RADIATION OF A BED OF COARSE ALUMINA PARTICLES

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Spectral and integral emissivity is calculated of a semiinfinite bed of alumina particles with diameters up to 1 mm which are at high temperatures.

Coarse ($\rho = 2\pi r/\lambda \gg 1$) alumina particles are often used as heat carriers in a boiling bed. To calculate the emissivity of such a bed it is assumed by us that the radiation intensity of scatter on the set of all particles in a small volume of the medium can be represented as a superposition of radiation intensities scattered by the individual particles of this volume. Under these assumptions density fluctuations have no effect on the emissivity for a semiinfinite bed. In industrial plants a boiling bed can in the majority of cases be considered as semiinfinite.

1. The problem will be solved in the diffusion approximation, which is equivalent to the R-1 approximation [1]. The transport of heat radiation in a bed was considered in [2] in the diffusion approximation. The solution for the emissivity of a semiinfinite bed was given by

$$\varepsilon_\lambda = \frac{2\sqrt{1-\gamma}}{\sqrt{\frac{3}{4}(1-\bar{\mu}\gamma)}+\sqrt{1-\gamma}}. \tag{1}$$

If

$$(1-\gamma)/(1-\bar{\mu}) \ll 1, \tag{2}$$

then (1) implies

$$\varepsilon_\lambda = \frac{4}{\sqrt{3}}\sqrt{\frac{1-\gamma}{1-\bar{\mu}}}. \tag{3}$$

The same result is obtained under the assumption (2) in the DR-1 approximation [3] or equivalently in the first approximation of the method of moments [4]. In Table 1 the emissivity as calculated in the diffusion approximation is compared with the exact solution for isotropic scattering [5]. For $\gamma \geq 0.8$ the agreement is satisfactory. In our case the condition $\gamma \geqslant 0.8$ is satisfied.

2. The alumina refraction index $m = n - i\varkappa$ was measured at high temperatures by Gryvnak and Burch [6]. Their results were used in [7] to compute the attenuation and absorption coefficients by using the Mie theory for particles with radius $r \leq 10\ \mu$. The table of alumina optical constants given in [7] was used in the present article. An ALGOL program for an electronic computer was prepared by the author for the coefficients of attenuation, scattering, absorption, and the mean cosine $\bar{\mu}$ in accordance with the theory. Deirmendjian's recommendations in [8] were taken into account when preparing the program. The computations were carried out on the Minsk-22 electronic computer up to the values of $\rho = 190$. Their accuracy is not sufficient for $\rho > 180$ in view of the error accumulation in the computations by recurrence relation of the imaginary part of circular functions. In practical applications one often has $\rho > 200$.

For alumina particles with a diameter $d \leq 10^3\ \mu$ and $0.5 \leq \lambda \leq 5\ \mu$ at a temperature $t \leqslant 2000$°C one has the inequality

$$4\rho\varkappa \ll 1. \tag{4}$$

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TABLE 1. Emissivity of Semiinfinite Bed for Spherical Scattering Indicatrix

γ	ε_λ by (1)	Exact value of ε_λ
0,8	0,683	0,6581
0,9	0,535	0,5130
0,95	0,411	0,3988
1,00	0	0

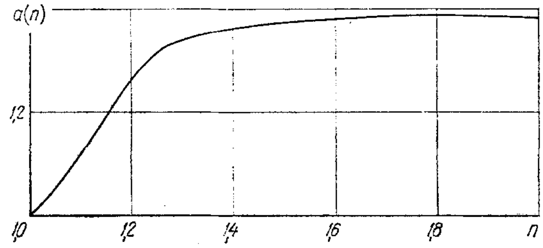

Fig. 1. Function $a_{(n)}$.

TABLE 2. Dimensionless Coefficients of Attenuation K, Absorption K_A, and Mean Cosine $\bar{\mu}$ of the Scattering Angle

	$m=1,8-i10^{-4}$			$m=1,8-i10^{-5}$			$m=1,8-i10^{-6}$		
ρ	K	K_A	$\bar{\mu}$	K	K_A	$\bar{\mu}$	K	K_A	$\bar{\mu}$
20	2,137	0,882(—2)	0,700	2,136	0,893(—3)	0,699	2,136	0,893(—4)	0,699
40	2,096	0,168(—1)	0,722	2,095	0,170(—2)	0,720	2,095	0,169(—3)	0,720
60	2,110	0,279(—1)	0,707	2,110	0,285(—2)	0,702	2,110	0,285(—3)	0,702
80	2,096	0,388(—1)	0,706	2,096	0,406(—2)	0,698	2,096	0,408(—3)	0,698
100	2,067	0,406(—1)	0,743	2,065	0,417(—2)	0,737	2,065	0,419(—3)	0,736
120	0,076	0,470(—1)	0,761	2,073	0,503(—2)	0,755	2,072	0,506(—3)	0,754
140	2,083	0,507(—1)	0,762	2,082	0,522(—2)	0,756	2,082	0,523(—3)	0,755
160	2,092	0,635(—1)	0,753	2,094	0,798(—2)	0,743	2,093	0,831(—3)	0,742
180	2,085	0,673(—1)	0,753	2,086	0,702(—2)	0,743	2,086	0,705(—3)	0,742

