DETERMINATION OF THE THERMAL EFFICIENCY FACTOR OF SURFACES BOUNDING A PLANE LAYER OF A NONISOTHERMAL NONDISSIPATIVE MEDIUM

V. P. Trofimov and K. S. Adzerikho

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A method to compute the thermal efficiency factor is proposed for a plane layer of nonisothermal and nondissipative medium with radiating and reflecting boundaries, and an analysis is given of its dependence on the optical thickness of the layer and the form of the temperature profile.

The analysis of the total heat transfer in stream generator fire boxes and furnaces of different desgination is based on the use of similarity theory. The dimensionless gas temperature at the output from the firebox is determined as a function of four criteria of the heating process, the Boltzmann criterion, the parameter M characterizing the progress of this process, particularly, the position of the temperature maximum in the chamber; the Bouguer criterion, and the thermal efficiency factor (TEF) of the heating surface.

Direct measurements, performed by a number of researchers [1-4], of the radiation flux q_{inc} incident on the combustion chamber wall and the return flux q_r directed from the wall into the firebox space, permitted the establishment of numerical values of the TEF defined by the formula [5]

$$\Psi = \frac{q_{inc} - q_r}{q_{inc}} \tag{1}$$

that are characteristic for different conditions of coal dust, fuel oil, and gas combustion.

Recommendations for the selection of the TEF as a function of the kind of screen, contamination of the heating surface, and species of fuel used, which are included in the standard method for a thermal analysis of boiler aggregates [6], are formulated on the basis of generalization of the experimental investigations mentioned.

The problem of an analytical determination of the TEF should include the condition of nonisothermy of the medium (because $\Psi \equiv 0$ for $\varepsilon_w + r = 1$ in the isothermal case). A considerable quantity of research investigating the nonisothermy of radiating media, particularly a theoretical analysis of the heat transmission process with the nonisothermy of the firebox space taken into account [7-9], has recently been performed.

An analytic method to determine the thermal efficiency factor of radiating and reflecting surfaces bounding a plane layer of a nonisothermal, nondissipative medium is proposed in this paper. This method is based on relationships obtained by the authors [10, 11] for the radiation intensity which result from an exact solution of the radiation transfer equation in such media. In this case, expression (1) can be written as follows for an axisymmetric temperature profile in the layer

$$\Psi = \frac{q_{inc} - q_r}{q_{inc}} = \frac{2\pi \int_0^1 I_{out}(0, \mu)\,\mu d\mu - 2\pi \int_0^1 I_r(0, \mu)\,\mu d\mu}{2\pi \int_0^1 I_{out}(0, \mu)\,\mu d\mu}. \tag{2}$$

The so-called condition of total diffusivity of the radiation [11]:

$$\int_0^1 I(\tau, \mu)\,\mu d\mu \cong \frac{1}{2} I(\tau, \mu)\Big|_{\mu=\frac{1}{2}} \tag{3}$$

A. V. Lykov Institute of Heat and Mass Transfer, Belorussian Academy of Sciences. Institute of Physics, Belorussian Academy of Sciences, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 1, pp. 102-108, July, 1980. Original article submitted October 4, 1979.

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can be used with good accuracy to obtain the relationship (2) that is convenient for practical application. Then the expressions for the outgoing and reflected radiation can easily be found

$$I_{out}(\tau_0) = \frac{1}{1-re^{-2\tau_0}}\left\{\varepsilon_W B(T_W)e^{-2\tau_0} + 2\int_0^{\tau_0} B[T(\tau')]e^{-2(\tau_0-\tau')}d\tau'\right\}, \tag{4}$$

$$I_r(\tau_0) = \varepsilon_W B(T_W) + rI_{out}(\tau_0)$$
$$= \frac{1}{1-re^{-2\tau_0}}\left\{\varepsilon_W B(T_W) + 2r\int_0^{\tau_0} B[T(\tau')]e^{-2(\tau_0-\tau')}d\tau'\right\}. \tag{5}$$

Using the integral notation

$$2\int_0^{\tau_0} B[T(\tau')]e^{-2(\tau_0-\tau')}d\tau' = \Phi(\tau_0),$$

we rewrite (4) and (5) as follows

$$I_{out}(\tau_0) = \frac{1}{1-re^{-2\tau_0}}[\varepsilon_W B(T_W)e^{-2\tau_0} + \Phi(\tau_0)], \tag{6}$$

$$I_r(\tau_0) = \frac{1}{1-re^{-2\tau_0}}[\varepsilon_W B(T_W) + r\Phi(\tau_0)].$$

Consequently, we have the following expression

$$\Psi = 1 - \frac{\varepsilon_W B(T_W) + r\Phi(\tau_0)}{\varepsilon_W B(T_W)e^{-2\tau_0} + \Phi(\tau_0)}. \tag{7}$$

to determine the thermal efficiency factor of the boundary surface.

