CONCLUSION

The experimental data obtained here and the corresponding analysis indicate the need to take account of thermal resistance in the contact zone of plates with the cooling system of the heat exchanger. This applies, above all, to heat exchangers of highly conducting material, in which the heating is from the unribbed plate, or multilayer heat exchangers. In these cases, stricter requirements must be imposed to ensure high-quality thermal contact of the plates with the cooling system.

NOTATION

a, thermal diffusivity; d_h, hydraulic diameter of channel; h_1, h_2, characteristic dimensions of heat-exchanger cell (Fig. 1); H, Heat-exchanger thickness; $K(R_T)$, coefficient defined in Eq. (8); $m = \sqrt{2\alpha/(\lambda\delta_r)}$; q, heat-flux density at heat-exchanger surface; R_{T1}, R_{T2}, thermal resistances at $x = h_1$, $x = h_2$; u, flow rate of water in channel; x, coordinate over the heat-exchanger thickness; α_0, heat-transfer coefficient from unribbed surface of channel; α, heat-transfer coefficient from ribbed surface of channel (from rib); $\alpha_{re} = q/\vartheta(h_1^-)$, reduced heat-transfer coefficient; δ_{ch}, δ_r, channel and rib width; $\varepsilon = \delta_{ch}/(\delta_{ch} + \delta_r)$; λ_{re}, λ, thermal conductivity of solder and heat-exchanger materials; $\vartheta = (t - t_w)$, excess temperature of heat exchanger with respect to water; $\Theta = \vartheta\lambda m/q$, dimensionless temperature; $\psi_i = \text{arcth}(\varepsilon\alpha_0/\{[(1 - \varepsilon) + \varepsilon\alpha_0 R_{Ti}]\lambda m\})$, dimensionless complex ($i = 1, 2$); $Pr = \nu/a$, Prandtl number; $Re = ud_h/\nu$, Reynolds number.

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INFLUENCE OF NONAXISYMMETRIC TEMPERATURE PROFILE IN LAYER OF DIFFERENT-TEMPERATURE COMPONENTS ON RADIANT HEAT TRANSFER

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On the basis of analysis of the radiant heat transfer in a layer of different-temperature components with a nonaxisymmetric temperature profile, the influence of the content of low-temperature components, the optical thickness of the layer, and the temperature profile on the resulting radiation flux is investigated. Practical recommendations for the design of steam-boiler furnaces are given.

The increasing utilization of the considerable reserves of young lignite, which contains more ash and moisture and tends to produce more slag, has a lower heat of combustion, is dangerously prone to explosion in the finely disperse state in air, and increases the ecological and size demands on steam boilers, has intensified the development and industrial introduction of new ignition methods and new furnaces, including low-temperature vortical (LTV) furnaces, furnaces with a circulating fluidized bed (CFB), flame-layer (FL) furnaces, etc. As shown in [1], the characteristics of ignition in such furnaces lead to the existence

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of considerable volume zones occupying half (in LTV furnaces) or all (in CFB furnaces) of the furnace volume, with the following properties:

there is considerable disruption of the conditions of local thermodynamic equilibrium (the temperature difference of different components of the furnace medium may reach 1000-1200 K); all the components make a considerable contribution to the optical thickness of the zone;

the furnace medium is radiating, absorbing, and strongly scattering; the presence of large disperse particles of solid phase means that the scattered radiation consists basically of the diffracted component and may be regarded as the transmitted component, on the basis of the data of [2, 3];

in the general case, there is no axisymmetry of the concentration fields of the solid phase and the temperatures of the furnace medium.

Existing methods of calculating the radiant heat transfer in coal-dust furnaces – both local [2] and approximate [3] – have been developed for a selective homogeneous noniso-thermal absorbing, radiating, and scattering furnace medium, all the components of which within any isolated volume zone are at the same (mean over the zone) temperature. Accordingly, the present work investigates the intensity of the intrinsic radiation of an isolated volume furnace zone containing significantly nonisothermal components; i.e., the radiation emitted by different components (the gas volume and the particle surfaces) is characterized by different temperatures.

