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PROBLEM OF DETERMINING THE EFFECTIVE TEMPERATURE IN COMBUSTION CHAMBERS OF HEAT AND POWER INSTALLATIONS

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The effect of the dimensions of the constant temperature core in a radiating planar, nonisothermal, nonscattering layer on the magnitude of the effective temperature is examined. Computed effective temperatures of such a layer, obtained with the use of various methods, are also compared.

As studies of the temperature fields in furnaces in modern large-volume boiler systems show, at some distance from the section in which the burners are located, the temperature of the furnace gases is equalized at the center [1]. As the number of burners increases, the probability for realizing a flat temperature profile increases. However, henceforth, the nature of the temperature profile T(x) along the flame in the furnace section changes due to convection, gradually transforming into a Shlikhting-type temperature profile [2]. In this connection, there naturally arises the problem of the effect of the size of the constant temperature core (plateau or "table") on the effective temperature T_{eff} of the radiating space, which has the type of cross-sectional temperature profile indicated.

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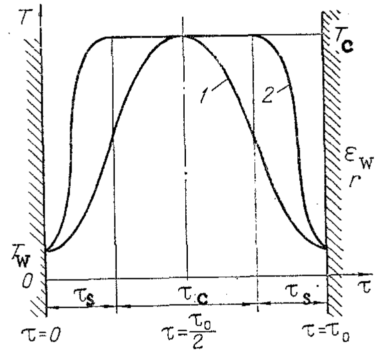

Fig. 1. Computational scheme for the temperature profile in a planar layer: 1) $\tau_c = 0$; 2) 0.5.

Taking into account the ratios of the linear dimensions of the cross section of the furnace of a powerful boiler system in the first approximation, in calculating heat exchange, the real system can be replaced by a model with a planar radiating layer. In a series of works [3, 4], methods are proposed for calculating the radiative heat exchange for such models with a given temperature field, while in [5, 6], justification was provided for correctly including the effective temperature of a planar radiating nonscattering layer, starting from an exact solution to the equation of radiative transfer in the presence of reflecting and radiating boundary surfaces. In particular, the temperature distribution existing at the center of the profile of the constant temperature core is examined in [6]. In the present work, we examine the effect of the size of this core on the value of the effective temperature determined, and the results are compared with the computed effective temperatures of a planar layer, obtained using approximate methods and presented in [3, 7, 8].

The model used for the computations consist of a symmetrical temperature profile (Fig. 1), in which the temperature in the near-wall region follows a third degree parabolic law and has a flat appearance (curve 2). Such a temperature profile for the reduced temperature $\Theta = \lambda T$ can be given analytically in the following form [6]:

$$\Theta(\tau) = \begin{cases} \Theta_W + (\Theta_c - \Theta_W)\cdot 6.75\,\dfrac{\tau^2(\tau - \tau_0)}{\tau_k^3}, & 0 \leqslant \tau \leqslant \tau_s; \\ \Theta_c, & \tau_s \leqslant \tau \leqslant \tau_0 - \tau_s; \\ \Theta_W + (\Theta_c - \Theta_W)\cdot 6.75\,\dfrac{(\tau_0 - \tau)^2(\tau - \tau_k - \tau_0)}{\tau_k^3}, & \tau_0 - \tau_s \leqslant \tau \leqslant \tau_0, \end{cases} \tag{1}$$

where $\tau = \int\limits_0^x \varkappa(x)\,dx$ is the optical thickness of the layer; $\tau_s = (2/3)\tau_k$.

In the calculations, the magnitude of τ_c, i.e., the region along the layer in which the temperature is constant and equals T_c, constituted 0, 0.2, 0.5, 0.8, and 0.9 of the total optical thickness of the layer τ_0. The computed effective reduced temperatures $\Theta_{eff} = \lambda T_{eff}$ [6] are obtained by varying the optical thickness τ_0 from 0.5 to 20; the maximum reduced temperature along the axis (in the core) Θ_c lies in the range $1\cdot10^{-3}$–$15\cdot10^{-3}$ m·K and the ratio Θ_c/Θ_W, which characterizes the gradient of the temperature distribution for values equal to 1.5, 2.0, 2.5, and 3.0. The limits for the maximum reduced temperature were chosen, as indicated in [6], according to the values of the real temperature and the region of wavelengths of thermal radiation that occur in the combustion chambers of power installations.

As could be expected, the results of the computations showed that the effective reduced temperature of a planar layer Θ_{eff} depends strongly on the form of the temperature distribution (Fig. 2). The sharpest change occurs when the size of the constant temperature zone (core) approaches in magnitude the total optical thickness of the layer τ_0. In addition, as the value of τ_0 increases, the dependence of Θ_{eff} on τ_c for $\Theta_c > 5\cdot10^{-3}$ m·K with $\tau \to 0$ reaches the asymptote (curves 4 and 5 on Figs. 2b and c). For small values of τ_0, the dependence of Θ_{eff} on τ_c approximates a linear function for the entire range of variation in Θ_c. Noting that the conclusions indicated above follow from the well-known fact that the radiation from the high temperature zones is "locked in" by the cold near-wall layers, it should also be noted that this well-known fact must be evaluated quantitatively. For this purpose, Fig. 2 displays the exact data, while the appropriate calculations are performed in [9].

