3. T. W. Schaff and D. Williams, J. Opt. Soc. Am., 63, No. 6, 726-732 (1973).
4. L. D. Landau and E. M. Lifshits, Mechanics of Continuous Media [in Russian], Moscow (1954).
5. A. Misnar, Thermal Conductivity of Solids, Liquids, Gases, and Their Composites [in Russian], Moscow (1968).
6. L. V. Gurvich, I. V. Veits, V. A. Medvedev, et al., Thermodynamic Properties of Individual Materials [in Russian], Vol. 1, Book 2, Moscow (1978).

RADIATIVE PARAMETERS OF SUSPENDED SULFIDE-CHARGE PARTICLES

M. N. Abramzon, F. N. Lisin, and L. N. Podobedova

UDC 536.3.621.745.32

Electromagnetic theory has been used to calculate the attenuation and scattering coefficients together with the spectral degree of blackness for polydisperse sulfide particles in a flame.

When high-intensity flame melting is applied to sulfides in nonferrous metallurgy, it is necessary to know the radiative parameters for the suspended-particle flows. Here we examine the radiation parameters for suspended particles of copper and lead–zinc charges.

Mie's theory [1] gives the radiation parameters for a single particle. Sulfide particles reacting with oxygen in a flame are covered by oxides; for example, a pyrrhotite particle may have a core composed of the initial material covered by layers of FeO, Fe_3O_4, and Fe_2O_3. One has to calculate the scattering properties for such a multilayer particle. From the viewpoint of electrodynamics, this is a boundary-value problem in diffraction for Maxwell's equations. Convenient formulas have been derived as recurrent relations between the Mie coefficients for particles having n and n + 1 layers:

$$a_l^{(n+1)} = \frac{y_{n+1}\psi_l(y_{n+1})\,p_l(Z_{n+1};a_l^{(n)}) - Z_{n+1}\psi_l'(y_{n+1})}{y_{n+1}\zeta(y_{n+1})\,p_l(Z_{n+1};a_l^{(n)}) - Z_{n+1}\zeta_l'(y_{n+1})}, \tag{1}$$

$$b_l^{(n+1)} = \frac{Z_{n+1}\psi_l(y_{n+1})\,p_l(Z_{n+1};b_l^{n}) - y_{n+1}\psi_l'(y_{n+1})}{Z_{n+1}\zeta_l(y_{n+1})\,p_l(Z_{n+1};b_l^{n}) - y_{n+1}\zeta_l'(y_{n+1})}, \tag{2}$$

where

$$p_l(X;\ f) = \frac{\psi_l'(X) - f\zeta_l'(X)}{\psi_l(X) - f\zeta_l(X)};\quad Z_n = K_n r_n;\quad y_n = K_{n+1} r_n;\quad K_i = \frac{2\pi}{\lambda} m_i;$$

$$\psi_l(X) = \sqrt{\frac{\pi X}{2}}\,J_{l+1/2}(X);$$

ζ_ℓ, a Riccati–Bessel function; r_n, radius of layer n; m, complex refractive index; and λ, wavelength.

The attenuation and scattering coefficients for such a particle are

$$k_{\text{at}\ \lambda} = \frac{2}{\rho^2}\sum_{l=1}^{\infty}\operatorname{Re}\{a_l + b_l\}, \tag{3}$$

$$k_{\text{sc}\ \lambda} = \frac{2}{\rho^2}\sum_{1}^{\infty}(2l+1)(|a_l|^2 + |b_l|^2), \tag{4}$$

where $\rho = 2\pi r_p \lambda$, r_p is particle radius.

The spectral attenuation and scattering coefficients averaged over the particle sizes and the mean scattering cosine for phase i are

All-Union Nonferrous Metal Processing Power Consumption Research Institute, Sverdlovsk.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 54, No. 1, pp. 108-111, January, 1988. Original article submitted September 9, 1986.

 0022-0841/88/5401-0084 $12.50

TABLE 1. Sulfide-Concentrate Scattering Parameters

Δr, μm	λ, μm	Copper charge: $\langle K\rangle_{at.\lambda}$, m²/g	Copper charge: $\langle K\rangle_{sc.\lambda}$, m²/g	Copper charge: $\langle\bar{\mu}\rangle_\lambda$	Lead–zinc charge: $\langle K\rangle_{at.\lambda}$, m²/g	Lead–zinc charge: $\langle K\rangle_{sc.\lambda}$, m²/g	Lead–zinc charge: $\langle\bar{\mu}\rangle_\lambda$
0	0,9	0,1291	0,1064	0,6795	0,1305	0,0912	0,750
	1,4	0,1309	0,1198	0,6035	0,1326	0,0981	0,700
	1,9	0,1331	0,1218	0,6018	0,1337	0,1337	0,5168
	2,4	0,1356	0,1233	0,5961	0,1361	0,1361	0,5128
	2,9	0,1348	0,1213	0,5780	0,1382	0,1382	0,4949
	3,4	0,1385	0,1385	0,5191	0,1397	0,1397	0,4960
2,0	0,9	0,1308	0,0948	0,793	0,1309	0,0896	0,770
	1,4	0,1335	0,0999	0,744	0,1333	0,0937	0,736
	1,9	0,1349	0,1031	0,769	0,1340	0,1295	0,536
	2,4	0,1384	0,1059	0,719	0,1364	0,1315	0,533
	2,9	0,1422	0,1020	0,747	0,1396	0,1336	0,522
	3,4	0,1433	0,1125	0,747	0,1407	0,1353	0,519

