THERMAL-PERFORMANCE COEFFICIENT FOR A SCREEN IN A STEAM-GENERATING BOILER

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A model is proposed for the thermal-performance coefficient for a screen in a steam-generating boiler.

The thermal-performance coefficient, which is defined as follows [1], is often used in relation to the rate of heat transfer due to radiation between the medium and the surrounding surfaces:

$$\Psi = q_{res}/q_{inc}. \tag{1}$$

The resultant radiation flux q_{res} is defined as the difference between the incidence flux q_{inc} and the effective flux $q_{w.ef}$ from the surface:

$$q_{res} = q_{inc} - q_{w.ef}.$$

An expression for Ψ is readily found from the radiation-transport equation for a layer of absorbing medium bounded by reflecting and radiating surfaces [2, 3]. In the present case we consider a planar layer of nonisothermal nonscattering medium. From the definition of (1) we have:

$$\Psi = \frac{\int_0^1 I_{inc}(\mu)\mu d\mu - \int_0^1 I_{w.ef}(\mu)\mu d\mu}{\int_0^1 I_{inc}(\mu)\mu d\mu}. \tag{2}$$

We substitute the explicit expression for I(μ) into (2) to get the formula for Ψ as [4]:

$$\Psi = 1 - \frac{\varepsilon_w B(T_w) + r_w \Phi(\tau_0)}{\varepsilon_w B(T_w) e^{-2\tau_0} + \Phi(\tau_0)}. \tag{3}$$

Here

$$\Phi(\tau_0) = 2\int_0^{\tau_0} B[T(\tau)] e^{-2(\tau_0-\tau)} d\tau.$$

This formula shows that the performance coefficient is substantially dependent on the radiation characteristics of the boundary surface, as well as on the parameters and state of the radiating medium. The I and consequently Ψ are very much dependent on the radiation frequency because of the complex structure of the emissivity of the CO_2 and H_2O combustion products.

If we introduce the effective temperature T_{ef} [2, 3] we can write (3) as

$$\Psi = 1 - \frac{(1 - e^{-2\tau_0}) r_w + b\varepsilon_w}{1 - (1 - b\varepsilon_w) e^{-2\tau_0}}, \tag{4}$$

where

$$b = \frac{B(T_w)}{B(T_{ef})} = \frac{\exp\frac{hc}{k\lambda T_{ef}} - 1}{\exp\frac{hc}{k\lambda T_w} - 1}. \tag{5}$$

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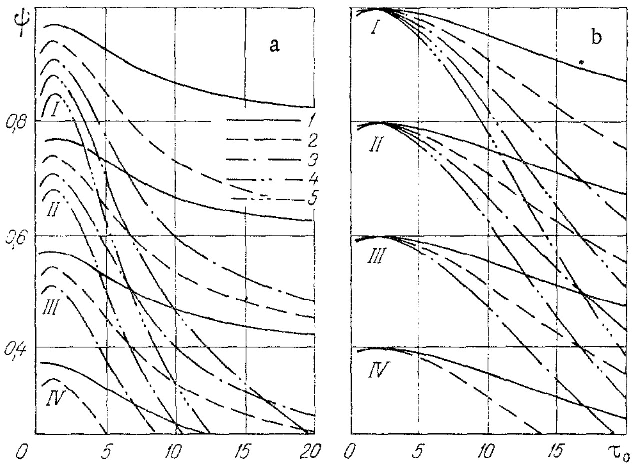

Fig. 1. Dependence of Ψ on τ_0 for a layer with the Schlichting temperature profile [5] for $\Theta_d = 5 \cdot 10^{-3}$ m•K (a — $\Theta_c/\Theta_w = 2$; b — $\Theta_c/\Theta_w = 3$): I) $r_w = 0$; II) 0.2; III) 0.4; IV) 0.6; 1) $\varepsilon_w = 0.2$; 2) 0.4; 3) 0.6; 4) 0.8; 5) 1.0.