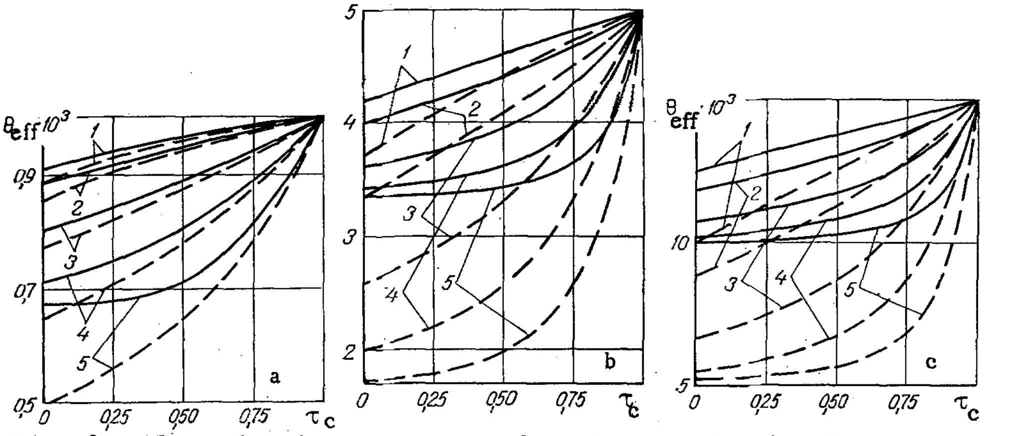

Fig. 2. The reduced temperature of a planar radiating layer as a function of the size of the constant temperature core τ_c (solid lines — $\Theta_c/\Theta_w = 1.5$; dashed lines — $\Theta_c/\Theta_w = 3.0$): a) $\Theta_c = 1\cdot10^{-3}$ m·K; b) $5\cdot10^{-3}$ m·K; c) $15\cdot10^{-3}$ m·K; 1) $\tau_0 = 0.5$; 2) 2; 3) 5; 4) 10; 5) 20.

The problem of radiation from nonisothermal spaces has, in principle, been examined from the very beginning of the theory of radiative transfer. The number of publications concerned with engineering applications of the theory of radiative heat exchange continuously increases. Recently, the idea of expanding characteristic radiation function (or Planck's function) in a series with respect to the coordinates has been widely disseminated. This method is presented in greatest detail in the researches of Mikk [3, 7, 8]. With the help of this technique, the author was able to deduce formulas for determining the effective temperature and the emissivity of nonisothermal spaces with different configurations (planar layer, semiinfinite slit, infinite cylinder, etc.). A numerical example of the computation of the effective temperature and radiation from a planar layer is examined in [3] for a temperature profile of the form

$$T = T_c \sqrt{1 - \frac{3}{4} p^2}, \quad 0 \leqslant p \leqslant 1, \tag{2}$$

or in our notation

$$T = T_c \sqrt{1 - \frac{3}{\tau_0^2}\left(\tau - \frac{\tau_0}{2}\right)^2}, \tag{3}$$

where $T_c = 2T_w = 2000°K$. In [3], the effective temperature is found for three cases: integral (gray) radiation and monochromatic radiation with wavelengths $\lambda = 0.65$ μm and $\lambda = 15$ μm. It is of interest to compare the results of these calculations with data on T_{eff} obtained with the use of an exact solution to the equations of radiative transfer for a planar layer as in [6]. A comparison, presented in Fig. 3, leads to the conclusion that the results computed according to these methods agree very well. The greatest disagreement is observed for the case of short wavelength radiation ($\lambda = 0.65$ μm), and furthermore, this disagreement with respect to the effective temperature T_{eff} determined according to our technique for this wavelength increases for larger values of the optical thickness of the layer from 0.3 to 7.2% for $\tau_0 = 10$. If for $\lambda = 0.65$ μm the effective temperatures T^* [3] are mainly higher than T_{eff}, then for $\lambda = 15$ μm, as can be seen in Fig. 3, for small values of τ_0 the magnitude of T^* is somewhat lower, while for large τ_0 it is somewhat higher, and in addition, the difference between them (T^* and T_{eff}) does not exceed 2% over the entire range of optical thicknesses of the planar layer examined ($\tau_0 = 1$–10).

The effective temperature T^* [3], determined for the integral radiation, differs from T_{eff} within the limits of the disagreement occurring for the cases of monochromatic radiation indicated above.

