constant; β, average absorption coefficient; N, number of particles emitted; M, number of particles traversing a given zone; E, particle energy; ΔE, change in energy of each zone due to radiative heat transfer; C, velocity of light; Δx and Δt, width of the zone and the sides of the time interval; Δ, thickness of the specimen; x and d, coordinate of the particle source and the distance the particle traverses before being absorbed; T_i and T_s, initial temperature of the specimen and the temperature of the bounding surfaces; $\tau_0 = \beta x$, optical thickness; $P = \beta K/(4n^2\sigma T_s^3)$, radiative–conductive parameter; $\Theta = T_s/T_i$, ratio of the temperature of the cold wall to the initial temperature of the specimen; n, index of refraction; c_2, spectral energy distribution constant in Planck's law; β_λ, spectral absorption coefficient.

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POROUS RADIATORS WITH SURFACE COMBUSTION IN THE FILTRATION OF A FUEL–OXIDANT MIXTURE

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A method is proposed for calculating porous radiators with the injection of fuel–oxidant mixture, taking the influence of all the basic parameters into account.

In [1], calculations were performed of porous radiators with the filtration through a permeable wall (porous or perforated) of liquid or gaseous fuel that reacts at the surface of the body with oxidant (oxygen) of the external medium. The case of filtration of a fuel–oxidant mixture is now considered, since porous radiators of this type are of broad practical application, but the method of calculation requires significant refinement.

The problem is formulated as follows.

Through a porous body of thickness $l = y_2 - y_1$ with internal energy sources or sinks q_V, a mixture of fuel and oxidant filters, with an initial temperature T_ε and a total filtration density j; $j = j_f + j_A$, where j is the transverse flux density of fuel and j_A is the transverse flux density of oxidant. This mixture burns at the "hot" surface of the wall, where $\bar{y} = \bar{y}_2 = 1$ in the oxygen filtering together with the fuel, the heat of combustion of which

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is Q_f. Consideration is confined to those non-Arrhenius functions of q_V (possibly temperature-dependent) for which the condition of a maximum of T at the "hot" surface is satisfied. At a distance of $l_g = y_3 - y_2$ from the "hot" surface, a part of thickness l_3 is located; this is heated by the radiator to a temperature T_{3U} on one side and is heat-insulated on the other. The values of ε_2, ε_3, and ε_g, and also the thermophysical coefficients of the interacting media are assumed to be piecewise constant. It is necessary to find the surface temperature T_2 of the radiator at which the part is heated to a specified value T_{3U} in a definite time τ. If the technology of heating of the part provides for its motion, it is possible to calculate the velocity v_3 at which heating to T_{3U} with a definite value of T_2 is ensured.

Under the above assumptions, the problem is written as follows

$$t'' - \xi t' + Q(\bar{y}) = 0, \quad \bar{y}_1 \leqslant \bar{y} \leqslant 1, \tag{1}$$

$$t_f'' - \xi_{rf} t_f' = 0, \quad -\infty \leqslant \bar{y} \leqslant \bar{y}_1, \tag{2}$$