For the radiation in the complete spectrum the parameter is

$$b = (T_w / T_{ef})^4. \tag{6}$$

A detailed study has been made [4] of the performance coefficients for boundary surfaces around a nonisothermal nonscattering layer in relation to the optical thickness of the latter, the temperature distribution in the layer, and the radiation characteristics of the boundary surfaces. The calculations incorporated the fact that the boundary surface may be partially transparent to the spectral radiation flux and to the total spectrum.

The radiation fluxes for a nonisothermal layer are very much dependent on the temperatures at the center and at the boundary, so a careful analysis was made of the effects of the performance coefficient on the form of the temperature distribution in the layer. A Schlichting profile for the steady-state turbulent flow [5] was given particular attention, and also a distribution representing a core of constant temperature in the profile.

Parts a and b of Fig. 1 show Ψ as a function of τ_0 for various values of r_w and ε_w for two values of T_c/T_w, viz., 2 and 3, and also for $\Theta_c = 5 \cdot 10^{-3}$ m•K.

Although (3) is complicated, it defines the dependence of the performance coefficient on the radiation characteristics of the boundary surfaces r_w and ε_w, together with the optical thickness τ_0 of the layer, and it is clear from detailed results that Ψ is nearly linearly dependent on ε_w over a wide range in τ_0. It is simple to analyze the dependence of the coefficient on the properties of the medium and the surface itself by considering the effective degree of blackness $\varepsilon_0 = 1 - e^{-2\tau_0}$ [2, 3] instead of τ_0.

We denote the thermal radiation fluxes by $q_0 = \pi\varepsilon_0 B(T_{ef})$ and $q_w = \pi\varepsilon_w B(T_w)$ and bear in mind that the bounding surface is opaque ($\varepsilon_w + r_w = 1$), which gives

$$q_{inc} = q_0 + (1 - \varepsilon_0)[q_w + (1 - \varepsilon_w) q_{inc}]$$

or

$$q_{inc} = \frac{\varepsilon_0 B(T_{ef}) + \varepsilon_{ст}(1 - \varepsilon_0) B(T_w)}{\varepsilon_w + \varepsilon_0 - \varepsilon_w \varepsilon_0}. \tag{7}$$

Similarly, we get for the effective flux on the wall

$$q_{w,ef} = \pi\varepsilon_w B(T_w) + (1 - \varepsilon_w) q_{inc}$$

or

$$q_{w,ef} = \pi\varepsilon_w B(T_w) + \pi(1 - \varepsilon_w) \frac{\varepsilon_0 B(T_{ef}) + \varepsilon_w (1 - \varepsilon_0) B(T_w)}{\varepsilon_w + \varepsilon_0 - \varepsilon_w \varepsilon_0}. \tag{8}$$

The resultant flux is

$$q_{res} = \pi\varepsilon_w \left[\frac{\varepsilon_0 B(T_{ef}) + \varepsilon_w (1-\varepsilon_0) B(T_w)}{\varepsilon_w + \varepsilon_0 - \varepsilon_w \varepsilon_0} - B(T_w)\right]. \tag{9}$$

Using (7) and (9) we readily get the performance coefficient:

$$\Psi = \varepsilon_w \left(1 - \frac{\dfrac{1}{\varepsilon_0} + \dfrac{1}{\varepsilon_w} - 1}{\dfrac{1}{\varepsilon_0} + \dfrac{1}{b\varepsilon_w} - 1}\right). \tag{10}$$

Expression (10) corresponds identically to (4).

Calculations from (10) show that the dependence of Ψ on ε_w is close to linear for these conditions on τ_0 and T_c/T_w; the formula allows us to calculate Ψ from experimental values of ε_w and ε_0, together with T_w and T_{ef}. Here the greatest difficulties arise in determining T_w. From simple balance relations, we have

$$(1-\Psi) q_{inc} = \pi\varepsilon_w B(T_w) + (1-\varepsilon_w) q_{inc}$$

or

$$B(T_w) = \frac{1}{\pi}\left(1 - \frac{\Psi}{\varepsilon_w}\right) q_{inc}. \tag{11}$$

For the integral radiation flux, (11) becomes

$$T_w = \sqrt[4]{\left(1 - \frac{\Psi}{\varepsilon_w}\right)\frac{q_{inc}}{\sigma_0}}, \tag{12}$$

which was derived by Mitor [1] for screened heating surfaces in steam generators. We see from (12) that Ψ cannot exceed ε_w in value.