Thus, the technique for calculating the radiation in nonisothermal spaces, developed by expanding the characteristic radiation function in a Taylor series with respect to the coordinate along the direction of a ray [3], is valid and, on the whole, gives results that agree well with the exact solution for a planar layer [5, 6].

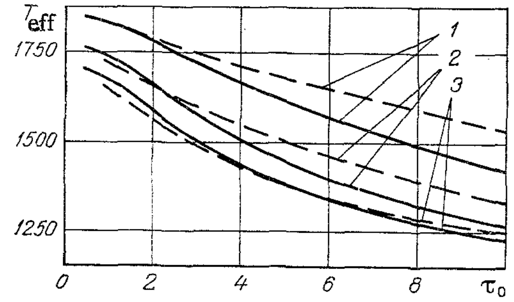

Fig. 3

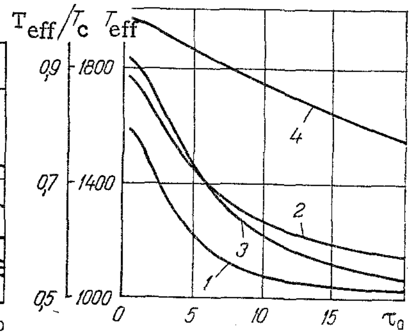

Fig. 4

Fig. 3. Comparison of the results of a calculation of the effective temperature of a radiating nonisothermal planar layer (T_c = 2000°K, $T_c/T_w = 2$): 1) $\lambda = 0.65$ μm; 2) integral (gray) radiation; 3) $\lambda = 15$ μm. Solid curves correspond to a calculation according to [6]; the dashed lines correspond to a calculation according to [3]. T_{eff} in °K.

Fig. 4. The ratio T_{eff}/T_c and the effective temperature of a planar layer with a nonisothermal medium T_{eff} (K) for T_c = 2000°K as a function of the optical thickness of the layer for different forms of the cross-sectional temperature profile: 1) $T_1(\tau)$ [2]; 2) $T_9(\tau)$ [3]; 3) $T_6(\tau)$ [6]; 4) $T_8(\tau)$ [6].

The differences occurring in the calculations (<10%) can be explained, in our opinion, as follows: for short wavelengths, by the great sensitivity of Planck's function to temperature; and, for $\tau \to \infty$ (for large values of τ_0), by the increase in the error when taking into account a large number of terms in the series expansion.

Figure 4 shows the effective integral temperature of a planar radiating nonisothermal layer as a function of the optical thickness for various forms of the temperature distribution throughout the cross section, computed according to the technique in [5]. Curve 1 corresponds to Shlikhting's temperature profile $T_1(\tau)$, realized in an established turbulent flow [2]:

$$T_1(\tau) = T_w + (T_c - T_w)\left\{1 - \left|1 - \frac{2\tau}{\tau_0}\right|^{1.5}\right\}^{1.6}, \tag{4}$$

curve 2 corresponds to the temperature profile $T_9(\tau)$ according to formula (3); curves 3 and 4 correspond to temperature profiles $T_6(\tau)$ and $T_8(\tau)$ according to formula (1) for the values $\tau_s = 0.25\tau_0$ and $\tau_s = 0.05\tau_0$, respectively.* Thus the last two temperature profiles have a constant temperature core equal to $\tau_c = 0.5\tau_0$ and $\tau_c = 0.9\tau_0$

The calculations were performed for the conditions T_c = 2000°K and $T_c = 2T_w$. However, since the form of the analytic expressions for the temperature as a function of the optical thickness of the layer for the indicated temperature profiles (1), (3), and (4) presumes a linear dependence of Teff on T_c, the results of the calculations can be generalized to arbitrary values of the given (design) quantity T_c, so that the figure contains a second scale that characterizes the ratio T_{eff}/T_c.

In conclusion, it should be noted that for convenience in practical applications, it is useful to represent the final results of the calculations of radiative heat exchange in the form of nomograms and graphs for temperature distributions that are most easily realized in combustion chambers of heat and power installations. A careful analysis of such representations will reveal simple analytic expressions for the correct determination of the effective temperature of heat carriers in power installations, as done in [9] for a nonisothermal, radiating, nonscattering, planar layer. This, undoubtedly, greatly simplifies the engineering method for computing heat exchange processes in different kinds of power installations.

*Here, the labels used for the temperature profile in [6] are retained.

NOTATION

T, temperature; T_{eff} and T^*, effective temperatures determined according to the techniques in [6] and [3], respectively; $\Theta = \lambda T$, reduced temperature according to [6]; τ, optical thickness of the layer; τ_0, total optical thickness of the layer being studied; τ_c, optical thickness of the constant temperature core; x, a coordinate; $\varkappa(x)$, absorption coefficient in the medium. The following indices are used: eff, effective; w, bounding surface (wall); c, center of the layer.

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