CALCULATION OF THE OPTICAL CHARACTERISTICS OF RADIATION HEAT TRANSFER IN FURNACE CHAMBERS

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UDC 535.34:535.36

A software system for calculating the problems of radiation heat transfer in two-phase media is considered. Results of the calculation of a radiation field in the combustion chamber of a specific steam generator are presented.

The problems of intensifying heat transfer in the furnace chambers of power plants necessitate a correct consideration of such factors as the selectivity of radiation from the gas components of the heat-transfer agent, its nonuniformity, the recurrence of scattering of radiation on the condensed phase particles, etc. Described below is a software system for calculating multidimensional problems of radiation transfer in the furnace chambers of power plants, which was developed with allowance made for the mentioned factors. The calculation of a radiation field for the mixture of molecular gases H_2O, CO_2, CO, and solid particles of the condensed phase of combustion products (soot, ash, and coke) is based on a numerical solution to the equation of radiant energy transfer by a finite-element method, which makes it possible to investigate the characteristics of radiation heat transfer in volumes of an arbitrary form.

We will illustrate the possibilities of the software system with the results of calculation of the optical characteristics of radiation heat transfer in the furnace of the TPP-312A steam generator (a = 8.7 m; b = 17.3 m, and h = 20 m). The combustion chamber is uniformly divided along the height into eight zones. The horizontal cross section of the furnace is a rectangular region (Fig. 1) with the prescribed spectral values of the emissivity factor of its heat-absorbing surface. The equation of radiation transfer, given the local thermodynamic equilibrium, is formulated in a two-dimensional statement in the form [1]

$$\bar{l}\,\mathrm{grad}\, I(x,\ y,\ \bar{l}) + (\varkappa + \sigma)\, I(x,\ y,\ \bar{l}) = \varkappa B(T) + \\ + \frac{\sigma}{4\pi} \int\limits_{(4\pi)} p(x,\ y,\ \bar{l};\ \bar{l}')\, I(x,\ y,\ \bar{l}')\, d\Omega' \quad (0 < x < a,\ 0 < y < b). \tag{1}$$

The boundary conditions take into account the radiation and reflection processes on the heat-absorbing surfaces of the chamber:

$$I(\Gamma,\ \bar{l})\Big|_{(\bar{l}\,\bar{n} < 0)} = \varepsilon B(T_w) + \frac{1-\varepsilon}{\pi} \int\limits_{(2\pi)} I(\Gamma,\ \bar{l}')\cos(\bar{l}',\ \bar{n})\, d\Omega'. \tag{2}$$

When describing the scattering properties of the heat-transfer agent, use is made of a transport approximation, in which the scattering indicatrix is represented in the form [2]

$$p(x,\ y,\ \bar{l},\ \bar{l}') = \beta(x,\ y) + 4\pi\,[1 - \beta(x,\ y)]\,\delta(\bar{l} - \bar{l}'), \tag{3}$$

which makes it possible by formally substituting $\beta\sigma$ for σ to reduce the problem to the case of isotropic scattering. Here β(x, y) is the doubled portion of back scattering of radiation in its interaction with the volume element of the medium; it is calculated according to Mie theory. The calculation of the absorption coefficient for the mixture of the molecular gases over the wavelength range $\lambda \in [1.34\text{-}5.56]$ μm is performed by the procedure described in [1].

Academic Scientific Complex "A. V. Lyukov Institute of Heat and Mass Transfer of the Academy of Sciences of Belarus," Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 64, No. 3, pp. 308-312, March, 1993. Original article submitted March 12, 1992.

TABLE 1. Temperature Distribution along the Line OL over the Furnace Cross Sections

Cross section No.	$T(2x/a)$, K						T_{fcs}, K
	0	0,2	0,4	0,6	0,8	1,0	
I	1650	1650	1625	1600	1550	1300	900
II	2000	2000	2000	2000	1900	1700	1500
III	1800	1800	1800	1800	1750	1650	1450
IV	1650	1650	1650	1650	1600	1500	1300
V	1600	1600	1600	1600	1550	1450	1200
VI	1550	1550	1550	1550	1500	1400	1150
VII	1500	1500	1500	1500	1450	1350	1100
VIII	1475	1475	1475	1475	1425	1325	1100

TABLE 2. Mass Concentration (C), Modal Radius (R), and Density (ρ) of Soot, Ash, and Coke Particles

Particles	Soot	Ash	Coke		
cross sections	I–VIII	I–VIII	I–II	IV	VIII
ρ, g/cm^3	1,2	2,6	3,6	3,6	3,6
R, μm	0,05	6,5	75	40	10
C, g/cm^3	$4\cdot10^{-7}$	$2\cdot10^{-6}$	$5\cdot10^{-5}$	10^{-5}	10^{-6}

Figure 1 shows the diagram of the horizontal cross section of the furnace. Hereinafter, in discussing the results we will bear in mind that the densities of the radiation fluxes refer to point L. Temperature distributions over the cross sections are given in Table 1.