From (10) and (12) we have

$$T_w = \sqrt[4]{\frac{\dfrac{1}{\varepsilon_0} + \dfrac{1}{\varepsilon_w} - 1}{\dfrac{1}{\varepsilon_0} + \dfrac{1}{b\varepsilon_w} - 1}\,\frac{q_{inc}}{\sigma_0}}. \tag{13}$$

Figure 2 shows how Ψ varies with ε_w, and also with τ_0 and Θ_c for $\Theta_c/\Theta_w = 2$ for a Schlichting temperature profile. The upper straight line corresponds to the limiting case where $\Psi = \varepsilon_w$ and $T_w = 0$; the effective flux from the wall under these conditions is due to reflection of the incident flux from the boundary layer.

The linear relationship of Ψ to ε_w of [4] is confirmed for the wide range of surface blacknesses $0.5 \leqslant \varepsilon_w \leqslant 1$ even in the most unfavorable case of Θ_c/Θ_w small. The maximum error of the linear approximation is not more than 6% in Ψ.

These formulas give a model for the thermal performance of receiving surfaces, e.g., screens in steam boilers. These screens are coated on the outside by low-conductivity deposits, which appreciably reduce the thermal uptake [1, 6-14]. In the present case, ε_w and T_w relate to the outer surface of the deposits. For the above conditions, the model describes the thermal operation of the screen when the fuel is gas or heavy oil. The combustion products include not only CO_2 and H_2O but also small particles of carbon, whose scattering coefficients are negligible in comparison with the absorption coefficient. Therefore, the scattering can be neglected.

The data of Fig. 1b relate to curve families II and III, and for optical thicknesses $\tau_0 \leqslant 5$ characteristic of steam generators one can interpret these as values for the thermal performance in the combustion of gas ($\Psi \approx 0.8$) and heavy oil ($\Psi \approx 0.6$). These values of Ψ are close to those found by experiment [1, 7, 8, 10-14].

Also, the performance factor is only very slightly dependent on τ_0 and ε_w for the above values $\tau_0 \leqslant 5$ and for the Θ_c/Θ_w and Θ_c found in steam generators. Therefore, the data justify the assumption [10] of constant numerical values for the performance coefficients independent

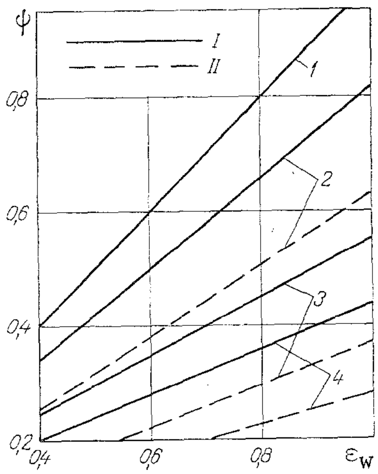

Fig. 2

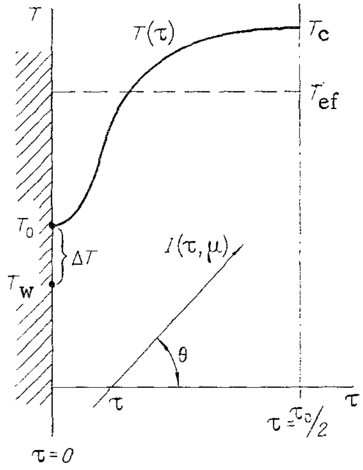

Fig. 3

Fig. 2. The $\Psi(\varepsilon_w)$ relation for a planar layer with a Schlichting temperature profile [5] with $\Theta_c/\Theta_w = 2$ (I — $\tau_0 = 0.5$; II — 5): 1) $\Theta_c = 1 \cdot 10^{-3}$ m·K; 2) $5 \cdot 10^{-3}$; 3) $10 \cdot 10^{-3}$; 4) $15 \cdot 10^{-3}$ m·K.

