CALCULATION OF RADIATIVE FLUXES IN FLAME POWER UNITS

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An engineering procedure is suggested for calculation of radiation properties of gas-dust media. It is based on using factors (attenuation, scattering factors, etc.) tabulated for discrete spectral ranges and averaged on particle size fractions. Application of the procedure is demonstrated using the example of a coal dust flame and the furnace working volume with account of ash and triatomic gases.

The results of thermal calculation in the stage of designing furnace and boiler units depend substantially on the accuracy of calculated properties of the gas-dust radiation. The properties depend on the phase composition, chemical and fractional composition of dust, geometry of radiating volumes, temperature, and other factors. Therefore, direct use of gas-dust radiation properties reported in the literature is often impossible. In addition, there are general relations predicted by spectral band models for gas-dust radiation and scattering theory [1], but they are too complicated for engineering calculations.

In this study, engineering procedures are proposed for a fairly simple calculation of radiation properties of every particular gas-dust medium.

Initial data for calculating the radiation properties of dust are chemical composition $\{C_i\}$ and discrete mass particle size distribution function $j\{\varphi_j\}$

$$\varphi_j = \int_{r_{j-1}}^{r_j} \varphi(r)\, dr, \tag{1}$$

$$\sum_j \varphi_j = 1, \tag{2}$$

where $\varphi(r)$ is the mass distribution function.

In practice $\{C_i\}$ is usually determined by mineralogical analysis of dust and $\{\varphi_j\}$ is found by mesh and sedimentation analyses. The latter is very important for choosing r_j: $r_0 = 0$; $r_1 = 2\ \mu$m; $r_2 = 5\ \mu$m; $r_3 = 10\ \mu$m; $r_4 = 20\ \mu$m; $r_5 = 50\ \mu$m. For particles with radius $r > r_3$ the diffraction parameter over the thermal range is $\rho = 2\pi r/\lambda >> 1$ and therefore the attenuation and scattering factors for such particles can be assumed equal to the asymptotic values at $r = \infty$ [2].

The procedure proposed is based on factors tabulated for discrete wavelength ranges and averaged on the particle sizes:

$$\overline{k}^s_{ijl} = \frac{1}{(\lambda_l - \lambda_{l-1})(r_j - r_{j-1})} \int_{\lambda_{l-1}}^{\lambda_l} d\lambda \int_{r_{j-1}}^{r_j} k_s\left(\frac{2\pi r}{\lambda},\ m_{i\lambda}\right) dr,\ s = \text{att., sct., ans} \tag{3}$$

where $m_{i\lambda}$ is the complex refraction index for the i-th species at the wavelength λ; $k_s(\rho, m)$ are the attenuation, scattering, and anisotropy factors of a dust particle with radius r.

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For particles with spherical symmetry $k_s(\rho, m)$ are expressed as the Mie series [2]:

$$k_{att}(\rho, m) = \frac{2}{\rho^2}\sum_{n=1}^{\infty} \mathrm{Re}\{a_n + b_n\},$$

$$k_{sct}(\rho, m) = \frac{2}{\rho^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2), \tag{4}$$

$$k_{ans}(\rho, m) \equiv \bar{\mu}(\rho, m)\, k_{sct}(\rho, m) =$$

$$= \frac{4}{\rho^2}\sum_{n=1}^{\infty}\frac{1}{n+1}\left((n+2)\, n\, \mathrm{Re}\left\{a_n a_{n+1}^* + b_n b_{n+1}^* + \frac{2n+1}{n} a_n b_n^*\right\}\right).$$

Even for homogeneous particles the coefficients a_n and b_n are rather complicated functions of ρ and m [2]. For radially inhomogeneous particles (e.g., mineral sulfide particles oxidized from the surface in the process of flame smelting of sulfide ores) a_n and b_n also depend on the particle infrastructure (e.g., on the oxide film thickness) and may be calculated from the recurrence formulas [3].