The value of the optical thickness is determined from the formula

$$\tau = \int\limits_{(OL)} (\varkappa + \sigma)\, d\xi. \tag{4}$$

Partial pressures of the molecular gases H_2O, CO_2, and CO were prescribed equal to 0.11, 0.15, and 0.01 atm, respectively. Table 2 gives the mass concentration, modal radius, and density of soot, ash, and coke particles.

The developed software system enables us in each cross section to obtain:

a) values of the coefficients of absorption and scattering in the furnace medium as well as the doubled portion of back scattering in its interaction with the volume element of the medium;

b) the field of spectral values of the radiation intensity in the region in question;

c) spectral values of the density of the radiation flux incident on the heat-absorbing surface and reflected from it as well as the coefficient of its thermal efficiency;

d) the density distribution of the incident and resulting radiation fluxes along the horizontal perimeter of the heat absorbing surface.

The spectral values of the density of the radiation fluxes incident on the chamber heat absorbing surface in furnace cross sections II and VIII, which are presented in Fig. 2, allowing for the presence of the condensed phase solid particles and ignoring it, show that over the wavelength range 3.5-6 μm the presence of the particles does not have a pronounced effect on the radiation fluxes. The reason is that the gas mixture has a coefficient of absorption several times as large as the overall coefficient of radiation scattering on the solid particles. Thus, hereinafter we will restrict our consideration to the range $\lambda \in [1.3; 3.5]$ μm. So as not to encumber the figures, we will not give the curves obtained for the other cross sections. We will only point out that a qualitative picture recurs to a large extent. The presence of the solid particles smooths out a pronounced selective character of the dependences, which is typical of a gas mixture.

Analysis of the curves given in Fig. 3, which characterize the influence of the mass concentration of ash particles on the incident radiation flux density, shows that additional "blackening" of the radiating volume with a nonuniform temperature may lead to both an increase and a decrease in the densities of the radiation fluxes incident on the heat-absorbing surface.

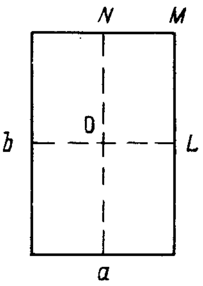

Fig. 1. Diagram of the horizontal cross section of the furnace.

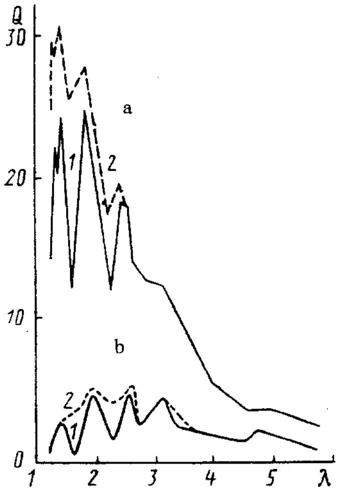

Fig. 2

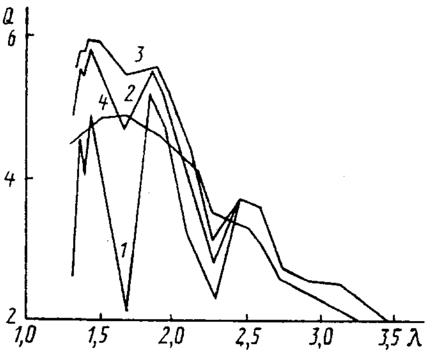

Fig. 3

Fig. 2. Density of the radiation flux incident on the heat absorbing surface Q (W/cm^2·μm) vs wavelength λ in cross sections II (a) and VIII (b): 1) gas; 2) mixture of gas and particles.

Fig. 3. Spectral dependence of the density of the radiation flux incident on the heat-absorbing surface of the chamber in cross section VIII on the mass concentration of ash particles (R = 6.5 μm): C = 0 (1); $5 \cdot 10^{-6}$ (2); 10^{-5} (3); $5 \cdot 10^{-5}$ g/cm^3 (4).