Fig. 3. A nonisothermal radiating layer with a temperature discontinuity at the wall.

of the load. The upper straight line in Fig. 2 also relates to minimum contamination of the receiving surfaces, where the temperature of the outer surface of a clean screen is low by comparison with the flame temperature. Under these conditions, the radiation from the screen itself can be neglected in comparison with the radiation from the flame [15]. The flux of effective radiation from the screen is due in that case only to reflection of the incident radiation.

Previous studies of such layers [2-4] were made on the assumption that the temperature at the wall T_0 is equal to T_w itself. This condition usually applies for an optically thick layer, where $\tau_0 \gg 1$ and the Rosseland diffusion approximation applies.

Under real conditions such as in steam generators, τ_0 is usually of the order of one. There is then a temperature discontinuity at the boundary between the flame and the wall (Fig. 3). Here T_w does not coincide with T_0. The temperature step is dependent on the optical thickness of the layer:

$$\Delta\vartheta = \frac{T_0 - T_w}{T_{ef} - T_w} = F(\tau_0).$$

For $T_0 = T_w$ there is no discontinuity and $\Delta\vartheta = 0$, while for $T_0 = T_{ef}$ in particular, viz., when the temperature over the layer is constant, $\Delta\vartheta = 1$, no matter what the relationship between T_{ef} and T_w.

The physical mechanism responsible for the temperature discontinuity is that the difference is due not only to direct heat transfer (thermal conduction and convection) for these values of τ_0 but also to radiation transfer between the wall and the other parts of the furnace, including the bounding surfaces.

We used a modified Rosseland approximation to write

$$B(T_0) - B(T_w) = \frac{4}{3}\left(\frac{1}{\varepsilon_w} - \frac{1}{2}\right)\left[\frac{dB(T)}{d\tau}\right]_{\tau=0}.$$

On the basis that $T = T(\tau)$, the value of the derivative in this equation is determined by the temperature distribution in the layer, i.e., by $B[T(\tau)]$:

$$\left.\frac{dB[T(\tau)]}{d\tau}\right|_{\tau=0} = \left.B[T(\tau)]\right|_{\tau=0}\left[\frac{e^{\frac{h\nu}{kT}}\frac{h\nu}{kT}}{e^{\frac{h\nu}{kT}} - 1}\right]_{\tau=0}\left[\frac{dT(\tau)}{d\tau}\right]_{\tau=0} =$$

$$= C\left.\{B[T(\tau)]\}\right|_{\tau=0}\left(\frac{1}{T^2}e^{\frac{h\nu}{kT}}\right)_{\tau=0}\left[\frac{dT(\tau)}{d\tau}\right]_{\tau=0} = D\left[\frac{dT(\tau)}{d\tau}\right]_{\tau=0}.$$

The expression for D contains quantities independent of the type of temperature distribution. Therefore, the temperature discontinuity is dependent on the blackness of the wall and the temperature distribution.

Example. We consider an exponential temperature distribution in the layer:

$$T(\tau) = T_c \exp\left[-\alpha\left(\tau - \frac{\tau_0}{2}\right)^2\right],$$

$$\left.\frac{dT(\tau)}{d\tau}\right|_{\tau=0} = T_c \exp\left[-\alpha\left(\tau - \frac{\tau_0}{2}\right)^2\right]_{\tau=0}\left[2\alpha\left(\tau - \frac{\tau_0}{2}\right)\right]_{\tau=0} = T_c \exp\left[-\alpha\frac{\tau_0^2}{4}\right]\alpha\tau_0 = \alpha\tau_0 T_W .$$

Then for $B(T_0) - B(T_W)$ we have a relationship of direct proportionality to α, which characterizes the gradient in the profile.

