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An analysis of radiant heat transfer in furnace chambers burning slagging coals

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Abstract—Results are presented which involve information on zoning calculation of heat transfer in furnaces burning slagging coals. New numerical methods are described which take into account the selectivity and scattering of radiation. Calculations of local heat transfer characteristics and of the processes of slagging on the surfaces of waterwalls under complex boundary conditions are presented. The spectral radiation characteristics of ash deposits and slags and of the fly ash particles were studied experimentally. Boilers with dry and wet systems of slag removal were investigated. Based on the results obtained some recommendations are given concerning rational combustion of slagging coals.

1. INTRODUCTION

THE DOMINATING mode of heat transmission in furnace chambers is that by radiation, the intensity and adequate organization of which affect the technical and economic efficiency of the entire boiler furnace. The refinement of the existing and development of new, more efficient furnace chambers, as well as the optimization of their heat regime impose increasingly rigorous requirements on the accuracy of radiant heat transfer calculations. This accuracy is particularly important in the case of the combustion of slagging coals when the conditions of local heat transfer in most characteristic zones of the furnace chamber largely determine the efficiency of its operation as a whole.

The calculation of the volumetric temperature field for a furnace filled with an optically non-uniform medium with allowance for closely associated processes more often than not motivates the selection of zoning methods as a basis for developing mathematical models of heat transfer in furnace chambers. This, in turn, brings forth new problems requiring the study of radiation heat transfer in furnaces. These are, on the one hand, theoretical problems that incorporate the development of numerical methods for taking into account the selectivity and scattering of radiation, calculation of the local radiant heat transfer under complex boundary conditions, and methods for taking into account the processes of slag formation on waterfall surfaces. On the other hand, there are some experimental problems involving the study of spectral radiation characteristics of ash deposits and slags, absorption and scattering properties of the flame in furnace chambers, etc. [1].

2. A MATHEMATICAL MODEL OF HEAT TRANSFER

The present paper considers some results of investigations of the above-listed problems on the basis of the three-dimensional zoning model of heat transfer. The temperature fields in a furnace were determined by solving a system of algebraic non-linear equations of heat transfer and of the heat balance of zones [2]

$$\sum_{i=1}^{m+n} a_{ij}^{\Sigma} T_i^4 + \sum_{i=1}^{l} g_{ij} T_i + g_{ij} T_j + Q_j = 0$$

$$j = 1, 2, \ldots, m+n. \quad (1)$$

The selective coefficients of radiation heat transfer over the entire spectrum a_{ij}^{Σ} (W K^{-4}) were determined as

for volume radiative zones i

$$a_{ij}^{\Sigma} = 4\sigma_0 V_i \frac{\sum_K^z \alpha_i^K (f_{ij}^K - \delta_{ij}) \int_{\Delta\omega K} E_{0,i}^{\omega}\, \mathrm{d}\omega}{\sum_K^z \int_{\Delta\omega K} E_{0,i}^{\omega}\, \mathrm{d}\omega}$$

$$i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, m+n; \quad (2)$$

for surface radiative zones i

$$a_{ij}^{\Sigma} = \sigma_0 F_i \frac{\sum_K^z \varepsilon_i^K (f_{ij}^K - \delta_{ij}) \int_{\Delta\omega K} E_{0,i}^{\omega}\, \mathrm{d}\omega}{\sum_K^z \int_{\Delta\omega K} E_{0,i}^{\omega}\, \mathrm{d}\omega}$$

$$i = m+1, m+2, \ldots, m+n; \quad j = 1, 2, \ldots, m+n, \quad (3)$$

where

NOMENCLATURE

A	absorptivity
E_0^ω	spectral black-body emitted flux [W m^{-3}]
F_i	area of zone i [m^2]
l	number of zones neighbouring the zone considered
m	number of volume zones in the system
n	number of surface zones in the systems
R	reflectivity
V_i	volume of zone i [m^3]
z	number of spectral intervals in the spectrum model.

Greek symbols

α, β	absorption and scattering coefficients [m^{-1}]
σ_0	Stefan–Boltzmann constant [W m^{-2} K^{-4}]
ω	wave number [m^{-1}].