Suppose that Kirchhoff's law holds approximately for the spectral absorptivities and emissivities of the components even with disruption of the local thermodynamic equilibrium. Consider the solution for zonal calculation methods, i.e., under the assumption that in the volume zone all the components forming the furnace medium are uniformly distributed and each has its own temperature T_i. (The indices corresponding to the direction of propagation of the radiation and the spectral indices are omitted, for the sake of space; where necessary, they are specially noted.) Suppose that the optical thickness of the isolated volume zone of the furnace medium must be divided into n components with respect to the absortion, on the basis of temperature index T_i

$$\tau_\Sigma = \sum_{i=1}^{n} \tau_i;\ \tau_i = \int_0^l \varkappa_i(l)\,dl;\ \tau_\Sigma = \int_0^l \Big(\sum_{i=1}^{n} \varkappa_i(l)\Big)\,dl. \tag{1}$$

Here $\kappa_i(\ell)$ is the absorption coefficient of the i-th component; ℓ is the effective layer thickness of the volume zone. The emissivity of the furnace medium in the zone and the emissivity of each component (in the case where it occupies the whole zone) are as follows

$$\varepsilon_\Sigma = 1 - \exp(-\tau_\Sigma);\ \varepsilon_i = 1 - \exp(-\tau_i). \tag{2}$$

It is obvious that

$$\sum_{i=1}^{n} \varepsilon_i > \varepsilon_\Sigma. \tag{3}$$

As shown in [1], the contribution of each of the components to ε_Σ is

$$\varepsilon_i' = \varepsilon_i + \sum_{k=1}^{n} (-1)^{k-1} \frac{1}{k} \sum_{m=1}^{k} \prod_i \{C_n^k(\varepsilon)\}. \tag{4}$$

Here $\sum_{m=1}^{n} \prod_i \{C_n^k(\varepsilon)\}$ is the sum of products of the emissivities consisting of combinations of k components from n components, one of which must be i. In this case, $\varepsilon_\Sigma = \sum_{i=1}^{n} \varepsilon_i'$, amd the intensity of the intrinsic radiation of the zone is

$$I_{\text{in}\,\Sigma} = \sum_{i=1}^{u} \varepsilon_i' B(Ti), \tag{5}$$

where $B(T_i)$ is the intensity of Planck radiation at temperature T_i. On the basis of Eq. (5), the concept of an effective temperature of the furnace-medium zone with n components may be introduced

$$I_{\text{in}\,\Sigma} = \varepsilon_\Sigma B(T_{\text{ef}\Sigma})$$

and hence

$$B(T_{ef\Sigma}) = \sum_{i=1}^{n} \varepsilon_i'' B(T_i); \quad \varepsilon_i'' = \varepsilon_i'/\varepsilon_\Sigma. \tag{6}$$

Thus, the actual furnace medium may be replaced by a hypothetical single-component furnace medium under the condition of equal spectral intensities of their radiation. For a grey furnace medium, the effective temperature is

$$T_{ef\Sigma} = (\sum_{i=1}^{n} \varepsilon_i'' T_i^4)^{0,25}. \tag{7}$$

In the case of limiting forward extension of the scattering index, on the basis of [2-5], the radiant-transfer equation in multicomponent media may be written in the form

$$\frac{dI_\Sigma(l, \Omega)}{dl} = -\left\{\sum_i \varkappa_i(l) + \sum_j \varkappa_j(l)\right\} I_\Sigma(l, \Omega) + \left\{\sum_i \varkappa_i(l) + \sum_j \varkappa_j(l)\right\} B\,[T_{ef\Sigma}(l)]. \tag{8}$$

Here $\kappa_i(\ell)$ and $\kappa_j(\ell)$ are the spectral absorption coefficients of the i-th molecular gas and of particles of type j; $T_{ef\Sigma}(\ell)$ is the effective temperature of the multicomponent furnace medium in the section of layer ($\ell - d\ell/2$, $\ell + d\ell/2$) determined from Eqs. (1)-(6). Note that according to Eq. (3)

$$\sum_i \varkappa_i(l) B[T_i(l)] + \sum_j \varkappa_j(l) B[T_j(l)] >$$

$$> \left[\sum_i \varkappa_i(l) + \sum_j \varkappa_j(l)\right] B[T_{ef\Sigma}(l)]. \tag{9}$$

In the general case of multicomponent media, the scattering of the radiation by solid-phase particles may be taken into account on the basis of [2-4, 6].

In [2, 4], the concept of the effective temperature of a one-component homogeneous non-isothermal nonscattering layer is introduced, on the basis of solution of the radiation-transfer equation in the form

$$\mu \frac{dI(l, \mu)}{dl} = -\varkappa(l) I(l, \mu) + \varkappa(l) B(T) \tag{10}$$

under the condition of completely diffuse radiation, i.e., $\mu = 0.5$. Using Eqs. (4)-(6) for the multicomponent medium, the following expression is obtained for the i-th component

$$T_{ef\,.i} \frac{c^2}{\lambda} = [\ln(1 + 1/A_i)]^{-1};$$

$$A_i = \frac{2}{1 - \exp(-2\tau_i)} \int_0^{\tau_i} \frac{[\exp(-2\tau_i - 2\tau_i')]\, d\tau_i'}{\exp\left(\dfrac{c_2}{\lambda T_i(\tau_i')} - 1\right)}.$$