Under these conditions, viz., when τ_0 is finite and of the order of one, we get a temperature discontinuity, and the effects of this on the thermal-performance coefficient may be estimated by representing (5) as

$$b = \frac{B(T_W)}{B(T_{ef})} = \frac{B(T_W)}{B(T_0)}\,\frac{B(T_0)}{B(T_{ef})} = \delta b_0. \tag{14}$$

We then naturally have $B(T_W)/B(T_0) \leqslant 1$ and $B(T_0)/B(T_{ef}) \leqslant 1$ by virtue of $T_{ef} \leqslant T_0 \leqslant T_{ef}$, so b may be determined as the product of two factors, of which $b_0 = B(T_0)/B(T_{ef})$ is the parameter for the nonisothermal nature of the medium and $\delta = B(T_W)/B(T_0)$ is the parameter characterizing the relative temperature discontinuity at the wall. For $T_0 = T_W$ we have $\delta = 1$ and $b = b_0$. The other limiting condition $T_W \ll T_0$ leads to $\delta = B(T_W)/B(T_0) \approx 0$, and then $\Psi = \varepsilon_W$ for $T_W \approx 0$, as would be expected from (10).

Parameter δ, the characteristic of the temperature discontinuity at the wall, plays an important part in the model. It is therefore of interest to make a detailed analysis of the performance coefficient as a function of δ.

We denote the Ψ for $\delta = 1$ by Ψ_0 and use (10) to determine b_0 in the absence of a temperature discontinuity:

$$b_0 = \frac{1 - \dfrac{\Psi_0}{\varepsilon_W}}{1 + \left(\dfrac{1}{\varepsilon_0} - 1\right)\Psi_0}. \tag{15}$$

Using (14) and substituting (15) into (10), we readily get Ψ for the presence of a temperature discontinuity as

$$\Psi = \varepsilon_W \frac{1 - \delta + \Psi_0\left(\dfrac{1}{\varepsilon_0} + \dfrac{\delta}{\varepsilon_W} - 1\right)}{1 + \delta\left(\dfrac{1}{\varepsilon_0} - 1\right)\varepsilon_W + (1-\delta)\left(\dfrac{1}{\varepsilon_0} - 1\right)\Psi_0} \tag{16}$$

or

$$\Psi = \frac{\left(\dfrac{1}{\varepsilon_0} + \dfrac{\delta}{\varepsilon_W} - 1\right)\Psi_0 + 1 - \delta}{\delta\left(\dfrac{1}{\varepsilon_0} - 1\right) + \dfrac{1}{\varepsilon_W} + (1-\delta)\left(\dfrac{1}{\varepsilon_0} - 1\right)\dfrac{\Psi_0}{\varepsilon_W}}. \tag{17}$$

Formula (17) relates Ψ and Ψ_0 and enables one to incorporate the effects of Ψ on δ explicitly. This implies some consequences of practical importance related to particular states of heat transfer.

The first consequence defines the conditions under which $\Psi = \Psi_0$; (17) shows that this condition is realized in two cases: 1) for $\delta = 1$, i.e., in the absence of a temperature discontinuity; and 2) for $\tau_0 \gg 1$, i.e., for an optically thick layer with $\Psi_0 \approx \varepsilon_W$. In the second case $\Psi = \Psi_0$ even if there is a temperature discontinuity at the wall, i.e., for any