We calculated and tabulated k^s_{ijl} for some materials which may be present in the dust of ferrous and nonferrous metallurgical and power-generating boiler furnaces. The materials include oxides and sulfides of iron, copper, zinc, lead; oxides of aluminum, silicon, magnesium, and some other metals; chalcopyrite, carbon. Factors k^s_{ijl} are also calculated for bilayer sulfide particles with oxide films.

Values from the tables of k^s_{ijl} used to determine dust radiation characteristics allow labor-consuming calculations based on Mie's theory to be avoided. Thus, spectral radiation characteristics of the i-th component of polydisperse dust are obtained from the formula:

$$K_l^s = \frac{3}{4\rho_i}\sum_{j=1}^{N}\frac{\varphi_j}{\bar{r}_j}\bar{k}^s_{ijl}, \quad s = \text{att., sct., ans} \tag{5}$$

where N is the number of particle size fractions ρ_i is the density of the i-th dust material component; r_j is the averaged particle radius of the j-th fraction determined by the formula

$$\bar{r}_j = \int_{r_{j-1}}^{r_j} r^3 n(r)\, dr \Big/ \int_{r_{j-1}}^{r_j} r^2 n(r)\, dr,$$

where n(r) is the predicted particle size distribution function. Assuming n(r) to be constant at $r_{j-1} \le r < r_j$, we obtain:

$$\bar{r}_j \approx \frac{3}{4}\,\frac{r_j^4 - r_{j-1}^4}{r_j^3 - r_{j-1}^3}. \tag{6}$$

The corresponding values for dust of a preset composition are determined by summing over all the components of the dust:

$$K_l^s = \sum_i C_i k_{il}^s, \quad s = \text{att., sct., ans} \tag{7}$$

Factors K^s_l are independent of the dust concentration and have dimension of m^2/kg.

Usually, in thermal calculations radiation properties of a dust flow, such as volumetric attenuation (β_λ), scattering (σ_λ), and absorption (α_λ) factors, are of interest. For the l-th wavelength range, these factors are determined from the formulas

$$\beta_l = \rho_{wc} K_l^{att}, \quad \sigma_l = \rho_{wc} K_l^{sct}, \quad \alpha_l = \beta_l - \sigma_l = \rho_{wc}(K_l^{att} - K_l^{sct}), \tag{8}$$

where ρ_{wc} is the weight concentration (density) of dust in the flow.

The single-scattering radiation albedo j_l in the dust is also important:

$$\gamma_l = \sigma_l/\beta_l = K_l^{sct}/K_l^{att}. \tag{9}$$

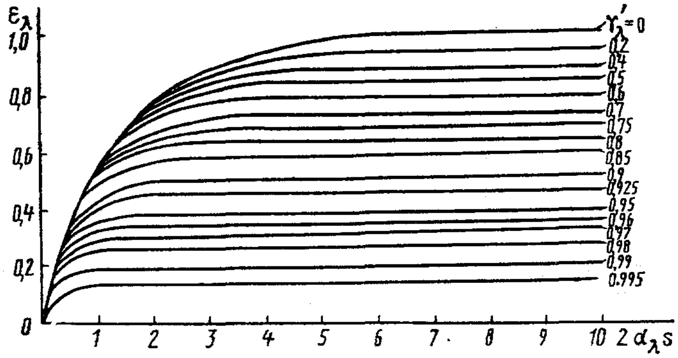

Fig. 1. Nomographs for the spectral emissivity of dust.

