REFINEMENT OF SPECIFIC PARAMETERS OF THE ZONAL METHOD OF CALCULATION

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On the basis of a generalization of experimental data, recommendations are made for calculating the radiation from triatomic gases, and coke and ash particles.

When calculating the heat exchange by radiation in the furnaces of boiling apparatus, the zonal method is widely used, by means of which one can determine the temperature of the furnace gases, the heat fluxes, and the temperature of the heated surface in the form of a piecewise-continuous function of the height of the furnace chamber.

As is well known, the basis of the zonal method of calculation is the energy equation for an isolated volume of the furnace chamber, which, taking into account the steady-state mode, neglecting second-degree factors, can be written as follows:

$$\int_V \operatorname{div}(wct)\, dV - \oint_{F_V} E_{\mathrm{res}}\, dF = \int_V q dV. \qquad (1)$$

For a number of specific conditions, Eq. (1) can be approximated by more simple algebraic relations. In general form the equation for calculating the temperature of the gases for the k-th zone of the furnace chamber has the form

$$t_2 = \frac{Q_l^{\mathrm{w}}}{100\,\Sigma V c_2} \cdot \frac{n_k\beta_k + \sum\limits_{i=1}^{\kappa-1} n_i\,\Delta\beta_i}{(n_{\mathrm{I}} + n_{\mathrm{II}} + \ldots + n_{\kappa})} + \frac{(n_{\mathrm{I}} + n_{\mathrm{II}} + \ldots + n_{\kappa-1})\, c_1 t_1 + n_{\kappa} c_{\mathrm{B}} t_{\mathrm{B}} + mr c_{\mathrm{g}} t_{\mathrm{g}}}{c_2 (n_{\mathrm{I}} + n_{\mathrm{II}} + \ldots + n_{\kappa})} - \left[1 + \left(\frac{T_2}{T_1}\right)^4\right] \frac{\sigma_0 \varepsilon_{\mathrm{T}} T_1^4 \Sigma\psi F}{2(n_{\mathrm{I}} + n_{\mathrm{II}} + \ldots + n_{\kappa})\, B_{\mathrm{p}}\, \Sigma V c_2}. \qquad (2)$$

Of the quantities defining the accuracy of the calculation in Eq. (2), the most uncertain is the degree of blackness of the furnace volume ε_t.

Analysis of the experimental data on local heat exchange in coal-dust furnaces of the BKZ-210-140PT, TP-230-B, TP-230-3, BKZ-210-140PT, TPP-210-A, P-49, TP-109, PK-39-P, and PPP-200-1 boiling apparatus showed that the experimental values of the degree of blackness of the furnace volume ε_{texp} in all zones of the furnace chamber are, on the average, 10% less than ε_{tcal} calculated from the existing recommendations [1]. The inaccuracy in determining ε_t by ±10% leads to an error in calculating the temperature of the gases at the exit of the furnace on average by 50°. It should be noted also that the difference between the experimental and theoretical values of ε_t taken from [1] depends on the dimensions of the furnace chamber. Thus, for the furnace chamber of the BKZ-210-140PT boiling apparatus, D_c = 210 tons/h, and $\Delta\varepsilon_t/\varepsilon_{texp}$ = 5.7%; for the TP-230-3 boiling apparatus D_c = 230 tons/h and $\Delta\varepsilon_t/\tau_{texp}$ = 6.9%; for the TPP-200-1 apparatus D_c = 1250 tons/h and $\Delta\varepsilon_t/\tau_{texp}$ = 17%. Consequently, the increase in the inaccuracy in calculating ε_t increases with the scale factor, i.e., as the thickness of the radiating layer l increases.

As can be seen from the above data, it is worth refining the existing recommendations on calculating the radiation of carbon-dust furnaces. It is well known that, when making calculations of the heat exchange, the radiation of the furnace medium is calculated in terms

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of the radiation characteristics of components. For carbon-dust furnaces the optical flux density of the furnace medium $\tau = \tau_g + \tau_a + \tau_c$, where

$$\tau_g = k_g r_t pl,\ \tau_a = k_a \mu_a pl,\ \tau_c = k_c x_1 x_2 pl.$$

The data obtained at the present time on the radiation of CO_2 are practically identical with the data on the basis of which the existing recommendations were drawn up for calculating the radiation of triatomic gases [2]. The data on the radiation of H_2O for $T > 1200°K$ disagree considerably, particularly at high temperatures. Thus, for $T > 1700°K$ the disagreement in the radiation of H_2O calculated from the data given by Lekner, Hottel, and Egbert is 25-30%.