TABLE 1. Values of δ for Various ΔT and T_w

T_w, K	λ, μm	δ				
		ΔT=100 K	ΔT=200 K	ΔT=300 K	ΔT=400 K	ΔT=500 K
400	1	$0,75 \cdot 10^{-3}$	$0,63 \cdot 10^{-5}$	$0,20 \cdot 10^{-6}$	$0,16 \cdot 10^{-7}$	$0,21 \cdot 10^{-8}$
	3	$0,85 \cdot 10^{-1}$	$0,16 \cdot 10^{-1}$	$0,55 \cdot 10^{-2}$	$0,23 \cdot 10^{-2}$	$0,12 \cdot 10^{-2}$
	5	0,23	$0,91 \cdot 10^{-1}$	$0,45 \cdot 10^{-1}$	$0,27 \cdot 10^{-1}$	$0,18 \cdot 10^{-1}$
	(0—∞)	0,41	0,20	$0,94 \cdot 10^{-1}$	$0,62 \cdot 10^{-1}$	$0,38 \cdot 10^{-1}$
500	1	$0,84 \cdot 10^{-2}$	$0,27 \cdot 10^{-3}$	$0,21 \cdot 10^{-4}$	$0,28 \cdot 10^{-5}$	$0,57 \cdot 10^{-6}$
	3	0,19	$0,65 \cdot 10^{-1}$	$0,27 \cdot 10^{-1}$	$0,14 \cdot 10^{-1}$	$0,84 \cdot 10^{-2}$
	5	0,39	0,20	0,12	$0,76 \cdot 10^{-1}$	$0,55 \cdot 10^{-1}$
	(0—∞)	0,48	0,26	0,15	$0,95 \cdot 10^{-1}$	$0,63 \cdot 10^{-1}$
600	1	$0,32 \cdot 10^{-1}$	$0,25 \cdot 10^{-2}$	$0,33 \cdot 10^{-3}$	$0,68 \cdot 10^{-4}$	$0,18 \cdot 10^{-4}$
	3	0,34	0,14	$0,76 \cdot 10^{-1}$	$0,44 \cdot 10^{-1}$	$0,28 \cdot 10^{-1}$
	5	0,50	0,33	0,19	0,14	0,10
	(0—∞)	0,54	0,32	0,20	0,13	$0,89 \cdot 10^{-1}$
700	1	$0,77 \cdot 10^{-1}$	$0,10 \cdot 10^{-1}$	$0,21 \cdot 10^{-2}$	$0,57 \cdot 10^{-3}$	$0,19 \cdot 10^{-3}$
	3	0,42	0,22	0,14	$0,83 \cdot 10^{-1}$	$0,58 \cdot 10^{-1}$
	5	0,59	0,39	0,28	0,21	0,16
	(0—∞)	0,58	0,36	0,24	0,16	0,12
800	1	0,13	$0,28 \cdot 10^{-1}$	$0,67 \cdot 10^{-2}$	$0,25 \cdot 10^{-2}$	$0,99 \cdot 10^{-3}$
	3	0,53	0,31	0,20	0,14	0,10
	5	0,66	0,42	0,35	0,27	0,22
	(0—∞)	0,62	0,41	0,28	0,20	0,14
900	1	0,20	$0,55 \cdot 10^{-1}$	$0,18 \cdot 10^{-1}$	$0,73 \cdot 10^{-2}$	$0,34 \cdot 10^{-2}$
	3	0,59	0,38	0,26	0,19	0,15
	5	0,71	0,54	0,42	0,35	0,29
	(0—∞)	0,66	0,45	0,32	0,23	0,17
1000	1	0,27	$0,90 \cdot 10^{-1}$	$0,36 \cdot 10^{-1}$	$0,16 \cdot 10^{-1}$	$0,82 \cdot 10^{-2}$
	3	0,64	0,44	0,32	0,25	0,19
	5	0,75	0,59	0,49	0,40	0,34
	(0—∞)	0,68	0,48	0,35	0,26	0,20
1100	1	0,33	0,13	$0,61 \cdot 10^{-1}$	$0,31 \cdot 10^{-1}$	$0,17 \cdot 10^{-1}$
	3	0,69	0,50	0,39	0,30	0,25
	5	0,79	0,64	0,54	0,45	0,40
	(0—∞)	0,70	0,51	0,38	0,29	0,22
1200	1	0,40	0,18	$0,91 \cdot 10^{-1}$	$0,50 \cdot 10^{-1}$	$0,30 \cdot 10^{-1}$
	3	0,73	0,56	0,44	0,36	0,30
	5	0,82	0,68	0,58	0,51	0,44
	(0—∞)	0,72	0,54	0,41	0,31	0,25
1300	1	0,46	0,21	0,13	$0,74 \cdot 10^{-1}$	$0,46 \cdot 10^{-1}$
	3	0,76	0,60	0,49	0,41	0,34
	5	0,83	0,71	0,62	0,54	0,49
	(0—∞)	0,74	0,57	0,44	0,34	0,27
1400	1	0,50	0,28	0,16	0,10	$0,72 \cdot 10^{-1}$
	3	0,79	0,64	0,53	0,45	0,39
	5	0,85	0,74	0,65	0,58	0,54
	(0—∞)	0,76	0,59	0,46	0,37	0,30
1500	1	0,55	0,32	0,20	0,13	$0,92 \cdot 10^{-1}$
	3	0,81	0,67	0,57	0,49	0,42
	5	0,87	0,76	0,68	0,63	0,57
	(0—∞)	0,77	0,60	0,48	0,41	0,32

