conditions and the spectral model for the absorption coefficient being the same as in the present paper. Comparing our results with those from [8], we see that, for the conditions considered, absorption of radiant energy in the boundary layer noticeably (as much as 20%) lowers the radiant heating of the surface of the body.

NOTATION

Re, Reynolds number; t, T, h, ρ, p, time, temperature, enthalpy, density, and pressure, respectively; s, arc length measured from the forward stagnation point; n, distance along the normal from the body surface; u, v, component of the vector velocity V in the s,n directions; k, curvature of a generator of the body surface; θ, angle of inclination of the generator to the undisturbed flow direction; θ_{co}, cone half-angle; r, distance between the axis of symmetry and the body surface; λ, total thermal conductivity; μ, dynamic viscosity coefficient; I_ν, spectral radiant intensity; κ_ν, linear spectral absorption coefficient with reference to forced emission; x, coordinate along the direction of radiation propagation; τ_ν, optical cocordinate for frequency ν; E_n, integro-exponential function; B_i, integral of equilibrium radiant intensity within a spectral interval; m, specified number of nodes on a ray; q_r, radiant heat flux; q_c, convective heat flux; C_f, friction coefficient; H, parameter determining density of coordinate lines to the body surface; ε, shock detachment distance. Indices: ∞, values of undisturbed flow parameters.

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PROPERTIES OF THE DEFORMATION OF TEMPERATURE FIELDS IN THE MOVEMENT OF AN OPAQUE GAS MEDIUM

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UDC 536.24

The deformation of temperature fields in the movement of a light-absorbing gas medium in a flat channel is studied analytically. It is shown that with an increase in the optical density of the stream its central part retains a high temperature level far from the entrance section owing to the high screening capacity of the boundary layers.

Let us consider the movement of a gas stream in a channel formed by two parallel isothermal and diffuse semiinfinite gray surfaces which are located a finite distance apart. The gas stream moving in the channel is assumed to be a homogeneous and isotropic gray medium which is in a state of local thermodynamic equilibrium and is able to emit and absorb radiant energy. The initial temperature distribution in the gas layer and the velocity profile of the movement of the gas stream can be assigned arbitrarily.

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In the case when the vector of the radiant energy flux is assigned in a strict integral form the equation describing the distribution of temperature θ in any longitudinal channel cross section X has the form

$$\beta(\tau/\tau_0)\frac{\mathrm{Bo}}{\tau_0}\frac{\partial\theta(X,\ \tau)}{\partial X}-N\frac{\partial^2\theta(X,\ \tau)}{\partial\tau^2}+4\theta^4(X,\ \tau)[1-G(\tau)]-4\left\{F(\tau)+\int\limits_0^{\tau_0}K(\tau,\ t)[\theta^4(X,\ t)-\theta^4(X,\ \tau)]\,dt\right\}, \quad (1)$$

where

$$G(\tau)=\frac{1-E_2(\tau)}{2[1-r_1r_2E_2^2(\tau_0)]}\{r_1[r_2E_2(\tau_0)E_2(\tau_0-\tau)+E_2(\tau)]+$$

$$+r_2[r_1E_2(\tau_0)E_2(\tau)+E_2(\tau_0-\tau)]\}+\frac{1}{2}[2-E_2(\tau)-E_2(\tau_0-\tau)], \quad (2)$$

$$F(\tau)=\frac{[\varepsilon_1\theta_1^4+r_1\varepsilon_2\theta_2^4E_2(\tau_0)]E_2(\tau)+[\varepsilon_2\theta_2^4+r_2\varepsilon_1\theta_1^4E_2(\tau_0)]E_2(\tau_0-\tau)}{2[1-r_1r_2E_2^2(\tau_0)]}, \quad (3)$$

$$K(\tau,\ t)=\frac{1}{2}\frac{r_1E_1(t)}{1-r_1r_2E_2^2(\tau_0)}[r_2E_2(\tau_0)E_2(\tau_0-\tau)+E_2(\tau)]+$$

$$+\frac{1}{2}\frac{r_2E_1(\tau_0-t)}{1-r_1r_2E_2^2(\tau_0)}[r_1E_2(\tau_0)E_2(\tau)+E_2(\tau_0-\tau)]+\frac{1}{2}E_1(|\tau-t|), \quad (4)$$

and $E_n(t)$ are well-known integro-exponential functions [1, 2]. The temperature distribution over the height of the gas layer in the cross section X = 0 is assigned in the form of a symmetrical curve which, according to the adopted classification of external heat exchange in combustion furnaces [3], corresponds to conditions of an equilibrium distribution; the velocity profile of the movement is assigned in the form of a parabola:

$$\beta(\tau/\tau_0)=a[\tau/\tau_0-(\tau/\tau_0)^2].$$

The temperatures of the two surfaces forming the channel are taken as equal to each other, i.e., $\theta_1 = \theta_2$. The effect of the cool boundary zone near the heat-absorbing surface on the formation of the temperature fields along the length of the furnace, and consequently on the heat transfer, is excluded to a considerable extent with this condition. Thus, the character of the temperature field and the mode of heat exchange far from the entrance section will be retained for quite a long time. The velocity of movement of the stream along the surfaces of the system is taken as relatively low, Bo = 20, in connection with which the gas stream is intensively cooled even at distances not very far from the entrance, and the temperature distribution over the height τ of the channel approaches an equilibrium distribution where the gas medium becomes purely absorbing and it does not depend on the longitudinal coordinate X. In this case ($\theta_1 = \theta_2$) the heat flux approaches the null value.