$$\bar{y} = -\infty, \quad t_f = t_\varepsilon, \tag{3}$$

$$\bar{y} = \bar{y}_1, \quad t = t_f = t_1, \tag{4}$$

$$t' = \lambda_{f\Sigma} t_f', \tag{5}$$

$$\bar{y} = \bar{y}_2 = 1, \quad t = t_g = t_2, \tag{6}$$

$$t' - \lambda_{g\Sigma} t_g' = q_f \xi_\Sigma + q_3^R, \tag{7}$$

$$\bar{y} = \bar{y}_3, \quad t = t_3, \tag{8}$$

$$dt_3/d\bar{\tau} = -\lambda_{g\Sigma} t_g' + q_2^R - q_4. \tag{9}$$

Here

$$\xi = \frac{jc_p y_2}{\lambda_\Sigma}; \quad \xi_f = \frac{jc_p y_2}{\lambda}; \quad \xi_\Sigma = \frac{j_f c_{pf} y_2}{\lambda_\Sigma};$$
$$\lambda_{f\Sigma} = \frac{\lambda}{\lambda_\Sigma}; \quad \lambda_{g\Sigma} = \frac{\lambda_g}{\lambda_\Sigma}; \quad Q(\bar{y}) = \frac{q_V(\bar{y}) y_2^2}{\lambda_\Sigma T_\infty};$$
$$q_f = \frac{\eta Q_f}{T_\infty c_{pf}}; \quad \bar{\tau} = \frac{\tau \lambda_\Sigma y_2^{-1}}{(lc_p\rho)_3}; \quad t = \frac{T}{T_\infty}; \quad \bar{y} = \frac{y}{y_2}; \tag{10}$$
$$q_4 = Q_4 y_2/\lambda_\Sigma T_\infty; \quad q_2^R = E(t_{2F}^4 - t_{3F}^4); \quad q_3^R = -q_2^R;$$
$$E = \frac{\sigma y_2 T_\infty^3}{\lambda_\Sigma \left[\ln\left(\frac{1}{1-\varepsilon_g}\right)^{0.75} + \frac{1}{\varepsilon_2} + \frac{1}{\varepsilon_3} - 1\right]},$$

where η is a coefficient characterizing the completeness of combustion of the fuel–oxidant mixture and depends on the form of the injectant, the quantitative composition, and the temperature of the smoky exhaust gases; c_{p3}, ρ_3, l_3, specific heat, density, and thickness of the heated part; c_p, specific heat of the filtering fuel–oxidant mixture; σ, Stefan–Boltzmann constant ($\sigma = 5.67 \cdot 10^{-8}$ W/m$^2 \cdot$K^4); λ, thermal conductivity of this mixture; $\lambda_\Sigma = (1 - \Pi)\lambda_T + \Pi\lambda$. For c_p and λ, the following expressions hold

$$c_p = c_{pf} C_f + c_{pA} C_A, \tag{11}$$

$$\lambda = \lambda_f Y_f + \lambda_A Y_A, \tag{12}$$

where C_f and C_A are the gravimetric concentrations of the filtering fuel injectant and oxidant (air); Y_f and Y_A are the corresponding mole fractions. The reliability of Eq. (12) is confirmed by the results of investigations [2] in which it was shown that the dependence of the thermal conductivity of a methane–air mixture accurately corresponds to the addition rule. The quantity λ_g appearing as a factor in Eq. (10) is determined from the formula

$$\lambda_g = \sum_i \lambda_i Y_i, \tag{13}$$

while the composition of the mixture with an excess-air coefficient $\bar{\alpha} = 1$ corresponds to the concentration of smoky gases.

The problem in Eqs. (1)-(9) coincides with the differential equations and boundary conditions given in [1], but the parameters defined in Eq. (10) which appear in Eqs. (1)-(9) are fundamentally different from the corresponding quantities characterizing the filtration solely of fuel injectant through a porous wall [1].

The conditions in Eqs. (5), (7), and (9) are the heat-balance equations at the "cold," "hot," and heated surfaces; q_2^R and q_3^R are the radiative heat fluxes between the radiator and the part. The first term on the right-hand side of Eq. (7) takes the heat of combustion of the filtering fuel into account.

For the derivative t'_g, appearing as a factor in the conditions in Eqs. (7) and (9) describing a steady process, the following expression is written:

$$t'_g = (t_{3F} - t_{2F})/(\bar{y}_3 - 1), \quad \bar{y}_2 \leqslant \bar{y} \leqslant \bar{y}_3, \tag{14}$$

where

$$t_{2F} = \sqrt{t_{2\mathrm{I}} t_{2\mathrm{U}}}, \qquad t_{3F} = \sqrt{t_{3\mathrm{I}} t_{3\mathrm{U}}}.$$

Dimensionless parameters of the form in Eq. (10), containing the coefficients c_p and λ, are used in Eqs. (1)-(9) because the wall cooling is due to the total specific heat and thermal conductivity of the fuel–oxidant mixture.

Solution of the problem in Eqs. (2)-(4) yields a relation for determining the injectant temperature at the plate surface

$$t_{\mathrm{f}} = (t_1 - t_\varepsilon) \exp[\xi_{\mathrm{f}}(\bar{y} - \bar{y}_1)] + t_\varepsilon, \quad -\infty \leqslant \bar{y} \leqslant \bar{y}_1. \tag{15}$$