We obtained the theoretical relationship for determining the total radiation of triatomic gases, refining the values of k_g at high temperatures [3]:

$$k_g = C_p\left[\left(\frac{315\,k_0'}{\sqrt{p_t l}} - 0.2\right)\ln\frac{3300}{T} + 0.1\right]. \tag{3}$$

The coefficient k_0', which depends on the composition of the combustion products, is calculated from the equation

$$k_0' = 0.4 + 0.35\,\frac{r_{H_2O}}{r_t}. \tag{4}$$

The dependence of the radiation of triatomic gases on the pressure is taken into account by introducing the coefficient C_p into the equation, where C_p is given by

$$C_p = 1 + 0.3\left(1 - 0.4\,\frac{T}{1000}\right)\ln p \cdot 10^{-5}. \tag{5}$$

In the pressure range from $0.9 \cdot 10^5$ to $1.3 \cdot 10^5$ Pa the correction C_p can be taken as unity.

The equation for calculating the absorption coefficient of beams of triatomic gases k_g is true when the defining parameters vary within the following limits: $0.32 < r_{CO_2}/r_{H_2O} < 5.6$; $p_{CO_2} l = (7\text{-}157) \cdot 10^3$ mPa; $P_{H_2O} l = (4\text{-}225) \cdot 10^3$ mPa; $700 < T < 2400°K$; $0.8 \cdot 10^5$ Pa $< p < 10^6$ Pa; i.e., for all forms of natural fuels within the working limits of the variation of the defining parameters.

Refinements are introduced into the calculations of the radiation of a flow of coke and ash particles on the basis of experimental data on the combustion and local heat exchange in the furnaces of boiling equipment. Analysis shows that the experimental values of the optical flux density of ash and coke particles averaged over the zones are functionally related to the product μl, which is shown in Figs. 1 and 2. The relations $\tau_a = f(\mu_a l)$ and $\tau_c = f(\mu_{ca} l)$ obtained are nonlinear. Hence, the absorption coefficients of the rays by the flow of coke particles k_c and ash particles k_a depend on the product μl. This is not taken into account in the existing recommendations [1].

It is also important to refine the values of the optical density of the flow of coke particles τ_c in the zones of the furnace chamber. The recommendations give values of τ_c for the combustion zone, and in the exit zone τ_a is taken to be zero. Analysis of the experimental data on heat exchange and combustion enabled us to establish the dependence of the optical density of the flow of coke particles in the zones of a furnace chamber on their concentration μ_c (see Fig. 2). To describe the relations $\tau_a = f(\mu_a l)$ and $\tau_c = f(\mu_c l)$ we can suggest the following equations:

$$\tau_{ai} = \frac{440}{\sqrt[3]{T_i^2 d_3^2}}\sqrt[4]{\mu_{ai} l},\quad p = 10^5\ \text{Pa}; \tag{6}$$

$$\tau_{ci} = \frac{137}{\sqrt{T_i}}\sqrt{\mu_{ci} l},\quad 10^{-2} < \mu_{ca} l < 3 \cdot 10^{-2},\quad p = 10^5\ \text{Pa}; \tag{7}$$

$$\tau_{ci} = \frac{2.8 \cdot 10^4}{T_i}\,\mu_{ci} l,\quad 0 < \mu_{ca} l < 10^{-2},\quad p = 10^5\ \text{Pa}. \tag{8}$$

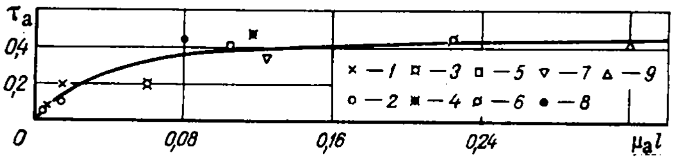

Fig. 1. Effect of the product $\mu_a l$ (m) on the optical density of ash particles τ_a for $p = 10^5$ Pa, $T = 1400°K$, and an effective diameter of the ash particles $d_a = 13$ μm: 1) ash ASh, bench investigations; 2) ASh from [1]; 3) ASh, experiments in the TP-230-B furnace; 4) industrial ash, TP-230-3 boiling apparatus; 5) T ash, BKZ-320-140-PT; 6) ASh, TPP-200-1; 7) T, TPP-210-A; 8) ASh, BKZ-210-140-PT; 9) Ekibastuz coal ash, PK-39-P boiler apparatus.

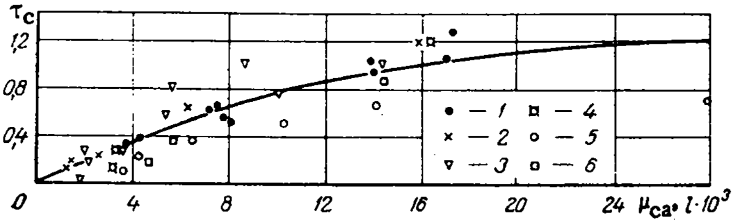

Fig. 2. Effect of the product $\mu_{ca} l$ (kg/m²) on the optical density of the flow of coke particles τ_c for $p = 10^5$ Pa; 1-6) experimental data of bench investigations on boiling apparatus TP-230-3, TPP-210-A, TP-230-B, TPP-200-1, and BKZ-320-140-PT, respectively.