Finally, for the multicomponent medium

$$T_{ef\Sigma} = \frac{c_2}{\lambda} [\ln(1 + 1/B)]^{-1}; \quad B = \sum_{i=1}^{n} \varepsilon_i'' \left[\exp\left(\frac{c_2}{\lambda T_{ef\,i}}\right) - 1\right]^{-1}; \tag{11}$$

$$\psi_\Sigma = 1 - \frac{b\varepsilon_{w} + (1 - \varepsilon_W)[1 - \exp(-2\tau_\Sigma)]}{1 - (1 - b\varepsilon_W)\exp(-2\tau_\Sigma)}; \tag{12}$$

$$b = \frac{B(T_W)}{B(T_{ef\Sigma})}.$$

Here ψ_Σ is the thermal efficiency of the screens; ε_W and T_W are the emissivity and temperature of the outer contaminant layer of the heating surface. In the case of a grey multi-component layer

$$T_{\text{ef}\,\Sigma} = \Big(\sum_{i=1}^{n} \varepsilon_i'' T_{\text{ef}\,i}^4\Big)^{0,25};$$

$$T_{\text{ef}\,i} = \frac{2}{1 - \exp(-2\tau_i)} \int_0^{\tau_i} T_i^4(\tau_i) \exp(-2\tau_i - 2\tau_i')\, d\tau_i'; \qquad (13)$$

$$\psi_\Sigma = \frac{1 - b^4}{1/\varepsilon_{\text{w}} + b^4/\varepsilon_\Sigma - b^4}; \quad b = T_{\text{w}}/T_{\text{ef}\,\Sigma}.$$

Analysis of Eqs. (4), (5), (8), and (11) leads to two important conclusions. The first is that the intrinsic radiation of the volume zone of the multicomponent furnace medium is not additive, i.e., is not equal to the sum of the intrinsic radiation of the components at temperature T_i when each one occupies the given zone alone. The mutual influence of the different-temperature components must be taken into account. The second conclusion is that the low-temperature components screen the radiation of the high-temperature components. Therefore, with increase in content of the low-temperature components in the furance medium, the incident and resultant radiation decreases, as does the effective temperature of the furnace medium.

Since it is desired to find the temperature of the furnace medium at the exit from the furnace chamber in calculating the heat transfer in furnaces, and since the local values of the gas component of the furnace medium are most easily measured in steam-boiler furnaces using a suction pyrometer, an explicit relation between $T_{\text{ef}\Sigma}$ and the temperature of the furnace mixture (denoted by T_{F}'') is now obtained

$$B(T_{\text{ef}\,\Sigma}) = B(T_{\text{F}}'')\,\bar{\varepsilon}_\Sigma = B(T_{\text{F}}'') \sum_{i=1}^{n} \varepsilon_i'' t_i; \quad t_i = B(T_i)/B(T_{\text{F}}''); \qquad (14)$$

$$I_{\text{in}\Sigma} = \varepsilon_\Sigma B(T_{\text{ef}\Sigma}) = \varepsilon_\Sigma \bar{\varepsilon}_\Sigma B(T_{\text{F}}'')$$

or for a grey furnace medium

$$T_{\text{ef}\Sigma} = T_{\text{F}}'' \bar{\varepsilon}_\Sigma^{0,25} = T_{\text{F}}'' \Big(\sum_{i=1}^{n} \varepsilon_i'' t_i\Big)^{0,25}; \; t_i = (T_i/T_{\text{F}}'')^4; \qquad (15)$$

$$q_{\text{in}\,\Sigma} = \varepsilon_\Sigma \bar{\varepsilon}_\Sigma \sigma_0 (T_{\text{F}}'')^4 = \varepsilon_\Sigma \sigma_0 T_{\text{ef}\,\Sigma}^4.$$

This approach permits the calculation of the radiant heat transfer in a furnace on the basis of experimental data on t_i obtained on an apparatus simulating the reaction conditions of a fuel particle in the furnace chamber, with temperature measurement of the particle surface and the surrounding gaseous medium. The influence of the content of low-temperature components (M_3) and the temperature distribution in the layer of three-component grey furnace

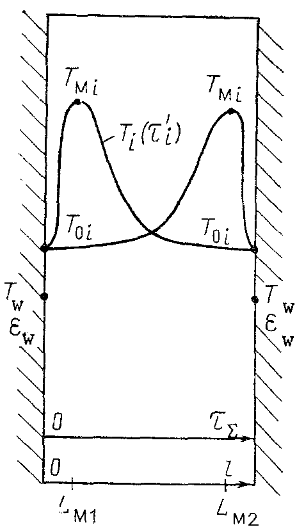

Fig. 1. Temperature profiles in layer.