The integral $\Phi(\tau_0)$ being examined is related by a simple relationship to the Planck function, the radiation of an absolutely black body under a specific effective temperature T_{ef} [11] for a given nonisothermal layer:

$$\Phi(\tau_0) = (1 - e^{-2\tau_0})B(T_{ef}). \tag{8}$$

We then write (7) in the form

$$\Psi = 1 - \frac{\varepsilon_W B(T_W) + r(1-e^{-2\tau_0})B(T_{ef})}{\varepsilon_W B(T_W)e^{-2\tau_0} + (1-e^{-2\tau_0})B(T_{ef})} = 1 - \frac{(1-e^{-2\tau_0})r + b\varepsilon_W}{1-(1-b\varepsilon_W)e^{-2\tau_0}}, \tag{9}$$

where $b = B(T_W)/B(T_{ef})$.

Values of the thermal efficiency factor for the boundary surfaces of a nonisothermal, nondissipative plane layer were computed as a function of the optical thickness, the values of the temperature at the boundary and at the center of the layer, and the radiation characteristics of the bounding surfaces. The limits of the temperature values were selected according to real temperatures which occur in power plant combustion chambers, particularly, steam generator fireboxes for the 1-10 μm radiation wavelength range, i.e., which is characteristic for the thermal radiation of industrial flames. Specific ranges of variation of the other design parameters are indicated in [11].

We performed an appropriate analysis of the influence of the kind of temperature profile on the magnitude of the TEF. The computations mentioned were performed on an EC-1022 electronic computer for five kinds of eight temperatures profiles given analytically and presented in [11]. The subscript i later denotes the number of the temperature distribution in conformity with the above-mentioned paper. Among them are the Schlichting profile for a steady turbulent flow [12], as well as temperature profiles assuming the presence of a core with a constant temperature at the center.

The characteristic dependences of the thermal efficiency factor of the boundary surfaces of the considered system on the optical thickness of a layer with Schlichting temperature profile are represented in Fig. 1. Here the radiation characteristics of this surface, the wall emissivity ε_W and the reflection coefficient r, are taken as parameters, where the condition $\varepsilon_W \leq 1 - r$ is conserved if the quantities ε_W and r are given. For moderate values of the reduced temperature at the center of the profile ($\Theta_C = \lambda T_C \leq 5 \cdot 10^{-3}$ m·K), the TEF dependences on τ_0 were obtained graphically in the form of a bundle of curves which diverge as τ_0 grows (Fig. 1a). The upper

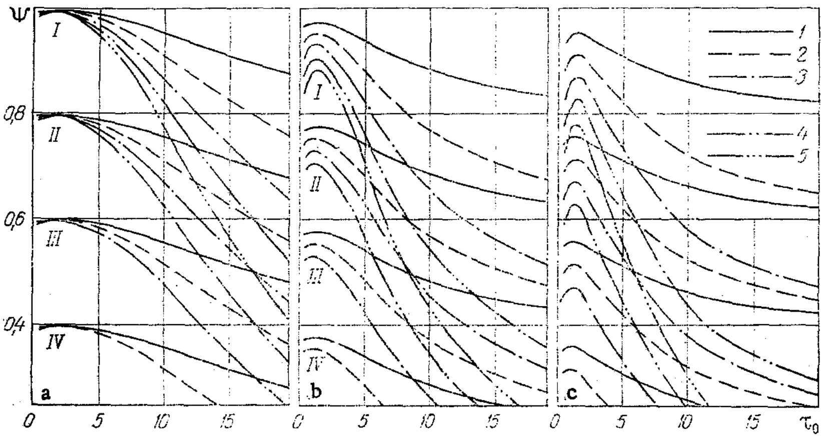

Fig. 1. Dependence of the thermal efficiency factor of the boundary surfaces on the optical thickness of the layer (Schlichting temperature profile [12], $\Theta_c/\Theta_w = 3.0$: a) $\Theta_c = 5 \cdot 10^{-3}$ m·k; b) $10 \cdot 10^{-3}$; c) $15 \cdot 10^{-3}$ [1) $\varepsilon_w = 0.2$; 2) 0.4; 3) 0.6; 4) 0.8; 5) 1.0; I) r = 0; II) 0.2; III) 0.4; IV) 0.6].