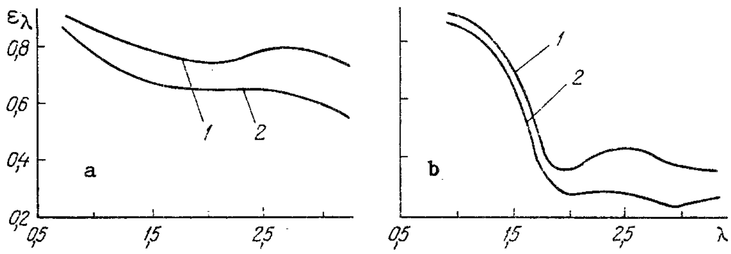

Fig. 1. Spectral degrees of blackness for copper charge (a) and flow of lead–zinc charge (b) at 500 g/m³: 1) Δr = 2 μm; 2) 1; λ in μm.

$$\langle K\rangle^i_{at.\lambda} = \frac{1}{4}\int_0^\infty k^i_{at.\lambda}\frac{dS}{dr}\,dr, \tag{5}$$

$$\langle K\rangle^i_{sc.\lambda} = \frac{1}{4}\int_0^\infty k^i_{sc.\lambda}\frac{dS}{dr}\,dr, \tag{6}$$

$$\langle\bar{\mu}\rangle^i_\lambda = \frac{1}{\langle K\rangle^i_{sc.\lambda}}\int_0^\infty k^i_{sc.\lambda}\bar{\mu}_\lambda\frac{dS}{dr}\,dr, \tag{7}$$

where dS/dr is the specific-surface distribution.

The corresponding spectral quantities for the entire charge are

$$\langle K\rangle_{at.\lambda} = \frac{1}{C}\sum_1^n C_i\langle K\rangle^i_{at.\lambda}, \tag{8}$$

$$\langle K\rangle_{sc.\lambda} = \frac{1}{C}\sum_1^n C_i\langle K\rangle^i_{sc.\lambda}, \tag{9}$$

$$\langle\bar{\mu}\rangle_\lambda = \frac{1}{C\langle K\rangle_{sc.\lambda}}\sum_1^n C_i\langle K\rangle^i_{sc.\lambda}\langle\bar{\mu}\rangle^i_\lambda, \tag{10}$$

where C_i is the mass proportion of component i.

The mineral composition of the copper charge in %: 25.8 $CuFeS_2$; 27.46 FeS_2; 5.34 CuS; 6.32 ZnS; 14.87 SiO_2; other components 20.21; that for the lead–zinc charge in %: 58.7 PbS; 8.6 FeS; 5.37 ZnS; 5.0 SiO_2; 4.0 FeO; 3.0 Al_2O_3, other components 20.67.

The calculations were performed for the main components in the oxidized charges; a pyrite particle was represented as consisting of an initial core, a layer of dissociation products,

TABLE 2. Integral Degrees of Blackness

Δr, µm	Copper charge				Lead–zinc charge			
	chamber diameter, m							
	1,0		1,5		1,0		1,5	
	particle concentration, g/m³							
	400	500	400	500	400	500	400	500
1	0,819	0,836	0,846	0,856	0,367	0,398	0,420	0,422
2	0,846	0,864	0,875	0,886	0,384	0,416	0,437	0,459

and layers of FeO, Fe_3O_4, Fe_2O_3. As the optical parameters of CuS_2 are unknown, the chalcopyrite particles were represented as having cores of initial material with layers of Fe_3O_4 and Fe_2O_3. The lead and zinc sulfide particles were represented as cores composed of initial material and layers of the corresponding oxides. The complex refractive indices were taken from [2-4]. Table 1 gives the averaged attenuation and scattering coefficients together with the anisotropy coefficient $K_{an} = \langle K \rangle_{sc,\lambda} \langle \bar{\mu} \rangle_\lambda$ for various oxide shell thicknesses Δr. The specific-surface distribution was taken as

$$\frac{dS}{dr} = Ar^n \exp(-mr), \qquad (11)$$

where r is particle radius.

In this case, A = 4.16; n = 3.4; m = 0.55.

The averaged coefficients were used in calculating the spectral degree of blackness as in [5] for a cylindrical layer of suspended particles at concentrations of 400 and 500 g/m³. Figure 1 shows the spectral degree of blackness as a function of wavelength in the near infrared.

The integral blackness is

$$\varepsilon = \frac{\int_0^\infty B(\lambda;\ T)\,\varepsilon(\lambda)\,d\lambda}{\int_0^\infty B(\lambda;\ T)\,d\lambda}, \qquad (12)$$

where $B(\lambda;\ T)$ is the Planck function.

Table 2 gives integral degrees of blackness for 1623 K. More accurate calculations require data on the temperature dependence of the complex refractive index.

Measurements [6] give the degree of blackness in copper melting as 0.78-1.0, which agrees satisfactorily with the calculations.

LITERATURE CITED

1. G. Van de Hulst, Light Scattering by Small Particles [Russian translation], Moscow (1961).
2. Yu. A. Popov and V. M. Polovnikov, Zh. Prikl. Spektrosk., 32, No. 1, 164-165 (1980).
3. A. Schlegel, J. Physics, 12, No. 16, 1157-1162 (1979).
4. D. G. Avery, Proc. Phys. Soc., 67, 1-25 (1954).
5. F. N. Lisin and I. F. Guletskaya, Inzh.-Fiz. Zh., 35, No. 1, 35-38 (1978).
6. L. N. Bazhanov, V. A. Lysenko, and E. N. Anan'in, Tsvetnye Met., No. 4, 46-49 (1979).