value of δ different from one. In passing we note that for $\tau_0 \gg 1$ we have $\varepsilon_0 = 1 - e^{-2\tau_0} \approx 1$ and $\Psi = \delta\Psi_0 + (1 - \delta)\varepsilon_w$, which means that for $\Psi_0 \approx \varepsilon_w$ we have $\Psi \approx \varepsilon_w$.

The second consequence is that the level of Ψ_0 determines the effects of the temperature discontinuity on Ψ; the larger Ψ_0, the less important the difference between Ψ and Ψ_0.

The third consequence confirms the generality of (17) and occurs because the following conclusion follows from (17): only when the temperature discontinuity at the wall is incorporated is it possible to obtain values of Ψ corresponding to real conditions even for an isothermal radiating layer. The solution of [4] for an isothermal layer without a temperature discontinuity ($T_w = T_0 = T_{ef}$) leads to $\Psi = 0$, i.e., an adiabatic wall ($q_{res} = 0$); on the other hand, when we incorporate the temperature discontinuity ($T_w \neq T_0 = T_{ef}$) we get for the same isothermal layer ($b_0 = 1$; $b = \delta$) that $\Psi = \Psi|_{b=\delta} \neq 0$, which indicates that here $q_{res} \neq 0$.

Table 1 gives numerical values of δ corresponding to the conditions characteristic of steam generators. We give the spectral values $\delta(\lambda)$ for λ of 1, 3, and 5 μm and also the value of δ for the full spectrum. Table 1 shows that the $\delta(\lambda)$ decrease appreciably to the shortwave side, which indicates that in the spectral range we have Ψ close to ε_w for high ΔT, and the effects of deposits on the tubes are slight. These temperature conditions correspond to fairly high δ for the total spectrum, particularly at high T_w. Also, there are falls in the spectral and integral values of δ as ΔT increases. The converse effect comes from increase in the wall temperature.

This model can be used in analyzing existing experimental data on the performance of screened heating surfaces in steam generators. The model involves the assumption that the combustion medium is nonscattering. These conditions occur in burning gas and fuel oil. The soot particles in the flame are so small that the scattering effect can be neglected.

The scattering effect cannot be neglected for the combustion of coal particles. The ash and carbon particles in the flame have dimensions considerably exceeding the basic wavelength of the thermal radiation in a steam generator. Scattering at these particles largely determines the structure of the incident radiation flux, while the details of the contamination layer on the tubes determine the structure of the effective wall flux.

If one has data on the optical constants of these particles, the concentrations in the flame, and the size distributions one can solve the analogous problem on the thermal performance.

NOTATION

Ψ, thermal performance coefficient of heating surface; q_{inc} and $q_{w.ef}$, radiation flux incident on wall and effective wall radiation flux, respectively; $I(\tau, \mu)$, radiation intensity at τ in the direction θ = arc cos μ (angle of observation); τ, optical thickness; τ_0, total optical thickness of layer; x, coordinate; $\varkappa$, absorptivity; ε_w, r_w, T_w, emissivity, reflectivity, and temperature of surface, respectively; B, Planck radiation intensity at temperature T; $1/\nu = \lambda$, wavelength; h, k, c, and σ_0, constants; $\Theta = \lambda T$, reduced temperature [3]; T_0, gas (medium) temperature at wall. Subscripts: ef, effective; res, resultant; w, boundary surface (wall); inc., incident; c, layer center.

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