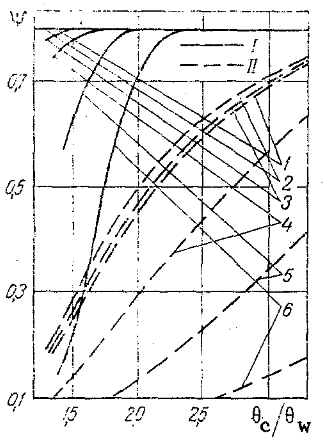

Fig. 2

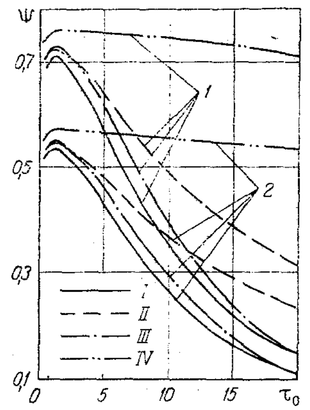

Fig. 3

Fig. 2. Dependent of the thermal efficiency factor of the boundary surfaces on the gradient of the temperature profile in the layer (Schlichting profile [12], $\varepsilon_w = 0.8$; r = 0.2); 1) $\tau_0 = 0.5$; 2) 1.0; 3) 2.0; 4) 5.0; 5) 10; 6) $\tau_0 = 20$; I) $\Theta_c = 1 \cdot 10^{-3}$ m·K; II) $10 \cdot 10^{-3}$ m·K.

Fig. 3. Dependence of the thermal efficiency factor of the boundary surfaces on the optical thickness for different kinds of temperature distributions in the layer ($\Theta_c = 10 \cdot 10^{-3}$ m·K; $\Theta_c/\Theta_w = 1.5$); 1) $\varepsilon_w = 0.8$; r = 0.2; 2) $\varepsilon_w = 0.6$; r = 0.4; I) i = 1; II) 3; III) 5; IV) i = 8 (numbers of the temperature distributions are given in conformity with [11]).

fan of curves I corresponds to the value r = 0, the next fan of curves II to r = 0.2, etc. The upper curve in each fan corresponds to the value $\varepsilon_w = 0.2$, the next to $\varepsilon_w = 0.4$, etc.

Therefore, for low values of the layer optical thickness τ_0 in the domain $\Theta \leq 5 \cdot 10^{-3}$ m·K, the quantity Ψ is practically independent of ε_w. It should also be noted that in the case $\varepsilon_w = 0$ the curves of the dependence of the TEF on the optical thickness τ_0 degenerate into straight lines parallel to the horizontal axis for any values of r, where $\Psi = 1$ for r = 0, $\Psi = 0.8$ for r = 0.2, etc. These lines are not shown on the graph for the cases mentioned.

The fan of curves already diverges for small τ_0 as the reduced temperature rises at the center of the layer (Fig. 1b). Other parameters of the computation being equal, a diminution in the absolute values of Ψ is observed. The greatest diminution in the absolute values of the TEF for plane layers with identical optical

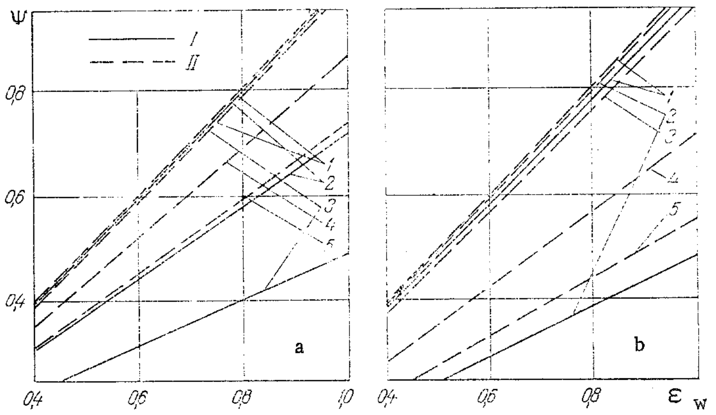

Fig. 4. Dependence $\Psi = f^*(\varepsilon_W)$ for a plane layer with a Schlichting temperature profile [12](a) τ_0=0.5; b) 5): 1) $\Theta_c = 1 \cdot 10^{-3}$ m · K; 2) $3 \cdot 10^{-3}$; 3) $5 \cdot 10^{-3}$; 4) $10 \cdot 10^{-3}$; 5) $\Theta_c = 15 \cdot 10^{-3}$ m · K; I) Θ_c/Θ_W = 1.5; II) 3.0.

