/St_0(\sqrt{\psi_1} = 1)^2$ on the temperature factor T_0/T_W^*. The mass flow rate of the main flow $\rho_0 W_0 \approx 105$ kg/(m^2·sec); the temperature of the impermeable wall $T_W \approx 1950°$ K; the temperature of the porous wall $T_S \approx 1510$–$1970°$ K; the density of the dense graphite ρ = 1925 kg/m^3. The experimental data are in satisfactory agreement with calculation using the formula (6)

$$\Psi_1 = \frac{T_0}{T_w^*}\left(\frac{2}{\sqrt{\psi_1}+1}\right)^2 \tag{6}$$

In the second and third series of experiments, argon and helium were blown through the initial porous section. This permitted investigating simultaneously the effect of all the parameters (M_W^*/M_0, T_0/T_W^*, ψ_1, and b_1^*) on the rate of burning-out of the graphite surface. The enthalpy factor of the nonisothermicity i_S/i_0 in the porous section varied from 3 with the blowing of argon to 34 with the blowing of helium. Figure 4a gives experimental data on the blowing of nitrogen 1 [$\rho_S w_S$ = 1.25 kg/(m^2·sec)], argon 2 [$\rho_S w_S$ = 0.8 and 1.88 kg/(m^2·sec)], and helium 3 [$\rho_S w_S$ = 0.8 and 1.4 kg/(m^2·sec)] through the porous section in the form of of the dependence of the diffusional Stanton number $St = j_C/\rho_0 w_0 b_1^*$ on R_Δ, calculated from the length of the dense graphite section. The mass flow rate of the main flow $\rho_0 w_0$ = 105 kg/(m^2·sec). Curve 4 represents calculation using formulas (4) and (1). As can be seen from the figure, there is a stratification of the experimental data. If, using formula (3), the experimental data are brought back to standard conditions and are worked up in the form of the dependence of the Stanton number $St_0 = j_C/\rho_0 w_0 b_1^* \Psi^{0.8}$ on R_Δ (Fig. 4b), they are satisfactorily correlated (curve 5) by the dependence

$$St_0 = St / \Psi^{0.8} = 2.9\cdot10^{-2} R_\Delta^{-0.2}\, S^{-0.6}\, (\mu_w/\mu_0)^{0.2}$$

Figure 5 gives the results of all the experiments on the rate of mass transfer at a burning-out graphite surface: 2) without blowing; 3, 4, 5) tangential blowing of nitrogen, argon, and helium; 6, 7, 8) burning-out beyond the section of the porous blowing of nitrogen, argon, and helium. As calculations show, under the conditions of these experiments, the effect of the transverse flow of mass on the heat and mass transfer did not exceed 10%, i.e., the principal effect was that of the nonisothermicity of the flow. Under the conditions of a screen, this effect is determined from formula (3) (curve 1), which is in satisfactory agreement with the experiments. The divergence of the experimental points from the calculation can be explained by the effect of thermodiffusion [4].

This figure also gives experimental data 9 (on the relative heat-transfer coefficients [5]) and 10 (on the friction coefficients [6]), obtained under conditions of large temperature heads (0.1 < ψ_1 < 7), in a turbulent boundary layer without a screen.

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