Superscript

is	isotropic.

Subscripts

i, j, p	zone numbers in the system
K	number of spectral interval.

$$\delta_{ij} = \begin{cases} 1, & i = j; \\ 0, & i \neq j. \end{cases}$$

The coefficients of convective heat exchange between zones g_{ij} in equation (1) take into account heat transmission from one volume zone to another by a moving medium, convective heat exchange between volume and surface zones and heat transfer from the surface zone of ash deposits on waterwalls to the heated medium [2]. The magnitude Q_j in equation (1) stands for heat release in volume zones or heat being transferred from outside into surface zones.

The reduced resolving radiation factors f_{ij}^K occurring in equations (2) and (3) were determined by solving the systems of linear algebraic equations which make it possible to take into account diffuse reflection on the surfaces of slag and ash deposits, and also the isotropic scattering in the furnace volume

$$f_{ij} = \psi_{ij}^K B_j^K + \sum_{p=1}^{m} \left(\frac{\beta^{\text{is}}}{\alpha + \beta^{\text{is}}} \right)_p^K \psi_{ip}^K f_{pj}^K + \sum_{p=m+1}^{m+n} R_p^K \psi_{ip}^K f_{pj}^K \quad i, j = 1, 2, \ldots, m+n \quad (4)$$

where

$$B_j = \begin{cases} \left(\dfrac{\alpha}{\alpha + \beta^{\text{is}}} \right)_j^K & \text{at} \quad j = 1, 2, \ldots, m; \\ A_j^K & \text{at} \quad j = m+1, m+2, \ldots, m+n. \end{cases} \quad (5)$$

The reduced view factors ψ_{ij}^K between the zones were determined by the Monte Carlo method. For the solution to be realized on a computer, special algorithms and programmes are worked out. They are generalized on the complex configuration radiative systems with non-uniform radiant characteristics of the flame.

3. THE EFFECT OF WATERWALLS SLAGGING

Along with the problem of purely external heat transfer, the model allows the solution of the related problem of heat transmission through the layer of ash deposits in the cooling chamber, and through the layer of slag in the combustion chamber with allowance for the non-uniform distribution of ash and slag deposits on waterwalls over the height of the furnace as well as for air inflow through small hatch holes and loosely mated structures of waterwalls.

A specific feature in the combustion of slagging coals is a strong dependence of the intensity of waterwall slagging on heat transfer parameters in the combustion chamber. Therefore, in the study of heat transfer in furnaces, the rate of slag formation was taken into account by simultaneously solving the system of heat balance zone equations (1) and of the relation referring to the influence of the local thermal resistance of ash deposits on the magnitude of the incident radiation heat flux over the given area of the waterwall. In this case account was taken of the experimentally discovered fact of a sharp increase in the slagging of waterwalls when incident radiation fluxes overshoot the critical values from 250 to 300 kW m^{-2} depending on the kind of coal being burnt [3].

Allowance for the relationship between the heat transfer rate and the rate of the slagging of waterwalls made it possible to explain the reason for a sharp decrease in the gas temperature at the furnace exit on an increase in the recirculation of smoke gases into the combustion core during the burning of slagging coals [3]. It was shown that the recirculation of outlet gases into the combustion core reduces the absorption of heat by waterwalls only in the lower and upper parts of the furnace. The absorption of heat by the middle part of the furnace (in the region of high temperatures) slightly increases in spite of the decrease in the values of incident radiative heat fluxes with an increase in the rate of recirculation from 0 to 0.1. Investigations showed that this is attributable to the extremity of the change in heat absorption by slagged waterwalls, which depends on the level of the incident radiative flux.

It is shown that there is the highest possible level for heat absorption in furnaces for slagging coals which is determined by the steam–water temperature, absorption properties and thermal resistance of ash deposits on the waterwall tubes.

4. THE EFFECT OF RADIATION SELECTIVITY

Fairly detailed and reliable information on heat interchange in the furnace chamber, when the spectral radiative properties of the flame and heating surfaces are simultaneously taken into account, is usually obtained when the radiation spectrum is subdivided into a great number of intervals [2]. However, such an approach is too cumbersome and requires extensive machine time.