thicknesses corresponds to the computed curves for Ψ as the quantity ε_W grows, i.e., with the reduction in the fraction of radiation from the layer which has passed through the boundary surface. Analogous dependences of $\Psi = \Psi(\tau_0)$ are displayed in Fig. 1c, but for a still higher value $\Theta_c = 15 \cdot 10^{-3}$ m · K. Results of the computations lead to a deduction about the strong dependence of the TEF on the gradient of the temperature distribution (Fig. 2) and the kind of temperature profile in the layer (Fig. 3). An increase in the constant-temperature core results in a strong growth of the TEF. Since the temperature profile in sections with the height of the boiler-aggregate firebox vaires from a flat-top to a Schlichting type profile, the quantity Ψ is not constant, but diminishes gradually to the exit from the firebox. This change in Ψ depends substantially on the type of boiler aggregate and the fuel burning conditions.

Despite the complexity of the analytical expression governing the dependence of the TEF on the radiation characteristics of the boundary surfaces of the plane layer of a radiating, nondissipating medium, an almost linear dependence is obtained $\Psi = f(\varepsilon_W)$ (Fig. 4). It should be noted that not the "pure" dependence $\Psi = f(\varepsilon_W)$ is displayed in this case for the other invariant parameters, but the obtained upon conservation of the condition $\varepsilon_W = 1 - r$. The "pure" $\Psi = f(\varepsilon_W)$ for r = const will evidently have a different graphical form. However, the dependence of Ψ on ε_W may be assumed linear for opaque boundary surfaces, which is quite important in the interpretation of experimental data.

A slight nonlinearity of the function $\Psi = f(\varepsilon_W)$ is observed for the computed results obtained for a plane layer with a low value of optical thickness on the order of $\tau_0 \sim 0.5$ for the values $\Theta_c > 3 \cdot 10^{-3}$ m · K. It should truly be noted that in the range $0.5 \leq \varepsilon_W \leq 1.0$, a linear dependence is also detected even for plane layers characterized by values of the optical thickness on the order of $\tau_0 \sim 0.5$ and by the reduced temperature $\Theta_c > 3 \cdot 10^{-3}$ m · K. Therefore, the linear nature of the function $\Psi = f(\varepsilon_W)$ is retained in the domain of values of the boundary surface emissivity, that occurs in the thermally stressed zones of the combustion chambers of thermal power plants.

The graphs presented (Fig. 4) are constructed from results calculated for a gradient of the profile $\Theta_c/\Theta_W = 1.5$. An analogous pattern is obtained for higher values of this ratio. But the linearity domain of the curves for the TEF diminishes in the parameter Θ_c in these cases and, particularly for the values $\Theta_c/\Theta_W = 3.0$, it is bounded by the reduced temperature range $\Theta_c > 7 \cdot 10^{-3}$ m · K.

Since the nonlinearity of the function $\Psi = f(\varepsilon_W)$ is insignificant, the computed curve can then be replaced by an approximate conditional line $\Psi = f^*(\varepsilon_W)$ passing through the origin and the center of the linear section of the computed curve located within the limits $0.5 \leq \varepsilon_W \leq 1.0$. To estimate the error thus admitted, we present a comparison of the exact and approximate results, determined for a plane layer with the following characteristics $\tau_0 = 0.5$; $\Theta_c = 15 \cdot 10^{-3}$ m · K and two limit values $\Theta_c/\Theta_W = 1.5$ and 3.0 (Table 1), as an illustration.

Therefore, a linear approximation in the determination of the thermal efficiency factor Ψ for a plane radiating layer with a low value of the optical thickness yields a maximum error on the order of 5-6% in the worst case (low values of the ratio Θ_c/Θ_W) for the range of variation in the emissivity of the boundary surfaces $0.5 \leq \varepsilon_W \leq 1.0$ of interest to us.