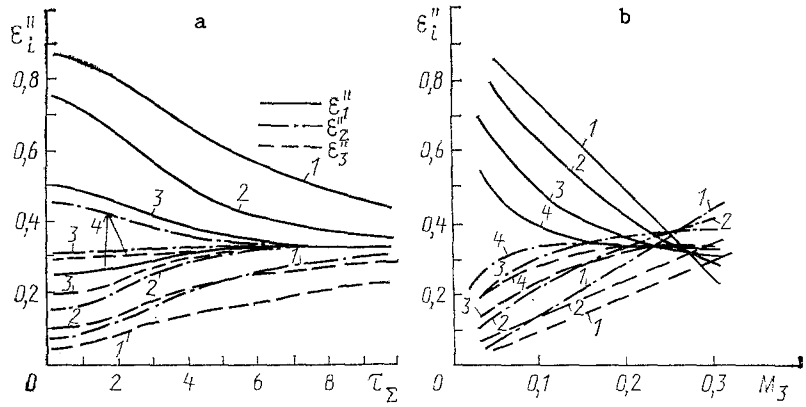

Fig. 2. Dependence of relative contribution of i-th component ε_i'' of three-component furnace medium to its total omissivity on the optical thickness of the furnace medium τ_Σ (a) when M_3 = 0.05 (1), 0.1 (2), 0.2 (3), and 0.3 (4) and on the content of low-temperature component (b) when τ_Σ = 0.25 (1)' 2.5 (2), 5.0 (3), and 10 (4).

medium on the effective temperature T_{ef}, effective emissivity of the furnace medium ε, thermal efficiency (TE) of the heating surface (ψ), and resulting radiation flux q_R is now calculated. It is assumed that the first component consists of gaseous combustion products, volatile-ash particles, and coke with temperature T_1 and optical thickness τ_1. The second consists of particles in the course of volatile-material departure with temperature T_2 and optical thickness τ_2. The third consists of nonburning reacting particles with temperature T_3 and optical thickness τ_3

$$\tau_\Sigma = \tau_1 + \tau_2 + \tau_3;\quad \tau_i = M_i\tau_\Sigma.$$

The relative content of the components in the optical thickness of the furnace medium is: M_3 = 0-0.3; $M_2 = 1.5M_3$; $M_1 = (1\text{-}2.5)M_3$.

In the combustion of Irsha-Vorodin coal in the LTV furnace of an E-420-140 boiler [1], the following relative surface temperatures of the component particles are adopted: $t_2 = (T_2/T_F'')^4 = 0.316$; $t_3 = 0.017$. The dependence of the integral emissivity of the walls on the temperature of the contaminant surface layer is taken from experimental data [3]

$$\varepsilon_W(T_W) = 1.54 - 1.54\,T_W/1000 + 0.56\,(T_W/1000)^2.$$

The temperature distribution in the layer $T_i(\tau_i)$ is described by the system of equations (Fig. 1)

$$T_i(\tau_i') = T_{0i} + (T_{Mi} - T_{0i})\left(1 - \left(1 - \frac{\tau_i'}{\tau_i\beta_M}\right)^{1,5}\right)^{1,6}$$

when $(\tau_i'/\tau_i) \le \beta_M$; $\beta_M = L_M/L$; and

$$T_i(\tau_i') = T_{0i} + (T_{Mi} - T_{0i})\left(1 - \left(1 - \frac{\tau_i - \tau_i'}{(1-\beta_M)\tau_i}\right)^{1,5}\right)^{1,6}$$

when $\beta_M < (\tau_i'/\tau_i) \le 1$.

Analysis of the dependence of ε_i'' on the optical thickness of the furnace medium and M_i (Fig. 2) shows that, at large optical thicknesses, the dependence of the contribution of the i-th component to the total emissivity of the n-component furnace medium on τ_Σ and M_i levels out and $\varepsilon_i'' \to 1/n$ as $\tau_\Sigma \to \infty$ when $M_i > 0$. At small optical thicknesses, the dependence of ε_i'' on τ_Σ depends significantly on M_i. At large M_i, ε_i'' decreases with increase in τ_Σ; at small M_i, conversely, ε_i'' increases with increase in τ_Σ.