Such particles are called almost-transparent by us. For soft ($|m-1| \ll 1$) and almost-transparent particles it follows from the Hulst formula for the absorption coefficient [9] that

$$K_A = \frac{8}{3}\varkappa\rho. \tag{5}$$

In a more general case, if the condition (4) holds, one can write

$$K_A = \frac{8}{3}a(m, \rho)\varkappa\rho. \tag{6}$$

(One takes one term in the expansion into a Taylor series of the dimensionless absorption coefficient in the powers of $\varkappa\rho$.) It follows from the concepts of geometric-optics that for coarse and almost-transparent particles, K_A is proportional to the particle radius, that is, the value of a is independent of ρ. If $\varkappa \ll n$ (which is true for alumina), then a is a function of only the refraction coefficient:

$$K_A = \frac{8}{3}a(n)\varkappa\rho. \tag{7}$$

The shape of this function obtained by averaging the computation results in accordance with the Mie theory is shown in Fig. 1. In Table 2 the calculated values are shown of the attenuation coefficient K, K_A, and $\bar{\mu}$ for $m = 1.8-i10^{-4}$, $m = 1.8-i10^{-5}$, and $m = 1.8-i10^{-6}$. It can be seen from the table that if the condition (4) is valid, then the varying of $\varkappa$ even by two orders hardly results in any change in a for fixed ρ. For higher ρ the deviation a(n) from the mean value declines, as shown in Fig. 1.

3. The computation results of the alumina spectral emissivity for t = 1200°C and t = 1700°C and the particle diameters varying from 0.1 to 1 mm are shown in Fig. 2. The calculations were carried out by using (7) and Fig. 1. By employing the results obtained by the Mie theory one obtained $\bar{\mu} = 0.76$ and the dimensionless attenuation coefficient K = 2 for coarse and almost-transparent particles of corundum. The strongly selective character of radiation of the corundum bed is clearly seen in the diagram.

In Fig. 3 the values of the integral emissivity ε are shown versus the particle diameter. The value ε was computed from the spectral emissivity by integrating over the spectrum and using the quadrature formula with the Planck weighting function [10] with three nodes. The integral emissivity increases with the particle diameter. The latter was confirmed experimentally for the boiling bed [11]. For d > 250 μ the growth of ε with increasing d is slight. The integral emissivity reaches its minimum at a temperature of approximately 1500°C. The increase of ε with t increasing is explained by the growth of the absorption coefficient $\varkappa$ with t increasing. The growth of ε with t decreasing for t $\leqslant$ 1500°C is due to the Wien law and the specific spectral dependence of emissivity.

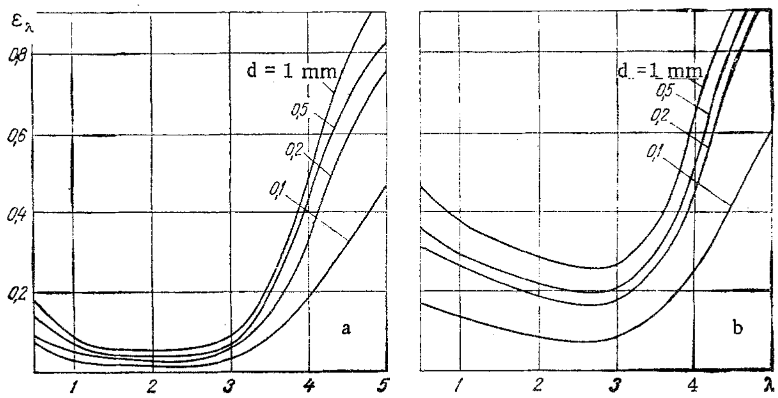

Fig. 2. Spectral emissivity of an alumina-particle bed for: a) t = 1200°C; b) t = 1700°C. λ, μ.

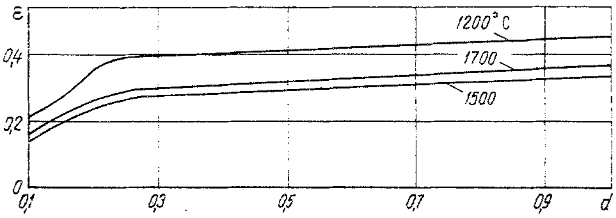

Fig. 3. Integral emissivity of an alumina-particle bed versus particle diameter d, mm.

The results obtained here may be applied in the computations of radiative heat exchange in a high-temperature boiling bed.

NOTATION

r, particle radius; λ, radiation wavelength; ρ, particle-size parameter; ε_λ, spectral emissivity; γ, scattering coefficient to attenuation coefficient ratio; $\bar{\mu}$, mean cosine of scattering angle at elementary scattering; n, refraction coefficient; ϰ, absorption coefficient; K_A, dimensionless absorption coefficient; K, dimensionless attenuation coefficient; m, complex-valued refraction index; t, temperature, °C; d, particle diameter; ε, integral emissivity.

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