In the present paper, engineering calculations of radiative heat transfer were based on the method of subbands. The spectral radiative properties of the flame were taken into account with the aid of a small number of large radiative bands formed on the principle of approximately identical spectral optical thickness of the flame. For these bands, matrices of the generalized angular coefficients were determined. The spectral radiative properties of the surface elements were taken into account by solving the systems of linear algebraic equations of radiative heat transfer (4) within a great number of spectral intervals (subbands). For this purpose, the information which deals with the spectral structure of radiation bands was used [4]. This allows one to obtain rather accurate calculations of temperature fields and heat fluxes with a smaller expenditure of machine time in three-dimensional systems in the presence of selectively radiating media and surfaces.

Calculations of heat transfer for a boiler with the steam-generating capacity of 320 ton h^{-1}, furnace volume of 1386 m^3 and a wet bottom system showed that the error in calculating various average zonal heat transfer characteristics by the proposed technique with the use of 4 bands (with different absorption coefficients of the flame) and 22 subbands (with different emissivities of the surfaces) does not exceed 1% in comparison with the 22-band model taken to give an exact solution. It should be noted that in the case of the use of 4 bands without the division into subbands the errors of calculations are from 6.5 to 7.3%.

5. THE EFFECT OF RADIATION SCATTERING

The specific feature of heat transfer in pulverized-coal furnace chambers is radiation scattering. Based on the Monte Carlo method, an algorithm was developed and used in the present paper for the zonal calculation of heat transfer with allowance for the anisotropic scattering phase function in three-dimensional radiative systems.

The polar angle of scattering θ was determined with the help of random numbers γ on the basis of the cumulative distribution function $F(\theta)$ of the scattering angle relative to the passing beam from the following relation

$$F(\theta) = \frac{1}{2}\int_0^{\theta} g(\theta)\sin\theta \,\mathrm{d}\theta = \gamma \qquad (6)$$

where $g(\theta)$ is the scattering phase function.

When the analytical description of the scattering phase function is very involved (as is the case for the majority of functions obtained experimentally), $F(\theta)$ may be given as a table of values at the points $\theta_K = K\pi/n$, $K = 0, 1, \ldots, n$. The angle θ is determined by linear interpolation

$$\theta = \theta_K + \frac{[\gamma - F(\theta_K)](\theta_{K+1} - \theta_K)}{F(\theta_{K+1}) - F(\theta_K)} \qquad (7)$$

where K is such that

$$F(\theta_K) < \gamma < F(\theta_{K+1}). \qquad (8)$$

In the present paper the cumulative function $F(\theta)$ was determined from experimental studies of the scattering properties of ash particles formed in the furnace burning slagging brown coals. The azimuthal scattering angle was also calculated with the use of random numbers provided that the scattering phase function is axisymmetric.

6. HEAT TRANSFER IN THE FURNACE CHAMBER

The mathematical model suggested made it possible to determine not only the mean, but also the local characteristics of heat transfer in the furnace of a boiler having a dry bottom system and steam-generating capacity of 2650 ton h^{-1} and intended for burning highly slagging brown coals [5]. The furnace chamber along its height was divided into 13 elements, each consisting of two volume zones (wall layer and axial zones) and two surface zones (side, front and rear waterwalls) (Fig. 1).

Calculations of heat transfer were carried out for burners tilted at 10° to the bottom [5] and firing 97.9 kg of pulverized coal (dried to 8% humidity) per second. The recirculation of gases withdrawn from the gas-turning chamber for drying coal amounted to 20%. The recirculation of gases at 360°C withdrawn downstream of the water economizer for the burners (15%) and into the upper section of the furnace was also taken into account.