Analysis of the calculation results, some of which are shown in Fig. 3, leads to a number of conclusions. The first is that, with increase in content of the low-temperature components in the furnace medium (M_3), $T_{ef\Sigma}$, ψ_Σ, and the resulting radiation (q_R) decrease significantly, whereas the effective emissivity (ε) increases. With increase in τ_Σ, these dependences level out, and when $\tau_\Sigma > 4$ and $M_3 > 0.2$ there is even some growth in q_R, $T_{ef\Sigma}$, and ψ_Σ with increase in M_3.

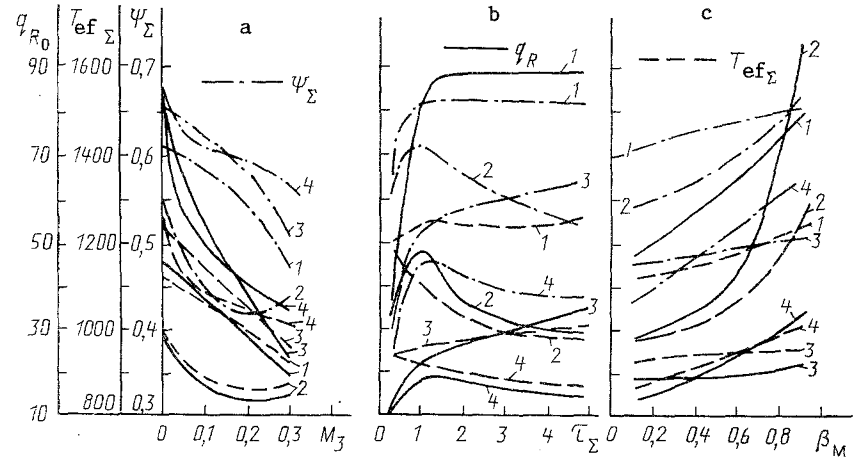

Fig. 3. Dependence of the resulting radiation q_R, effective temperature $T_{ef\Sigma}$, and thermal efficiency of the screens ψ_Σ on the content of low-temperature components M_3 (a), optical thickness of the furnace medium τ_Σ (b), and relative position of the maximum-temperature zone β_M (c): a) $\beta_M = 0.1$, $\tau_\Sigma = 1$ (1); 0.1, 4.75 (2); 0.9, 1 (3); 0.9, 4.75 (4); b) $M_3 = 0$, $\beta_M = 0.9$ (1); 0, 0.1 (2); 0.3, 0.9 (3); 0.3, 0.1 (4); c) $M_3 = 0$, $\tau_\Sigma = 1$ (1); 0, 4.75 (2); 0.3, 1 (3); 0.3, 4.75 (4). q_R, kW/m^2; $T_{ef\Sigma}$, K.

The second is that $T_{ef\Sigma}$, ψ_Σ, q_R increase considerably as the maximum-temperature zone approaches the heating surface, while the effective emissivity slightly decreases. The dependence of $T_{ef\Sigma}$, ψ_Σ, and q_R on β_M becomes stronger with increase in relative thickness of the flame and becomes weaker with increase in content of the low-temperature components. With a nonaxisymmetric layer of furnace medium, q_R, $T_{ef\Sigma}$, ψ_Σ are directional in character even for boundary heating surfaces with identical radiational characteristics; the greater the deviation from axisymmetry, the greater the total resulting radiation. The third conclusion is that, with different temperature profiles in the furnace-medium layer ($\beta_M = 0.1$ and $\beta_M = 0.9$), there are different dependences of q_R, $T_{ef\Sigma}$, and ψ_Σ on the optical thickness of the flame. When $\beta_M = 0.9$, q_R, ψ_Σ, and $T_{ef\Sigma}$ increase with increase in τ_Σ; after $\tau_\Sigma > 1.5$, the increase in these quantities is extremely slight. When $\beta_M = 0.1$, there is an optimal value of the optical thickness $\tau_\Sigma^{opt} = 0.75$-1.25 at which q_R and ψ are a maximum. In the region $\tau_\Sigma < \tau_\Sigma^{opt}$, increase in q_R and ψ_Σ is observed with increase in τ_Σ, whereas $T_{ef\Sigma}$ decreases; when $\tau_\Sigma > \tau_\Sigma^{opt}$, q_R and ψ_Σ decrease with increase in τ_Σ. The optimum region of τ_Σ expands with increase in the content of low-temperature components in the furnace medium, while τ_Σ^{opt} is shifted to higher values. Thus, to ensure the maximum resulting radiation in low-temperature furnace chambers burning large disperse fuel in a gas-suspension state, it is expedient to section the furnace so that the optical density of the flame in the sections is of order $\tau_\Sigma = 1$-1.5, when the maximum-temperature zones are at the wall.

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