The thermal resistance to the movement of the gas stream is not the same for different values of its optical density τ_0 with one and the same initial temperature field: for small optical densities of the medium the initial temperature field changes little; with an increase in τ_0 the temperature field loses similarity with the initial field, in the cross section X = 0, considerably more rapidly, approaching an equilibrium distribution which does not depend on X.

This is connected with the fact that at small values of τ_0 the radiation of the hot core of the stream is weakly absorbed by the medium, as a result of which the initial temperature field can be preserved for a rather long time. With an increase in the optical density the absorption by the medium of radiation of the central part of the stream proceeds much more intensively, and therefore at the same distances from the entrance the core of the gas stream cools considerably more and resemblance with the initial temperature field is lost faster.

As shown by numerical studies of the system of equations (1)-(4) (the method of straight lines and the Runge–Kutta method were used, performed on a BESM-4 computer), this situation occurs only up to certain optical densities τ_0. With a further increase in the optical density of the stream ($\tau_0 > 2$) the temperature of its central part is deformed less than at moderate optical densities of the medium. This effect is shown in Fig. 1 for a symmetrical temperature field (because of the symmetry of the temperature distribution this field is shown up to the axis of the system, from $\tau = 0$ to $\tau = \tau_0/2$).

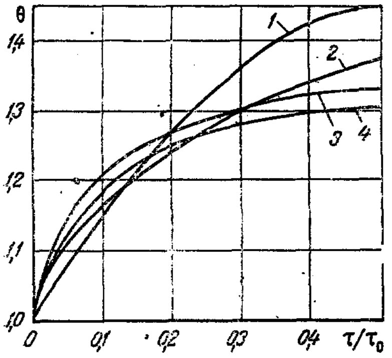

Fig. 1

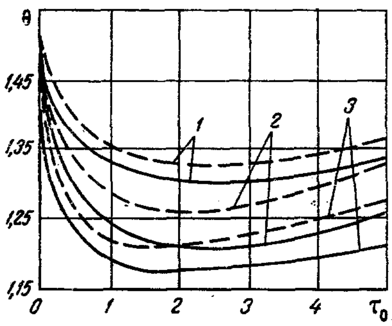

Fig. 2

Fig. 1. Deformation of temperature fields in the movement of streams of different optical densities for an equilibrium distribution mode of heat exchange ($\theta_1 = \theta_2 = 1.0$; $\varepsilon_1 = \varepsilon_2 = 0.8$; Bo = 20; X = 1.0): 1) $\tau_0 = 0.1$; 2) 0.5; 3) 5.0; 4) 3.0.

Fig. 2. Variation in axial temperature of stream as a function of the optical density ($\theta_1 = \theta_2 = 1.0$; Bo = 20): 1) X = 1.0; 2) 2.0; 3) 3.0 (solid curve: $\varepsilon_1 = \varepsilon_2 = 0.8$; dashed curve: $\varepsilon_1 = \varepsilon_2 = 0.5$).

As follows from Fig. 2, the variation in the maximum temperature of the stream (along its axis in this case) as a function of the optical density of the medium has an extremal character and the gas temperature at the point $\tau = \tau_0/2$ passes through a certain minimum. It is obvious that the location of this minimum can be determined by the combination of a series of factors — the temperature field in the initial section of the system, the magnitude and nature of the velocity of movement of the stream, the distance from the initial section, etc.

This investigation showed that in the case of a symmetrical temperature field the optical density corresponding to the minimum value of the axial temperature τ (X, $\tau_0/2$) hardly changes with an increase in the reflectivity of the surfaces ($\varepsilon_1 = \varepsilon_2 = 0.5$) for different distances X from the entrance and remains equal to $\tau_0 = 2.0$. A decrease in the emissivity of the surfaces participating in the heat exchange promotes the maintenance of the temperature of the central part of the stream at a higher level than with $\varepsilon_1 = \varepsilon_2 = 0.8$, since with an increase in the reflectivity of the surfaces the latter participate less and less in the heat exchange, ceasing to be heat sinks. This is seen especially well for large optical densities of the medium (Fig. 2).

