NOTATION

a, thermal diffusivity, m^2/sec; a_1 and a_2, absorptivities for the incident flux with a black spectrum at a temperature T_*, single and double passes (double pass includes total reflection after the first pass); ε_1, volume emmissivity; $\bar{\varepsilon}$ and $\bar{a}$, reduced emissivity and absorptivity of the furnace space; $I_{o\omega}$, Planck intensity, $W\cdot cm/(m^2\cdot sr)$; A_ω, spectral absorptivity, dimensionless; A, surface absorptivity; $R = 1 - A$; ω, wave number, cm^{-1}; α_k, heat-transfer coefficient from medium to heating surface, $W/(m^2\cdot K)$; λ, thermal conductivity, $W/(m\cdot K)$; τ, heating time, sec; Δ, penetration depth of varying temperatures, m; τ_0, period of furnace rotation, sec; φ, angular coefficient from lining to lining without absorption; $\sigma = 5.67\cdot 10^{-8}$ $W/(m^2\cdot K^4)$; T and T_*, temperatures of the medium and lining surface, °K; T_{*min}, initial temperature constant over the depth, °K; $Bi = \alpha_k\Delta/\lambda$; $Bo = \lambda/(\bar{\varepsilon}\sigma T^3\Delta)$; $Fo = a\tau/\Delta^2$; $\beta = T_{*min}/(bT)$; $z = 1.5Fo/(bBo_e)^2$; $b = \sqrt[4]{\bar{\varepsilon}/\bar{a}}$; $\Theta_* = (T_* - T_{*min})/(T - T_{*min})$; $y = q/(\bar{\varepsilon}\sigma T^4)$. Subscripts * and 0, lining surface and charge surface; A, surface absorptivity.

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RADIATIVE CHARACTERISTICS OF COKE PARTICLES OF A COAL-DUST FLAME

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UDC 536.3.001.24

An experimental investigation is made of the complex index of refraction of the cokes of solid fuels. The spectral coefficients of absorption and scattering needed to calculate the thermal emission of coke particles in a coal-dust flame are determined on the basis of the results obtained.

The thermal emission of a coal-dust flame is determined by the emission of the triatomic gases CO_2 and H_2O and of the ash and coke particles contained in the stream of these gases. As volatiles escape and the coke residue burns up, the sizes and concentration of the coke particles vary, whereas for ash particles they remain approximately constant over the height of the furnace box. In connection with the foregoing, the radiative properties of the solid disperse phase vary considerably in the process of combustion.

By now the radiative properties of triatomic gases and particles of ash dust have been studied in sufficient detail. But as for coke particles, all the available data are confined to the results of investigations [1] of the optical constants of coke in the visible region of the spectrum at $\lambda = 0.546$ μm. And yet the main transfer of radiant energy in the furnace boxes of boiler plants takes place mainly in the infrared region of the spectrum in the wave-

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TABLE 1. Elementary Composition of Coals

Type of coal	Working mass, %			Combustible mass, %			A, %	Q, kcal/kg	v^g, %
	C_w	H_w	S_w	C_c	H_c	S_c			
Anthracite	77,15	1,23	1,87	93,50	1,49	2,27	15,93	6510	2,54
Dry-burning coal	74,01	2,47	3,07	88,66	2,96	3,68	15,22	6738	12,74
Gas coal	72,84	5,43	3,14	83,51	6,25	3,62	11,83	6980	38,92

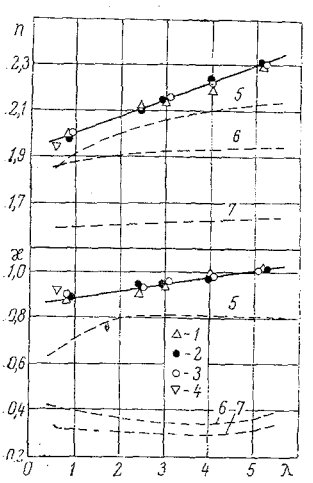

Fig. 1. Dispersion of the optical constants of coke and coals (λ, μm): 1) anthracite coke; 2) coke of dry-burning coal; 3) coke of bituminous coal; 4) coke according to the data of [1]; 5) anthracite according to the data of [4]; 6) dry-burning coal according to the data of [4]; 7) bituminous coal according to the data of [4].

length range from 1 to 6 μm. The emission in the visible region is negligibly small compared with the emission in the infrared region of the spectrum.