TABLE 1. Comparison of Exact and Approximate Results

ε_w	0,2	0,4	0,6	0,8	1,0
		$\Theta_c/\Theta_w = 1{,}5$			
$\Psi = f(\varepsilon_w)$	0,060	0,112	0,157	0,197	0,232
$\Psi = f^*(\varepsilon_w)$	0,049	0,099	0,148	0,197	0,246
Error, %	−17,8	−12,0	−5,6	0	+6,3
		$\Theta_c/\Theta_w = 3{,}0$			
$\Psi = f(\varepsilon_w)$	0,159	0,311	0,456	0,596	0,730
$\Psi = f^*(\varepsilon_w)$	0,149	0,298	0,447	0,596	0,746
Error, %	−6,2	−4,2	−1,7	0	+2,1

As is known, methods of computing boiler-aggregate fireboxes were compiled on the basis of using the "grey" approximation for the emissivity. The use of a "grey" model for heat transfer computations in the fireboxes of modern powerful boiler aggregates cannot assure the accuracy needed. In this connection, intensive investigations of the spectral characteristics of firebox media (the combustion products) and heating surfaces, including those covered by incrustations ([13-15] for instance), have been performed recently.

Therefore, the results of the present paper make available a broad possibility of a theoretical analysis of the spectral values of the TEF of heating surfaces over the height of a boiler-aggregate firebox, and correspondingly, exact computations of the local $\Psi(\lambda)$ for known experimental results of $\tau(\lambda)$ and $\varepsilon_w(\lambda)$ for definite temperature profiles.

NOTATION

Ψ, thermal efficiency factor (TEF) of the heating surface; q_{inc}, q_r, incident and return radiation fluxes, respectively; $I_{out}(0, \mu)$ and $I_r(0, \mu)$, intensity of radiation going out from and reflected back to the layer, respectively; $\theta = \arccos\mu$, angle of observation; τ, optical thickness of the layer; τ_0, total optical thickness of the layer under investigation; ε_w, r, and T_w, emissivity, reflexivity, and temperature of the boundary surface, respectively; $B = B[T(\tau)] = (2h\nu^3/c^2)(e^{h\nu/kT} - 1)^{-1}$, Planck radiation; λ, radiation wavelength; $\Theta = \lambda T$, reduced temperature in according to [10]. Subscripts: ef, effective; w, boundary surface (wall); c, center of the layer.

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ON THE OPTIMAL TEMPERATURE PROFILE OF SELECTIVE GASES UNDER RADIANT HEAT TRANSFER

Yu. A. Popov, M. M. Mel'man, and A. S. Nevskii

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It is shown that a selective gas temperature profile exists for which radiant heat flux is a maximum in the heating surface. The mean, minimum, and maximum gas temperatures are determined.

The paper [1] is devoted to the question of the influence of furance gas temperature profiles on the resultant radiant heat flux q in a heating surface. The necessity is shown there for taking account of the real temperature field in evaluating the quantity q. Computations were executed taking the selectivity of the gas radiation into account. It is shown here that there exists a temperature profile for which q is a maximum. For simplicity, we assume the lining to be absolutely black and adiabatic, the heating surface nonselective, and we simulate the furnace geometry by a plane layer. The higher the emissivity of the lining, the greater the q since the intrinsic radiation of the lining is transmitted better by a selective gas than the reflected radiation containing the gas band in its spectrum.

Let Q_1 be the intrinsic gas radiation on the heating surface and Q_2 on the lining. The expression for q has the form

$$q=-Q_{01}+(1-r)\left[Q_1+D_2(l)\,Q_{02}\right]. \tag{1}$$

From the adiabatic condition of the lining, we have

$$Q_{02}=Q_2+D_1(l)\,Q_{01}+rQ_1D_3(l)+Q_{02}D_2(2l) \tag{2}$$

and we obtain from (1) and (2)

$$q=-Q_{01}+(1-r)\left\{Q_1\left[1+r\frac{D_2(l)\,D_3(l)}{1-rD_2(2l)}\right]+Q_2\frac{D_2(l)}{1-rD_2(2l)}+\frac{Q_{01}D_2(l)\,D_1(l)}{1-rD_2(2l)}\right\}. \tag{3}$$

For a fixed mean gas temperature, the coefficients of Q_1, Q_2, and Q_{01} are practically independent of Q_1, Q_2, and r. Then, if the coefficient of Q_2 in (3) is greater than the coefficient of Q_1, then it is energetically advantageous to organize the furnace heating scheme with the greatest possible value of Q_2, i.e., when the torch is directed to the crown (indirect mode). The condition for preference of the indirect over the direct heating mode

$$\frac{D_2(l)}{1-rD_2(2l)}>1+\frac{rD_2(l)\,D_3(l)}{1-rD_2(2l)}, \tag{4}$$

follows from (3), and can be written as

$$r>\frac{1-D_2(l)}{D_2(2l)-D_2(l)\,D_3(l)}. \tag{5}$$

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