It follows from Eqs. (6)-(8) that for a pressure in the furnace chamber $p = 10^5$ Pa

$$k_{at} = \frac{440}{\sqrt[4]{T_t^2 d_a^2}} (\mu_{at} l)^{-\frac{3}{4}}; \tag{9}$$

$$k_{ct} = \frac{137}{\sqrt{T_t}} (\mu_{ct} l)^{-\frac{1}{2}}, \ 10^{-2} < \mu_{ca} l < 3 \cdot 10^{-2}; \tag{10}$$

$$k_{ct} = \frac{2.8 \cdot 10^4}{T_t}, \ 0 < \mu_{ca} l < 10^{-2}. \tag{11}$$

Equations (6)-(11) describe the radiation of coke and ash particles when μl varies within the following limits: (6) and (9) for $0 < \mu_a l < 0.35$ m, (7) and (10) for $10^{-2} < \mu_{ca} l < 3 \cdot 10^{-2}$ kg/m², and (8) and (11) for $0 < \mu_{ca} l < 10^{-2}$ kg/m². With regard to higher concentrations, for these cases it is necessary to obtain the appropriate experimental material.

The range of variation of $\mu_{ca} l$ from 0 to 10^{-2} kg/m² is characteristic for the zones of furnace chambers where after burning and cooling of the combustion product occurs. In these zones the coke particles have dimensions exceeding 50 μm. The radiation of such particles approximates to gray radiation, and, as a consequence, the relation $\tau_c = f(\mu_c l)$ becomes linear. In the combustion zones the product of the concentration of coke particles and the effective thickness of the radiating layer varies in practice from 10^{-2} to $3 \cdot 10^{-2}$ kg/m². The furnace medium contains a large quantity of finely disperse carbon particles, the radiation of which is extremely selective. Hence, for these zones of the furnace chamber k_c depends to a large extent on the product $\mu_c l$.

The calculation of ε_t using the above equations is in good agreement with theoretical data. The relative error in calculating ε_t on the average for the furnace chambers investigated is ±5%.

The relations obtained not only increase the accuracy in the calculation of ε_t (particularly for high-efficiency boilers), but also enable one to calculate the radiation characteristics of the furnace medium of powdered coal furnaces in any zone of the furnace chamber.

NOTATION

w, c, and t, velocity, specific heat, and temperature of the combustion products, respectively; E_{res}, resultant heat flux over the surface of the volume considered; q, heat released per unit volume; Q_l^W, lowest heat of combustion of the working mass of fuel; n and m, fraction of the fuel and recirculation per layer, respectively; β, degree of burning of the fuel in the zone; $\Delta\beta$, degree of burning in a specified zone from the combustion of the fuel introduced into previous zones; t_1, t_2, c_1, and c_2, temperature and heat capacity of the combustion products at the entrance and the exit from the zone, respectively; t_g, c_g, and r, temperature, heat capacity, and fraction of the recirculation gases; B_p, theoretical fuel flow rate; ψ, thermal efficiency; F, surface bounding the zone; Vc_2, total heat capacity of the combustion products for t_2; $\Delta\varepsilon_t = \varepsilon_{tcal} - \varepsilon_{texp}$, difference between the theoretical degree of brightness of the surface volume and the experimental value; r_t, r_{CO_2}, and r_{H_2O}, total volume fraction of triatomic gases and the volume fraction of CO_2 and H_2O, respectively; μ_a, dimensionless concentration of ash particles; d_a, effective diameter of the ash particles; $\varkappa_1$ and $\varkappa_2$, quantities which take into account the concentration of coke particles in the combustion product; p_p, total partial pressure of the gases; T, temperature of the combustion products; $\mu_c \mu_{ca}$, dimensionless and actual concentration of coke particles; and σ_0, emissivity of blackbody.

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PROBABILISTIC MODELING OF VIBRATIONALLY NONEQUILIBRIUM DIATOMIC GASES IN THE THEORY OF RADIATION TRANSFER

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The radiation transfer in a vibrationally nonequilibrium diatomic gas is described by a system of equations which can be reduced to one integrodifferential equation for the vibrational energy density. A method for the numerical solution of this equation by using the theory of Markov chains is proposed in the paper.

The investigation of radiation transfer in nonequilibrium gases is closely associated with such areas of application as spectroscopy, low-temperature plasmas, molecular gasdynamic lasers, radiation gasdynamics, and physics of the upper layers of a planetary atmosphere. In the general case, the problem reduces to solving a system of equations of Boltzmann type for material particles and photons [1, 2]. Obtaining concrete results by direct integration of the system of equations is hence a very complex mathematical problem. Hence, examination of such physical situations when the problem allows of specific simplifciations is of interest. The present paper is devoted to an investigation of radiation energy transfer in nonequilibrium diatomic heteronuclear gases (CO, HCl, NO, etc., for example) both because of the relative simplicity of configuration of diatomic molecules and the practical importance of such gases for radiation gasdynamics and atmospheric optics problems. Radiation processes exert a substantial effect, together with inelastic collisions on the population of the vibrational–rotational molecule levels at reduced pressures of the radiating medium $p \sim 10^{-4}$–10^{-3}

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