In calculations of heat exchange by the standard method of thermal calculation of boiler plants [2] the radiative properties of ash and coke particles are taken into account separately. For ash particles they are based on the available experimental data, while for coke particles they are based on the results of approximate calculated estimates from data on the optical constants of carbon in the infrared region of the spectrum. And yet the optical constants of coke can differ considerably from the analogous data for amorphous carbon.

In connection with the foregoing, one of the most important problems in the further improvement of the method of calculating the thermal emission of a coal-dust flame is the problem connected with determining the radiative characteristics of coke particles in the infrared region. For this purpose we made tests on determining the dispersion of the complex index of refraction of coke, $m = n - i\varkappa$, in the wavelength region from 0.8 to 5 μm. Coke specimens of anthracite, dry-burning, and bituminous coals were investigated. The elementary composition of these coals is presented in Table 1.

The investigation procedure is presented in detail in [3, 4]. It is based on the measurement of the specular reflection of optically smooth surfaces of the specimens under investigation at angles of incidence close to normal. One measurement is made with reflection into an air medium and another is made with reflection into a medium of carbon tetrachloride. With

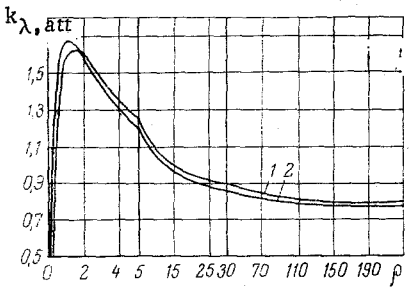

Fig. 2

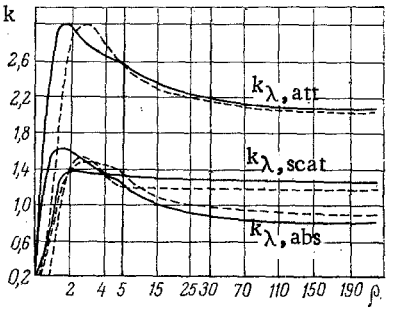

Fig. 3

Fig. 2. Spectral absorption coefficient of coke particles as a function of the parameter ρ.

Fig. 3. Spectral attenuation, absorption, and scattering coefficients of coke (solid curves) and bituminous coal (dashed curves) at λ = 1 μm.

such a test setup it was possible to determine directly both the index of refraction n and the absorption coefficient $\varkappa$ at different radiation wavelengths λ.

The data obtained on the optical constants of coke in the IR region are presented in Fig. 1. They correlate well with the data of [1] pertaining to the visible region at λ = 0.546 μm for various coke specimens. And the initial specimens of coal in [1] were characterized by the same carbon and hydrogen content as in our tests.

Along with the data on the optical constants of coke in Fig. 1 we also present data of [4] on the optical constants of anthracite, dry-burning, and bituminous coals, the starting material for obtaining the investigated coke specimens. The coke test specimens with which the tests were made were obtained by heating the coals in a nitrogen atmosphere to 950°C at a rate of 2-3 deg/min. This assured the complete escape of the volatiles included in the composition of the original fuel.

As is seen from these data, the optical constants n and $\varkappa$ of coke considerably exceed the optical constants of the original coal specimens in numerical values. This additionally confirms the conclusion drawn in [5] that an increase in the carbon content in a material results in a pronounced increase in its absorption coefficient and index of refraction in the entire radiation wavelength region of importance for heat exchange in furnaces.

From the data obtained we get the important conclusion that the optical constants n and $\varkappa$ of coke do not depend on the kind of fuel burned. In application to any solid fuel, therefore, one can speak of common primary radiative characteristics of coke particles. The dispersion of the optical constants of coke in the range of wavelengths λ from 0.8 to 5.0 μm can be described by functions of the type $n = 1.95 + 0.07\lambda$ and $\varkappa = 0.86 + 0.03\lambda$ on the basis of the results of these tests.

The data obtained on the complex index of refraction pertain to a massive specimen. But sometimes the optical properties of a substance in the dispersed state can differ from the properties of the same substance in a massive specimen, as pointed out in [6]. These deviations may be connected mainly with the difference in structure and chemical composition. As our investigations showed, such differences were not observed for coke particles relative to coke in a massive specimen.

Using the data obtained on the complex index of refraction of coke, it is simple to calculate the dimensionless spectral absorption and scattering coefficients. According to the Mie theory [7], the absorption and scattering coefficients $k_{\lambda,abs} = k_{\lambda,abs}(m, \rho)$ and $k_{\lambda,scat} = k_{\lambda,scat}(m, \rho)$ can be represented in the form of infinite, slowly converging series in the diffraction parameter $\rho = \pi x/\lambda$

Numerical data on the quantities $k_{\lambda,abs}$ and $k_{\lambda,scat}$ for coke particles in the spectral region from 0.8 to 5.0 μm were obtained on the basis of computer calculations.