The temperature distribution over the thickness of the permeable wall is found by solving differential Eq. (1) with the boundary conditions in Eqs. (4) and (6)

$$t = \left[t_2 - t_1 - \frac{1}{\xi} \int_{\bar{y}_1}^{1} Q(\bar{y})\, d\bar{y} + \exp\xi \int_{\bar{y}_1}^{1} Q(\bar{y}) \exp(-\xi\bar{y})\, d\bar{y}\right] \times$$

$$\times \frac{\exp\xi\bar{y} - \exp\xi\bar{y}_1}{\exp\xi - \exp\xi\bar{y}_1} + t_1 - \exp\xi\bar{y} \int_{\bar{y}_1}^{\bar{y}} Q(\bar{y}) \exp(-\xi\bar{y})\, d\bar{y} + \frac{1}{\xi} \int_{\bar{y}_1}^{\bar{y}} Q(\bar{y})\, d\bar{y}, \quad \bar{y}_1 \leqslant \bar{y} \leqslant 1. \tag{16}$$

When $Q = \gamma = \mathrm{const}$, Eq. (16) is transformed to the simpler form

$$t = \frac{\exp\xi - \exp\xi\bar{y}}{\exp\xi - \exp\xi\bar{y}_1} t_1 + \frac{\gamma(\bar{y} - \bar{y}_1)}{\xi} + \left[t_2 - \frac{\gamma(1 - \bar{y}_1)}{\xi}\right] \frac{\exp\xi\bar{y} - \exp\xi\bar{y}_1}{\exp\xi - \exp\xi\bar{y}_1}, \quad \bar{y}_1 \leqslant \bar{y} \leqslant \bar{y}_2. \tag{17}$$

From the boundary condition in Eq. (5), using the solution in Eqs. (15) and (16), an analytical dependence is obtained for the temperature at the "cold" surface t_1 appearing as a factor in Eqs. (16) and (17)

$$t_1 = \left[t_2 - \frac{1}{\xi} \int_{\bar{y}_1}^{1} Q(\bar{y})\, d\bar{y} + \frac{\exp\xi}{\xi} \int_{\bar{y}_1}^{1} Q(\bar{y}) \exp(-\xi\bar{y})\, d\bar{y}\right] \exp[\xi(\bar{y}_1 - 1)] + t_\varepsilon [1 - \exp(\xi(\bar{y}_1 - 1))]. \tag{18}$$

When $Q(\bar{y}) = \gamma = \mathrm{const}$, Eq. (18) takes the form

$$t_1=\left\{t_2-\frac{\gamma}{\xi}\left\{(1-\bar{y}_1)+\frac{1}{\xi}[1-\exp\xi(1-\bar{y}_1)]\right\}\right\}\exp[\xi(\bar{y}_1-1)]+t_\varepsilon\{1-\exp[\xi(\bar{y}_1-1)]\}. \tag{19}$$

From the thermal-balance Eq. (7), a dependence is found for the calculation of the dimensionless temperature of the "hot" wall surface; determining the derivative t' in Eq. (1) from the solution in Eq. (16) and taking Eq. (14) into account, it is found that

$$Et_2^4+[\xi+\lambda_{g\Sigma}/(\bar{y}_3-1)]\,t_2-\xi t_\varepsilon-q_f\,\xi_\Sigma-q_4-\lambda_{g\Sigma}t_3/(\bar{y}_3-1)-Et_3^4-\int_{\bar{y}_1}^{1}Q(\bar{y})\,d\bar{y}=0, \tag{20}$$

where $t_2 = t_{2F}$, $t_3 = t_{3F}$.

When $Q(\bar{y}) = \gamma = \text{const}$, Eq. (20) transforms to an algebraic equation of fourth order in t_2. In this case, the last term in Eq. (20) is given by the expression

$$\int_{\bar{y}_1}^{1}Q(\bar{y})\,d\bar{y}=\gamma(1-\bar{y}_1).$$

Determining the temperature t_2 from Eq. (20), the condition in Eq. (9), characterizing the increase with time in the temperature of the heated part (the derivative $dt_3/d\bar{\tau}$), yields the following result when Eq. (14) is taken into account

$$dt_3/d\bar{\tau}=A \tag{21}$$

or in terms of the geometric-mean dimensional value T_{3F} ($T_{3F} = \sqrt{T_{3I}T_{3U}}$)

$$dT_{3F}/d\tau=A/\delta, \tag{22}$$

where

$$A=\lambda_{g\Sigma}(t_2-t_3)_F/(\bar{y}_3-1)+E(t_2^4-t_3^4)_F-q_4,$$
$$\delta=y_2(lc_p\rho)_3/\lambda_\Sigma T_\infty.$$