Using similarity relations, dust with scattering anisotropy can be approximated by a medium with scattering isotropy having the same absorption factor $\alpha_l = \alpha_l$ and effective single-scattering albedo:

$$\gamma'_l = \frac{K_l^{\text{sct}} - K_l^{\text{ans}}}{K_l^{\text{att}} - K_l^{\text{ans}}}. \tag{10}$$

In order to determine the spectral emissivity of a cloud of dust particles, an approach similar to the conventional procedure for gases may be used [5]. Using the solution of the radiation transfer equation for a plane layer and a cylinder, nomographs $\epsilon(j', \alpha' L_{\text{eff}})$ are obtained [6], where $L_{\text{eff}} = 4V/F$ is the effective beam length in the power unit or in the calculated zone; V and F are the volume and surface area of the power unit (zone) (see Fig. 1). In this case, in solution of the transfer equation the average flow methods [7] and RTS [6, 8] were used and, whenever possible, checked with the exact results. Emissivities are determined immediately from the nomographs:

$$\varepsilon_l = \varepsilon(\gamma'_l,\ \alpha'_l L_{\text{eff}}), \tag{11}$$

Then the integral emissivity of the dust is obtained by summing over the spectral ranges

$$\varepsilon_s = \sum_l (f_{0-\lambda_l} - f_{0-\lambda_{l-1}})\,\varepsilon_l, \tag{12}$$

where $f_{0-\lambda}$ is the first-kind radiation function tabulated in [1].

The integral emissivity of gas was determined with the procedure reported in [5] as a function of the content of triatomic gases (CO_2, SO_2, H_2O). Nomographs for CO_2 and H_2O are given in [9], for SO_2, in [10]. The total ϵ for gas is obtained from the following approximate formula:

$$\varepsilon_{\text{gas}} = \varepsilon_{H_2O} + \varepsilon_{CO_2} + \varepsilon_{SO_2} - \xi\varepsilon_{H_2O}\,\varepsilon_{CO_2} - \varepsilon_{SO_2}\,\varepsilon_{H_2O}, \tag{13}$$

where ϵ is a correction factor for overlapping of H_2O and CO_2 bands [5].

The emissivity of the gas-dust medium is determined in a similar way [11]:

$$\varepsilon_\Sigma = \varepsilon_s + \varepsilon_{\text{gas}} - \varepsilon_s\,\varepsilon_{\text{gas}}. \tag{14}$$

The procedure described allows the radiation properties of gas-dust media to be calculated with a microcalculator. Moreover, a Fortran software package was developed which realizes all the computation steps for radiative properties of dust: forming (using Mie's formulas) a data bank containing k^s_{ijl} for the dust components; particle size, chemical composition, and wavelength averaging of the radiative properties; calculation of the emissivity for one- and two-dimensional plane and axi-symmetrical volumes containing absorbing and scattering medium.

The procedure developed was compared both with the standard method [9] and with experiment. In particular, it was shown that in calculation of the emissivity of dust-gas medium in waste-heat boilers following the procedure suggested the temperature of exit gases at the edge of the radiative zone agreed better with experimental data than the calculation

TABLE 1. Minerological Composition of Coal Dust

i	1	2	3	4	5
Component	SiO_2	Al_2O_3	Fe_2O_3	MgO	C
C_i	0,448	0,147	0,07	0,035	0,3

TABLE 2. Minerological Composition of Ash

i	1	2	3	4
Component	SiO_2	Al_2O_3	Fe_2O_3	MgO
C_i	0,64	0,21	0,10	0,05

TABLE 3. Fractional Composition

j	1	2	3	4	5	6
Particle radius, μm	0—2	2—5	5—10	10—20	20—50	50
φ_j, %	0,7	2,3	4,0	8,0	18,0	67,0

TABLE 4. Attenuation, Scattering, and Anisotropy Factors

j	1	2	3	4	5	6
$\bar{k}_{ijl}^{att}$	2,4793	2,2724	2,1661	2,1055	2,0550	2,0550
$\bar{k}_{ijl}^{sct}$	1,2518	1,3357	1,3105	1,2914	1,2850	1,2800
$\bar{k}_{ijl}^{ans}$	0,8898	1,1127	1,0988	1,083	1,0800	1,0800

with the standard method did. Application of the suggested procedure will be illustrated by calculation of two parameters typical of flame combustion of coals: emissivity of the coal dust flame and working volume of the furnace, including ash and triatomic gases.