In Fig. 2 it is shown how the dimensionless spectral absorption coefficient $k_{\lambda,abs}$ of coke particles varies as a function of the parameter ρ for two radiation wavelengths, λ = 1 μm

(1) and $\lambda = 4$ μm (2). It is seen from the graph that for the region of $\rho > 1.5$ longer radiation wavelengths λ correspond to lower values of the spectral absorption coefficient. Conversely, for $\rho < 1.5$ an increase in wavelength λ results in an increase in the spectral absorption coefficient $k_{\lambda,abs}$. Here the position of the maximum as a function of ρ varies noticeably. At values of $\rho > 100$ the absorption coefficient is stabilized and practically ceases to depend on ρ. The sole factor having some influence on the absorption coefficient in this region of values of ρ is the radiation wavelength, determining the dispersion of the optical constants of coke.

Coke particles not only absorb but also considerably scatter the radiation incident on them. In Fig. 3 we present data showing how the spectral attenuation, absorption, and scattering coefficients vary as the parameter ρ varies. Data on the radiative characteristics of particles of bituminous coal are presented in the same graph for comparison. For the region of $\rho > 5$ the spectral attenuation coefficients for coke and bituminous coal particles practically coincide, approaching their asymptotic value of two as ρ increases. For this region of ρ the spectral absorption coefficient for coke particles is characterized by somewhat lower values than for bituminous coal particles. The opposite relation is observed for the scattering coefficient, stabilization of which is reached at $\rho \approx 5$. At the same time, stabilization of the spectral absorption coefficient and the spectral attenuation coefficient is reached at higher values, $\rho > 100$. Thus, along with absorption, one must allow for the influence of the effect of scattering on radiant energy transfer in calculations of heat exchange in furnaces for both ash and coke particles.

For $\rho > 10$ the spectral absorption and scattering coefficients are described by functions of the type $k_{\lambda,abs} = 0.80 + \frac{2.5}{\rho}$ and $k_{\lambda,scat} = 1.25 + \frac{0.8}{\rho}$. In the limit as $\rho \to \infty$ the quantities $k_{\lambda,abs}$ and $k_{\lambda,scat}$ cease to depend on ρ, approaching constant numerical values.

The data presented on the spectral absorption and scattering coefficients pertain to individual particles. To use them in application to real polydisperse systems one must have access to data on the particle size distribution.

We determined the size distribution function of coke particles in accordance with the procedure of [8] with allowance for the influence on the combustion of diffusion and kinetic factors, the qualitative characteristics of the furnace, the conditions of delivery of the dust–air mixture into the furnace box, and the operating parameters of the process.

The data obtained show that for the zone of maximum heat release, which has the strongest influence on the conditions of heat exchange, the size distribution of coke particles is described by a function of the type $N(x) = Ax e^{-\delta\sqrt{x}}$, where the coefficient $A = 4/(3x_m^2)$ is determined from the conditions of normalization of the function $N(x)$ while the parameter $\delta = 2/\sqrt{x_m}$ is determined from the extremum of the function $N(x)$. The quantities A and δ are functions of the modal size x_m of the particles.

Typical curves of the size distribution of coke particles are presented in Fig. 4 for three kinds of fuel — anthracite, bituminous, and brown coals.

The differences in the disperse composition of the coke particles are connected with two circumstances: first, with differences in the fineness of pulverization of the fuel, and second, with differences connected with the conditions of burning of the coke particles. Coke particles formed in the burning of anthracite are characterized by the finest disperse composition ($x_m = 2$ μm); in the transition to bituminous and brown coals the modal size of the particles grows to 4 and 6 μm, respectively.

Designating the number density of particles per unit volume of gas as N_0, the expression for the spectral absorption and scattering coefficients of a polydisperse system of coke particles can be written in the form

$$\tilde{k}_{\lambda,abs} = \frac{\pi}{4} N_0 \int_0^\infty k_{\lambda,abs}\, x^2 N(x)\, dx, \quad \tilde{k}_{\lambda,scat} = \frac{\pi}{4} N_0 \int_0^\infty k_{\lambda,scat}\, x^2 N(x)\, dx.$$

The quantity μ, characterizing the weight concentration of coke particles, is usually used instead of the quantity N_0 in engineering calculations. Since

