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ALLOWANCE FOR PARTICLE ROUGHNESS IN DESCRIBING RADIATIVE TRANSFER IN AN AEROSOL

A. V. Gorbatov and E. V. Samuilov UDC 536.3

A model of the propagation of thermal radiation in an aerosol containing rough opaque particles is proposed within the framework of a diffusion approximation for total radiation.

The kinetic equation for thermal radiation in an aerosol contains the radiative characteristics of the particles: absorption efficiency factor Q_a, scattering factor Q_s, scattering indicatrix $p_s(\theta)$. These quantities depend on both on the state of the particle surface and on particle size and shape and the complex refractive index $m = n - i\varkappa$ of the substance comprising the particles. They are calculated in accordance with the Mie theory [1, 2] for spherical particles (for which the deviation of Δ from ideal sphericity due to microroughness is small $\Delta \ll R$). The theory was subsequently extended to include optically smooth particles ($\Delta \ll \lambda$, [3, 4]). There are no recommendations on calculating Q_a and Q_s for rough particles ($\Delta \gtrsim \lambda$). There are studies in which the authors have attemped to allow for particle roughness, however. The radiative transport equation was solved in [5] for a gas suspension of coal dust. The suspension contained "gray" particles with a size no smaller than 40 μm. Here, it was assumed that $Q_a = \varepsilon$, $Q_s = 1 - \varepsilon$, while the form of p_s was postulated. The relationship between the proposed method of describing the raiative properties of particles and the widely-used method based on the Mie theory was not discussed in [5]. The authors of [5] also did not indicate the range of application of the approximation. The authors of [6-8] examined spherical particles of coal with a radius $R \gtrsim 10$ μm. The value of Q_a determined from the Mie theory was used in the calculations performed in [6-8], while Q_s was assumed to be equal to $Q_s = 1 - \varepsilon$. In the determination of the indicatrix in [6-8], it was assumed that the surface of the coal particles was very rough. For the characteristic wavelengths of thermal radiation corresponding to temperatures $T \gtrsim 1600$ K, the diffraction parameter $X = 2\pi R/\lambda \gg 1$. In this case, the scattered radiation can be divided into diffracted and reflected parts. The diffracted component is concentrated in a narrow solid angle near the direction of the incident beam. This makes it possible to assume that it is not scattered from the beam. The reflected component for an opaque particle is determined by the condition of its surface. In the case of a very rough particle, the direction opposite the direction of the incident beam is dominant for scattering [9]. Thus, it was assumed in [6, 7] that $p_s = 1 - \cos\theta$. As a result, it can be concluded that the approach used in [6-8] is elective. In this approach, Q_a was calculated from the Mie theory on the one hand, while on the other hand the roughness of the particle surface was considered in calculating the indicatrix. It follows from this that the question of the radiative properties of rough particles remains unanswered.

The goal of the present investigation is to use a diffusion approximation to obtain an equation for the total radiant flux in a gas suspension of opaque rough particles for the plane-parallel case. By allowing for the roughness of the particle surface, we increase the

G. M. Krizhizhanovskii Energy Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 3, pp. 364-367, September, 1989. Original article submitted April 25, 1988.

emissivity and absorptivity of the particles and we change the indicatrix. The effect of allowing for roughness on the velocity of a flame front in a mixture of air and coal dust can be judged on the basis of the results presented in [6, 7]. Three cases were examined in these studies within the framework of the diffusion approximation. Case "A" involved the use of the asymptotic value $Q_a = 0.84$ calculated from the Mie theory for the limiting case of large coal particles ($R \geq 10$ μm) without allowance for the dispersion of the complex index of refraction. Here, it was assumed that the indicatrix was highly extended in the backward direction. In case "B", the particle was assumed to have been black ($Q_a = 1$), and there was no scattering. In case "C", scattering was not considered, while $Q_a = 0.84$. It turned out that, other conditions being equal, the rate of flame propagation in case "A" was lower than in case "B" which was in turn lower than in case "C". This mean that allowing for the effect of particle roughness on the indicatrix [6, 7] leads to a reduction in flame velocity. It can be concluded from the foregoing remarks that the velocity of a flame in an aerosol for which particle roughness is considered will be lower than in case "A".