It will be assumed that the mineralogical composition of coal dust and ash can be determined from Tables 1 and 2 and the fractional dust composition from Table 3. The fractional compositions of coal dust and ash are assumed to be the same.

The flame temperature is $T_1 = 1373$ K and the furnace volume-averaged temperature is $T_2 = 1173$ K. The whole spectral range will be divided into five subranges: $\lambda_0 = 0$; $\lambda_1 = 2$ μm; $\lambda_2 = 4$ μm; $\lambda_3 = 6$ μm; $\lambda_4 = 8$ μm; $\lambda_5 = \infty$. As an example, a fragment from the table of radiative properties k^s_{ijl} of carbon fractions in the range of $\lambda = 0$ to 2 μm (l = 1) (see Table 4) is given.

Using Table 4 and similar tables for other dust components and wavelength ranges, properties of coal dust and ash can be obtained from formulas (5)-(7) and the data from Tables 1-3 (see Table 5). For coal flame $\rho_{wc} = 0.5$ kg/m^3, L_{eff} = 2.3 m, and gas phase with 17% CO_2, 10% H_2O and 3% SO_2, are assumed $T_1 = 1373$ K. Table 6 contains the results of complete calculation from formulas (9)-(14) and with the data of Table 5.

In calculating the emissivity of the furnace working volume $\rho_{wc} = 0.015$ kg/m^2, $T_2 = 1173$ K, $L_{eff} = 5$ m, and gas phase containing 9% CO_2, 10% H_2O and 5% SO_2 are assumed. For this case calculation results are given in Table 7.

Thus, here the flame radiation is mainly determined by the coal dust emission, while the contribution of the solid phase (ash) to the emissivity of the furnace working volume does not exceed 3%.

NOTATION

C_i, mass fraction of the i-th component; φ_j, mass fraction of the j-th particle fraction; n(r), calculated function of the particle size distribution; r, particle radius; λ, radiation wave length; ρ, diffraction parameter; m, complex refraction

TABLE 5. Radiation Properties of Coal Dust and Ash

l	Spectral ranges, μm	Coal dust in flame			Ash in furnace working volume		
		K_l^{att}	K_l^{sct}	K_l^{ans}	K_l^{att}	K_l^{scb}	K_l^{ans}
1	0—2	25,117	19,180	14,582	15,309	16,618	11,190
2	2—4	27,134	21,272	14,457	16,619	16,618	10,998
3	4—6	27,173	21,784	15,606	16,508	16,161	8,830
4	6—8	33,680	25,093	13,524	14,365	13,916	9,843
5	8	34.094	21.754	11.522	17.086	15.265	7.668

TABLE 6. Emissivity of Coal Dust Flame

l	1	2	3	4	5
ε_l	0,82	0,80	0,78	0,77	0,76
Integral values					
ε_s	ε_{CO_2}	ε_{SO_2}	ε_{H_2O}	ε_{gas}	ε_Σ
0.80	0.14	0.10	0.15	0.36	0.87

TABLE 7. Emissivity of the Furnace Working Volume

l	1	2	3	4	5
ε_l	0,00008	0,00008	0,030	0,040	0,100
Integral values					
ε_s	ε_{CO_2}	ε_{SO_2}	ε_{H_2O}	ε_{gas}	ε_Σ
0.040	0.170	0.270	0.240	0.590	0.610

index of the particle material; k_s, attenuation, scattering, and scattering anisotropy factors for individual particles; K_s, attenuation, scattering, and scattering anisotropy factors for the whole dust; μ, averaged scattering anisotropy cosine; a_n, b_n, Mie coefficients; β, σ, α, volumetric attenuation, scattering, absorption factors for a dust flow; γ, single-scattering albedo; ϵ, emissivity.

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