A supply of a more finely ground fuel with a smaller modal radius of coke particles to the furnace causes some increase of the absorption coefficient of the medium, which tends to increase the flux of radiation on the heat-absorbing surface (Fig. 4) under the conditions in question.

Of much interest is the density distribution of radiant fluxes along the perimeter of the chamber horizontal cross section. By symmetry of the problem, Fig. 5 gives the distributions Q/Q_{max} solely for the section of the boundary LMN (see Fig. 1). Here Q_{max} is the maximum value of the density of the radiation flux incident on the indicated section of the boundary. Analysis of the results of the calculations allows the following conclusions.

1. If the furnace cross section is an irregular polygon, then in the angular points there is a discontinuity in the value of the radiation flux incident on the different sides of the angle, this discontinuity being the larger, larger the ratio a/b and the closer to unity the optical density of the medium. The latter is explained by different values of the directed emissivity factor of the radiating volume. We note that this fact may lead to an increased thermal factor of the indicated sections of the boundary and deterioration in reliability of the heat-absorbing elements.

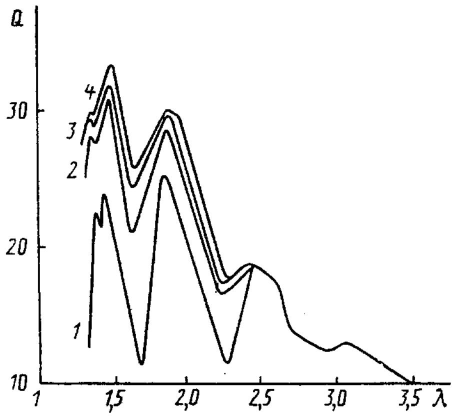

Fig. 4

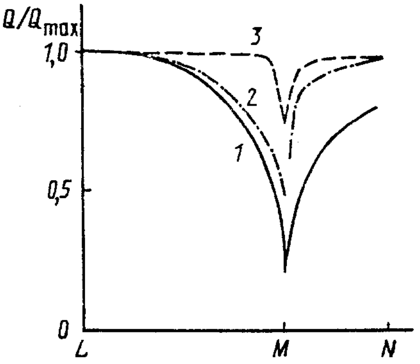

Fig. 5

Fig. 4. Influence of the modal radius of coke particles on the density of the radiation flux incident on the chamber heat-absorbing surface in cross section II, Q ($C = 5 \cdot 10^{-5}$ g/cm^3): R = 60 (1); 75 (2); 40 (3); 20 μm (4).

Fig. 5. Distribution Q/Q_{max} along the perimeter LMN of the chamber horizontal cross section: $\tau = 0.1$ (1); 1 (2); 10 (3).

2. The radiation flux density decreases toward the angular point of the boundary (the decrease may amount to as much as 50%; true, as the number of angular points increases, it is not that prominent). It follows herefrom that it is more advantageous to use furnace chambers whose horizontal cross section is a regular polygon.

The given density distributions of the radiation fluxes incident on the heat-absorbing surface are in qualitative agreement with the experimental data described in [4].

In conclusion, we note that the calculation time on a PC/ETI 386 personal computer for each cross section at the furnace in 32 points of the wavelength range $\lambda \in [1{,}34; 5.56]$ μm is less than 10 min, which enables us to make good use of the developed software system for diagnosis of boiler equipment as the regime parameters of the process of operation vary.

NOTATION

$I(x, y, \bar{l})$, spectral intensity of radiation at the point (x, y) in the direction $\bar{l}$; B(T), spectral intensity of black body radiation at the temperature $T = T(x, y)$; $\varkappa$, σ, spectral coefficients of absorption and scattering of radiation; $\bar{n}$, external normal to the boundary of the region; ϵ and T_ω, spectral emissivity factor and temperature of the heat-absorbing surface; Q, density of the radiation flux incident on the chamber heat-absorbing surface.

LITERATURE CITED

1. K. S. Adzerikho, E. F. Nogotov, and V. P. Trofimov, Radiation Heat Transfer in Two-Phase Media [in Russian], Minsk (1987).
2. K. S. Adzerikho and V. P. Nekrasov, Inzh.-Fiz. Zh., **34**, No. 5, 894-896 (1978).
3. D. Deirmendzhan, Scattering of Electromagnetic Radiation by Spectral Polydisperse Particles [Russian translation], Moscow (1971).
4. S. L. Shagalova and I. N. Shnittser, Burning of Solid Fuel in Furnaces of Steam Generators [in Russian], Leningrad (1976).