When the temperature profile in the initial section of the system is asymmetric (direct or indirect modes of heat exchange) the nature of the variation in the region of the maximum stream temperatures as a function of the optical density is fully retained. However, whereas for a symmetrical temperature profile the ordinate of its maximum temperature is constant, for an asymmetrical field the ordinate of the axial temperature varies for different cross sections — different values of X and τ_0.

The explanation for this effect evidently consists in the fact that although the radiation of the hot core of the stream is intensively absorbed by the medium with an increase in its optical density, the so-called "blanking" effect begins to operate, the essence of which is the following: the optical density of the boundary layers becomes high enough so that the core screens itself, not transmitting the radiation of the hotter part of the stream, as a result of which its temperature is maintained at a rather high level. Owing to this the boundary layers themselves also have a high temperature, which exceeds the analogous values for low and medium optical densities of the gas stream, and this, in turn, strengthens the "blanking" effect (Fig. 1).

The deformation of the temperature fields discussed above (Fig. 1) was obtained on the assumption that the fraction of the convective—conductive component of the complex heat exchange is negligibly small in comparison with the radiant component, i.e., $N \to 0$. With an increase in the fraction of convective—conductive transfer the temperature field is deformed even more because the temperature jumps in the gas stream at the boundary surfaces are smoothed out. This explains the fact that the "blanking" effect is manifested even more sharply (Fig. 3) when the interaction of radiation and convection is taken into account ($N \neq 0$).

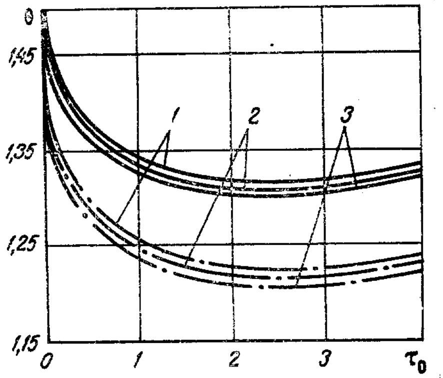

Fig. 3. Influence of the conductive–convective component of heat exchange on the "blanking" effect: 1) N = 0; 2) 0.01; 3) 0.1; solid curves: X = 1; dashed curves: X = 2.

In the region of low optical thicknesses the presence of the convective component deforms the axial temperature of the stream considerably more strongly than in the case of N = 0, since in this range of optical thicknesses the influence of convection is manifested most strongly. With an increase in the optical density τ_0 of the stream the fraction of the convective–conductive component in the overall heat transfer decreases, and even for such large values of the parameter N, which characterizes the ratio of the conductive–convective and radiant heat fluxes, as N = 0.1 its influence on the "blanking" effect is extremely small, which is illustrated by Fig. 3.

Thus, the interaction of several mechanisms, which are in opposition to a certain extent, occurs in the movement of gas streams of different optical densities in which the temperature distributions in the initial sections are the same. On the one hand, in the movement of weakly absorbing gas media the initial temperature field is retained rather far from the entrance, and the heat transfer to the heating surface can be quite large owing to the retention of high temperatures of the gas stream, although its optical density is low. On the other hand, in the movement of a gas stream of higher optical density the temperature field even at a small distance from the entrance differs considerably from the initial field and the medium cools intensively owing to the fact that its radiation is vigorously absorbed by the stream itself. The heat transfer can be rather high, however, because the emissivity of the layer is low. Finally, in the case of the movement of optically dense gas media the temperature level of the stream is higher (for the same cross sections along the X coordinate) than for medium values of the optical density.

In this case, however, the values of the radiant heat transfer, which dominates in the overall heat transfer for higher τ_0, can prove to be lower than the fluxes of radiant energy corresponding to medium values of τ_0, since the boundary layers of gas, the temperature of which is lower than the temperature of the central part and whose emissivity is high, screen the radiation of the hot core of the stream.

Therefore, in the movement of gas streams of different optical densities the values of τ_0 which correspond to the maximum values of the radiant heat transfer in the different radiation modes are determined by which of the indicated mechanisms prevails in the given concrete case.

NOTATION

$Bo = v\rho c_p/\sigma T_*^3$, dimensionless parameter characterizing the ratio of the heat flux transported in the direction of movement of the medium to the radiant heat flux; c_p, heat capacity at constant pressure; $N = k\lambda/\sigma T_*^3$, dimensionless parameter characterizing the ratio of the conductive–convective and radiant fluxes; k, coefficient of attenuation of the radiation by the medium; $r = 1 - \varepsilon$, reflection coefficient; T_*, arbitrary (scale) temperature; t, additional variable of integration; v, velocity; X, dimensionless coordinate; β, function determining the velocity profile of the gas stream; ρ, density; ε, emissivity; $\theta = T/T_*$, dimensionless temperature; σ, Stefan–Boltzmann constant; τ, optical coordinate; τ_0, optical density of gas layer.

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