The distribution of radiation characteristics of ash deposits along the height of the furnace waterwalls was specified on the basis of experimental data [6]. The change in the thermal resistance of ash deposits on waterwalls R (m^2 K kW^{-1}) along the furnace height was determined from the piecewise-linear dependence constructed on the basis of the data of ref. [3] with allowance for the high contamination of waterwalls at the level of the zone of active combustion

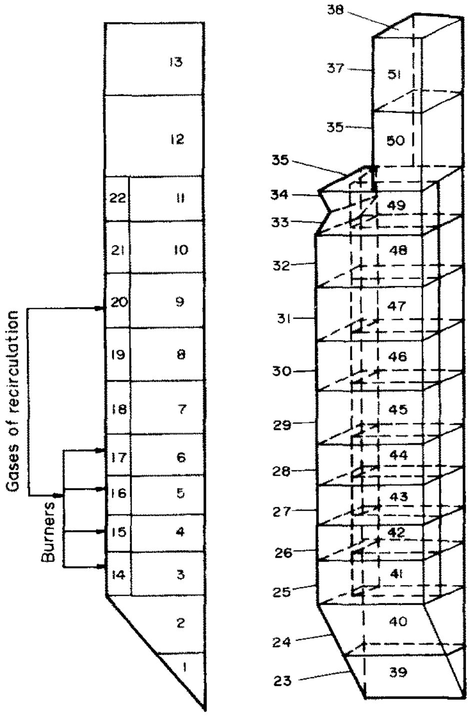

FIG. 1. Division of the boiler furnace chamber into zones (1–22, volume zones; 23–51, surface zones). A quarter of the furnace is shown.

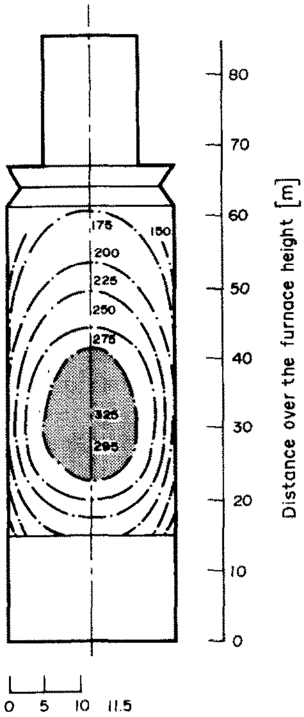

FIG. 2. Lines of identical radiant fluxes (kW m^{-2}) incident on the surface of the side waterwall of the boiler furnace chamber. The region of most intensive slagging is hatched.

$$R = \bar{R}\begin{cases} 0.186+0.069h & 0 \leqslant h \leqslant 15\ \text{m}; \\ 1.227 & 15\ \text{m} \leqslant h \leqslant 35\ \text{m}; \\ 1.658-0.0123h & 35\ \text{m} \leqslant h \leqslant 84.6\ \text{m}. \end{cases} \qquad (9)$$

The mean (over the furnace) level of heat resistance $\bar{R}$ amounted to 2.58 $\text{m}^2\ \text{K kW}^{-1}$.

The calculations gave the distributions of the local incident radiative heat flux and heat absorption as well as of the surface temperature of ash deposits over the width of waterwalls at different heights of the furnace. It is shown that the maximum difference over the width of the side waterwall is: 80 kW m^{-2} for incident radiant flux, 30 kW m^{-2} for heat absorption, 100 K for the surface temperature of ash deposits.

Figure 2 presents the calculated lines of the level with identical radiant fluxes on the side waterwall. The region of greatest slagging in the case of firing brown coals was identified. The maximum radiant fluxes were revealed in the middle of the waterwall at the height of about 28–30 m from the lower cut of the cold funnel. The results of calculations of the local heat transfer characteristics for the boiler furnace with the solid bottom system and steam-generating capacity of 2650 ton h^{-1} indicate the expediency of installing refiners at the center of the closed curves of equal incident radiant fluxes.

To select the rational conditions for burning slagging coals in boiler furnaces, an algorithm and programmes were developed that allowed the computation of the optimum values of fuel consumption and degrees of smoke gas recirculation into different areas of the furnace chamber that correspond to maximum heat absorption by waterwall surfaces with limitation of the magnitudes of incident radiant fluxes and outlet gas temperature. Thus, the regimes selected ensure the highest intensity of heat exchange in the furnace with minimum slagging of both radiative and convective heating surfaces.