The question of particle roughness arises in the case when the size of the particle is considerably greater than the wavelength of the radiation, i.e., $X >> 1$. At high temperature $T \sim (1500\text{-}3500)$ K, more than 90% of the energy of the equilibrium radiation is concentrated in the wavelength interval from $\lambda_{min} = 0.5$ μm to $\lambda_{max} = 6$ μm. Thus, the question of the roughness of the surface of the particles can be addressed if its radius is approximately $R \geq (10\text{-}20)$ μm. If the particles have not been specially prepared, then there are no grounds for assuming their surface to be optically smooth. Thus, when calculating radiative transfer in an aerosol consisting of particles with $R \geq (10\text{-}20)$ μm, the roughness of the particle surfaces should be considered. For an opaque particle ($R >> \delta \simeq \lambda/4\pi x$), $Q_a = \varepsilon_\lambda$ in the geometric optics approximation [9, 10]. This relation is valid for both optically smooth particles and rough particles. The value of ε_λ is measured in experiments with flat opaque bodies. Thus, the problem of determining Q_a for opaque rough particles has been reduced to the measurement of ε_λ of a specimen whose surface is in the same condition as the surface of the particles. Values of ε_λ are presented in handbooks on radiant heat transfer. As in [6-8], we will assume that radiation is reflected from a rough particle in the same manner as from an opaque sphere with a diffuse surface [9]. Strong backscattering occurs in this case and is described by the linearly anisotropic indicatrix $p_s = 1 - \cos\theta$ [6, 7, 11]. Let us write the system of equations of the diffusion approximation for the total radiation for a plane-parallel layer of monodisperse rough particles. The energy equation for total radiation has the following form in the general case [4]:

$$dq/dy = N(P_r - P_a), \tag{1}$$

$$P_a = \pi R^2 \int_0^\infty Q_a(\lambda) G_\lambda(y)\, d\lambda \tag{2}$$

being the power absorbed by a particle from the radiation field;

$$P_r = 4\pi^2 R^2 \int_0^\infty Q_a(\lambda) B_\lambda(T)\, d\lambda \tag{3}$$

being the power radiated by a particle having the temperature T. The gas is assumed to be diathermal [6-8]. For opaque particles in the geometric approximation [10]

$$P_r = 4\pi R^2 \varepsilon\sigma T^4. \tag{4}$$

Equation (2) for P_a takes the simple form:

$$P_a = \pi R^2 \varepsilon G(y) \tag{5}$$

in the following cases: 1) the aerosol particles are gray ($\varepsilon = Q_a$); 2) the radiation incident on the particles is close to equilibrium ($I_\lambda \sim B_\lambda(T)$) or can be considered gray [5] ($I_\lambda \sim kB_\lambda(T)$; $k < 1$). Here, G(y) is the spatial density of the incident integral radiation. For these cases, the diffusion equation for total radiation generally has the form

$$dG/dy = -3N\pi R^2 [1 - (1 - \varepsilon) f_1] q, \quad -\frac{1}{3} \leqslant f_1 \leqslant \frac{1}{3}. \tag{6}$$

In the case of strong forward scattering, the parameter characterizing anisotropic scattering $f_1 = 1/3$. For strong backscattering, $f_1 = -1/3$. Thus, with allowance for roughness, Eq. (6) takes the more compact form:

$$dG/dy = -N\pi R^2 [4 - \varepsilon] q. \tag{7}$$

Thus, in the present approach, calculation of radiative transfer in an aerosol consisting of opaque rough particles reduces with allowance for (4) and (5) to the solution of two differential equations (1) and (7) relative to two unknown functions q and G. The value of ε in Eqs. (4), (5), and (7) is assumed known, since it can be taken from handbooks. According to [13], scattering anisotropy has little effect on radiative transfer in closed systems.

To evaluate the effect connected with particle roughness, we will examine a problem concerning the decay of a radiant heat flow incident on the boundary of a uniform layer of a monodisperse aerosol for which $T \approx 0$. We use Eqs. (1) and (6) to obtain

$$q = q_0 \exp[-(y - y_0)/L], \quad L^{-1} = \{3\varepsilon[1 - (1-\varepsilon) f_1]\}^{0.5} N\pi R^2$$

being the relaxation length over which there is appreciable decay of the heat flow. For ideally smooth coarse carbon particles [2], $\varepsilon = 0.6$, while $f_1 = 1/3$. For rough particles, $f_1 = -1/3$, while the value of ε measured in experiments with massive carbon specimens $\varepsilon \geq 0.8$ [12]. Calculations show that allowing for roughness leads to a reduction in L by at least 22%.

NOTATION

θ, scattering angle; ε_λ, ε, spectral and integral hemispherical emissivities of a particle; λ, wavelength; λ_{max} and λ_{min}, maximum and minimum wavelengths of thermal radiation; δ, depth at which waves of thermal radiation attenuate; n, ϰ, indices of refraction and absorption of the particle material; q, projection of the vector of the resulting integral radiant flux on the y axis; $G_\lambda(y)$, spatial density of incident monochromatic radiation; B_λ, Planck function; σ, Stefan–Boltzmann constant; I_λ, intensity of radiation; k, proportionality factor; y_0, distance, reckoned from the boundary of the layer, at which the diffusion approximation begins to be valid; q_0, heat flux at $y = y_0$.

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