If the dimensionless time $\bar{\tau}$ of heating of the part is divided into periods within which the dependence of t_3 on $\bar{\tau}$ is linear, the following relation will hold for the n-th section of the curve:

$$(dt_3/d\bar{\tau})_n=(t_{3U}-t_{3I})_n/(\bar{\tau}_U-\bar{\tau}_I)_n. \tag{23}$$

The following result may be obtained from Eqs. (21)-(23):

$$(\bar{\tau}_{3U}-\bar{\tau}_{3I})_n=[(t_{3U}-t_{3I})\,A]_n. \tag{24}$$

According to the method adopted for the calculation of permeable media, the quantity t_2 is determined from Eq. (20) for specified values of the parameters q_f, Q, ξ, t_ε, t_{3I}, t_{3U}, ε_2, ε_3, ε_g, $\bar{y}_1$, $\bar{y}_2$, $\bar{y}_3$, and l_3. Then the change in temperature with time is determined from Eq. (21) or (22). The total time τ_3 for heating of the part to the specified temperature is determined by summation of the terms in Eq. (24):

$$\tau_3=\sum_n(\tau_{3U}-\tau_{3I})_n.$$

Comparison of the results of calculation and experiment will be given in a subsequent work.

NOTATION

y, coordinate normal to the wall surface; T, temperature; ρ, density; q^R, dimensionless radiant component of the heat flux; Q_4, specific heat losses through the layer thermally insulating the heated part. Subscripts: T, skeleton of porous body; f, fuel gas; A, air (oxidant); F, geometric-mean value; g, gas layer; 1, 2, "cold" and "hot" surface of permeable wall, respectively; 3, surface of heated part; ∞, value as $y \to \infty$; ε, value as $y \to -\infty$; I, initial; U, ultimate.

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DEVELOPMENT AND BURNOUT OF A FLAME IN A PLANE-FLAME BURNER

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The features of the formation, development, and burnout of a flame in a plane-flame burner are established. The optimal conditions of burner use, at which the fuel-component content in the combustion products is within normal limits, are determined.

In the heat treatment of surfaces in various technological processes, use is made of gas-burner devices forming flames in basically conical form; considerable flame length and width of the reaction region are characteristic of these devices. It is known that heat-exchange processes in the interaction of an open flame with the surface depend on the magnitude of its thermal stress, which, in turn, is determined by the flame length and the thickness of the reaction region [1]. According to the investigations of [1], decrease in reaction-region thickness leads to decrease in flame length and increase in thermal stress. On the basis of these conclusions, an injectional slit gas burner was developed [2]; in this burner, the gas burns in a plane flame of comparatively small length.

Below, the processes of flame formation and burnout of gas–air mixtures in atmospheric conditions are analyzed.

The investigation was conducted for a burner designed for the ignition of 0.5-1.7 m^3/h of the vapor phase of liquified gas (50% propane and 50% butane, percentage by volume) at pressures at 10-110 kPa, with structural elements of the following dimensions: mixing-chamber diameter d_{mi} = 0.05 m and length $l_{mi} = 2.5d_{mi}$; diffusor length $l_D = 4d_{mi}$ and aperture angle 60°; height of slit in aperture h_S = 0.006 m and slit length $l = 50h_S$. The features of flame development were investigated in isothermal conditions by the method of [3]. From the distribution of the dynamic head in the flame, which was measured by a three-channel cylindrical probe with blowing of air through the burner, the aerodynamic axis of the flame, the aperture angle, and the velocity attenuation were determined.

In Fig. 1 (curve 1), in dimensionless coordinates, the resutls of measuring the relative dynamic head h_D/h_D^{max} as a function of the dimensionless flame length L/h_S are shown. Extinction of the jet is observed at $L/h_S = 50$, i.e., at a distance equal to the flame-front length. The aperture angle of the flame was determined by measuring the dynamic head in the profile plane at a distance from the burner slit of 0.03 m. The dynamic head h_D was measured at points in the axial and peripheral planes of the flow. At a distance of 0.01 m from the axial plane, the ratio $h_D/h_D^{max} = 0$. This parameter determined the aperture angle of the flame in the plane of reaction-region thickness, which was obtained by calculation, taking the geometric dimensions of the burner slit into account, and was found to be 10-13°.

In exothermal conditions, the degree of burnout of the flame, the temperature distribution over its length, and the composition of the combustion products were found.

The degree of burnout of the flame was estimated from the content of carbon dioxide in the combustion products as a function of the relative distance from the burner slit. In

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