The mathematical models and the algorithm developed for computing radiative heat transfer were used for improving thermal regimes in furnace chambers and also for working out the means of spectral optical diagnostics and controlling the processes in furnaces firing slagging coals.

REFERENCES

1. A. G. Blokh, *Heat Transfer in Steam Boiler Furnaces*, p. 283. Hemisphere Publishing Corporation, New York (1988).
2. Yu. A. Zhuravlev, *Radiant Heat Exchange in Fire-technical Equipment*. Izd. Krasnoyarsk. Univ., Krasnoyarsk (1983).
3. A. N. Yefimenko and E. S. Karasina, Thermal resistance of slag-ash deposits and heat exchange in furnace chambers burning Kansk–Achinsk coals, *Teploenergetika* No. 2, 66–68 (1982).
4. Yu. A. Zhuravlev, Simultaneous allowance for the radiation selectivity of media and surfaces in calculations of radiant heat exchange, *Teplofiz. Vysok. Temp.* **21**, 716–724 (1983).
5. V. Ye. Doroshchuk and V. B. Rubin (Editors), Boiler and turbine installations of 500 and 800 MW energy units.

In *Design and Mastering*, pp. 112–159. Izd. Energiya, Moscow (1979).
6. Yu. A. Zhuravlev, A. G. Zadvornyi, M. Ya. Protsailo, V. V. Mechev and B. V. Kedrov, Investigation of the spectral emissivities of ash deposits of Kansk–Achinsk coals, *Teploenergetika* No. 3, 47–50 (1982).

ANALYSE DU TRANSFERT RADIATIF DANS LES FOYERS AVEC CHARBON PULVERISE

Résumé—On présente des résultats concernant le calcul par zonage du transfert thermique dans des foyers brûlant des charbons pulvérisés. Des nouvelles méthodes numériques sont décrites pour prendre en compte la sélectivité et la diffusion du rayonnement. Les caractéristiques spectrales du rayonnement des dépôts de cendres et de l'envol des particules de cendre sont étudiés expérimentalement. Des chaudières avec des systèmes secs ou humides d'enlèvement des slags sont étudiés. A partir des résultats obtenus, on donne quelques recommandations concernant la combustion rationnelle du charbon pulvérisé.

UNTERSUCHUNG DER STRAHLUNGSWÄRMEÜBERTRAGUNG IN BRENNKAMMERN MIT SCHLACKE-BILDENDEN KOHLEN

Zusammenfassung—Es werden Ergebnisse über die zonenweise Berechnung der Wärmeübertragung in Öfen bei der Verbrennung schlackebildender Kohlen vorgestellt. Neue numerische Verfahren werden beschrieben, welche die Selektivität und die Streuung der Strahlung berücksichtigen. Die örtliche Wärmeübertragung und die Vorgänge bei der Schlackebildung an der Oberfläche der wassergekühlten Wände werden bei komplizierten Randbedingungen berechnet. Die spektralen Strahlungseigenschaften der Ascheablagerungen, der Schlacken und der Flugaschepartikel werden experimentell untersucht. Dabei werden Verdampfer mit trockenen und nassen Systemen für die Schlackeentfernung betrachtet. Auf der Grundlage dieser Ergebnisse werden einige Empfehlungen für die sinnvolle Vorgehensweise bei der Verbrennung schlackebildender Kohlen gegeben.

АНАЛИЗ РАДИАЦИОННОГО ТЕПЛООБМЕНА В ТОПКАХ ПРИ СЖИГАНИИ ШЛАКУЮЩИХ УГЛЕЙ

Аннотация—В статье представлены результаты совершенствования и применения комплекса методов и информационное обеспечение для зональных расчетов и оптимизации теплообмена в топках при сжигании шлакующих углей. Описаны новые численные методы, учитывающие селективность и рассеяние излучения, расчеты локальных характеристик теплообмена, процессы шлакования на поверхностях экранов при сложных граничных условиях. Спектральные радиационные характеристики золовых отложений и шлаков, а также потока золовых частиц определены экспериментально. Исследованы котлы с твердым и жидким шлакоудалением. На основе полученных результатов даны некоторые рекомендации, касающиеся рациональных условий сжигания шлакующих углей.