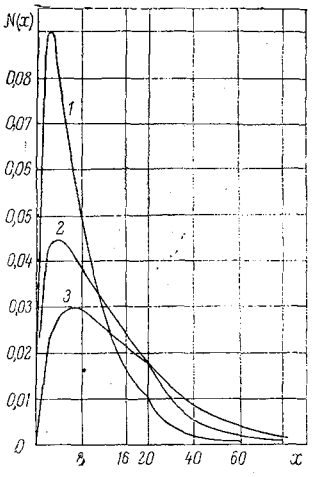

Fig. 4. Size distributions of coke particles: 1) anthracite coke; 2) bituminous coal coke; 3) brown coal coke. x, μm; N(x), 1/μm.

$$N_0 = \frac{6}{\pi\gamma}\frac{\mu}{\int_0^\infty x^3 N(x)dx},$$

the expression for the spectral absorption and scattering coefficients can be written in the following form convenient for practical calculations:

$$\tilde{k}_{\lambda,\,\mathrm{abs}} = \frac{3}{2}\frac{\mu}{\gamma}\frac{\int_0^\infty k_{\lambda,\,\mathrm{abs}}\, x^2 N(x)\,dx}{\int_0^\infty x^3 N(x)\,dx},$$

$$\tilde{k}_{\lambda,\,\mathrm{scat}} = \frac{3}{2}\frac{\mu}{\gamma}\frac{\int_0^\infty k_{\lambda,\,\mathrm{scat}}\, x^2 N(x)\,dx}{\int_0^\infty x^3 N(x)\,dx}.$$

Thus, the collection of data on the radiative characteristics of coke particles and their size distributions establishes a basis for calculations of the radiative properties of a stream of coke particles in a coal-dust flame.

NOTATION

λ, wavelength, μm; $m = n - i\varkappa$, complex index of refraction; $\varkappa$, absorption coefficient; n, index of refraction; $\rho = \pi x/\lambda$, diffraction parameter; x, particle size, μm; $k_{\lambda,\mathrm{att}}$, dimensionless spectral attenuation coefficient; $k_{\lambda,\mathrm{abs}}$, dimensionless spectral absorption coefficient; $k_{\lambda,\mathrm{scat}}$, dimensionless spectral scattering coefficient; $\tilde{k}_{\lambda,\mathrm{abs}}$, spectral absorption coefficient of a polydisperse system, 1/m; $\tilde{k}_{\lambda,\mathrm{scat}}$, spectral scattering coefficient of a polydisperse system, 1/m; γ, density of coke particles, g/cm³; N_0, number density of particles per unit volume of gas, 1/cm³; μ, weight concentration of coke particles, g/cm³; N(x), size distribution of coke particles, 1/μm.

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HEAT EXCHANGE BETWEEN THREE STREAMS IN PIPES OF VARIABLE CROSS SECTION

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A method of calculating the thermal characteristics in the interaction of three streams in pipes of variable cross section in the presence of heat exchange with the ambient medium is discussed.

A method of calculating the temperature and heat-flux profiles during heat exchange between three media moving in pipes of constant cross section in the absence of heat exchange with the ambient medium was discussed in [1]. In [2] the analytical apparatus of this problem was simplified, and the problem of calculating the thermal characteristics in the interaction of three streams in pipes of constant cross section with allowance for heat exchange with the ambient medium was also considered.

The problem of heat exchange between three streams in pipes of constant cross section without allowance for the ambient medium was also discussed earlier in [3-6], although the solutions obtained then did not make it possible to extend them directly to more complicated cases: the interaction of a larger number of media, variable stream cross sections, or both factors together.

The latter problem is solved rather simply on the basis of the approach used in [2]. For determinacy, let us consider heat exchange during the direct-flow–counterflow motion of three streams in pipes of variable cross section with allowance for the thermal interaction with the ambient medium (Fig. 1).

Streams enter a system of three coaxially arranged pipelines of length l_e from different ends. Water with an assigned temperature $t_{1,e}$ enters the central pipe and air with an assigned temperature $t_{3,e}$ enters the outer annular channel from the end with the coordinate l_e. A stream (combustion products) with an assigned temperature $t_{2,o}$ enters the intermediate annular channel in the initial cross section $l = 0$. The temperature of the ambient medium is taken as constant and equal to t^*. We neglect the thermal resistance of the pipe walls, the radial temperature gradient of the streams, and the temperature dependence of the thermophysical properties.

The geometry of the pipelines changes in the cross section with the coordinate l^*. The pipeline system can thereby be divided into two sections (I and II), in each of which the cross sections remain constant and the equations obtained in [2] for determining the lengthwise variation of the stream temperatures remain valid:

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