Experimental and theoretical study on the radiation of gases containing dust particles

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Abstract. The attenuation of thermal radiation within a dilute cloud of pulverised coal and ash is investigated experimentally and theoretically, for different ranges of particle size. An empirical expression is developed for obtaining the absorptivity and emissivity of a coal/ash cloud. A new nomogram is also presented on the basis of this expression.

Nomenclature

- $A$: specific projected area for particle cloud
- $a$: absorptivity of dusty cloud or absorption coefficient
- $B$: dust burden
- $b$: exponential constant
- $b_s$: peak factor of the magnetic fluctuation
- $C_1$: Wien’s constant
- $c_e$: peak factor of the electrical fluctuation
- $D_p$: dust factor
- $d$: diameter of the particles ($d = 2r$)
- $f_v$: solid volume fraction
- $I$: intensity
- $i$: $\sqrt{-1}$
- $K$: extinction coefficient
- $k$: total attenuation efficiency
- $L$: total length of optical path
- $M_1$: proportionality constant, Eq. (8)
- $M_2$: proportionality constant, Eq. (9)
- $m$: complex refractive index
- $n$: index of refraction
- $N$: number of particles in volume $V$
- $p$: size parameter $= \pi d/\lambda$
- $Q$: efficiency
- $r$: particle radius
- $S$: position vector
- $T$: radiation source temperature
- $V$: air volume flow
- $\theta$: polar angle

Indices

- $x$: index of absorption
- $\lambda$: wavelength of incident radiation
- $v$: frequency of incident radiation
- $\varrho$: density of solid material
- $a$: scattering coefficient
- $\Phi$: scattering phase function
- $\omega$: solid angle

Subscripts

- $a$: absorption
- $b$: blackbody
- $d$: diffraction
- $e$: extinction
- $ref$: reflection
- $s$: scattering
- $t$: transmission
- $\lambda$: wavelength

1 Introduction

Many modern and practical engineering systems require the knowledge of the radiative properties of a particulate medium. Some examples that involve highly concentrated small particles are fluidized and packed-bed combustors, packed-bed catalytic reactors, microsphere insulations, combustors with deposited soot on the walls, M.H.D. generators, diesel engines and furnaces laden with agglomerated particles. The radiation transfer through atmospheric aerosols is of considerable interest in atmospheric transmission calculations. In these systems the absorption and scattering of thermal radiation by particles plays an important role in the overall energy transfer, and its understanding is central to the prediction and evaluation of system performance.

Within a suspension of particulate matter, thermal radiation can be either enhanced or attenuated, depending upon the size and concentration of particulates, the temperature distribution, and the radiative properties of the matter. Even for a pure material such as carbon, the specification of the pertinent radiative properties is not straightforward. The crystalline structure of the carbon and the surface condition can greatly affect the spectral emissivity [8, 23]. For a hetero-
homogeneous substance such as coal, the difficulties are multiplied since the particulate cloud can be made up of varying fractions of unreacted coal, char, ash and soot, each of which has its own optical properties dependent upon wavelength, temperature and particle size. Stull and Plass [17], Buckius and Hwang [5], Viskanta et al. [22], Grosshandler and Montiero [8], Tien [20], Mackowski et al. [14], Kumar and Tien [13] have examined the importance of some of these parameters (mean particle radius, size distribution, temperature, back-scatter) for polydispersions of various coals and fly-asch using experimental and theoretical models (Lorenz-Mie or Rayleigh theory) with average or precise spectral properties. Whitson [23] has compiled comprehensive data from more recent measurements of the refractive index and emissivity of graphite and carbonaceous material at high temperatures. The results of over twenty-five references were summarised in graphical and tabular form for the spectral region between 0.4 and 12.5 µm. Blokh [1-3] has reviewed the results of many experiments on bulk coal, soot, flame, and pulverised coal. Using Mie’s theory, the absorption and scattering coefficients of different coals were calculated as a function of particle size. The emissivities of twenty different dusty materials have been measured and interpreted by Biermann and Vortmeyer [4]. The radiative characteristics of polished specimens of several coals have been determined by Foster and Howarth [12]. They found significant differences between the spectral refractive index for coal and polycrystalline graphite.

Recently, Kumar and Tien [13] have presented a complete model for predicting the absorption and scattering characteristics of homogeneous dense particulate systems by including the near-field interparticle effect (where the internal field of each particle is affected by the presence of the others) and that of coherent addition (i.e. taking into account the constructive/destructive interference of the scattered radiation by each particle in the far field, which is manifested by a change in the scattered field). Engineering radiative heat transfer in absorbing-scattering-emitting media have been presented by many authors and have been extensively discussed by Van de Hulst [21], Hottel and Sarofim [9], and Siegel and Howell [16], among others.

This study is undertaken to determine the extinction coefficient, absorption and emissivity coefficients of different coals and ash, under conditions similar to the early pyrolysis zone of a pulverised coal furnace. Several different coal and ash types have been experimentally investigated. The dependence of the total emissivity and absorptivity on mean particle diameter, size distribution, fractions of unreacted coal, temperature, chamber furnace and place of extraction of fuel are all demonstrated graphically. The theoretical background on thermal radiation attenuation is also briefly reviewed in this paper. From this background and using the considerable experimental data of Blokh [2, 3], Biermann and Vortmeyer [4] and Stasiek et al. [18, 19] a new nomogram is designed and equations are formulated. These may be used for the determination and calculation of emissivity and absorptivity of dust clouds. Its optical properties are dependent on wavelength, temperature, particle size and concentration. Particle diameters are typical of furnace operation, covering two ranges of 10 to 200 µm and 0.2 to 0.6 mm, and temperatures ranging from 300 to 2200 K.

2 Theoretical background

Computation of the transport of thermal radiation in the particulate system requires an accurate knowledge of the extinction and the scattering coefficients. This is evident by considering the propagation of radiation within an absorbing, emitting and scattering medium which is governed by the Eq. of transfer [15, 16]:

$$\frac{dI_d(S, \omega)}{dS} = - K_d I_d(S, \omega) + a_d I_{\omega, \omega} (S, \omega) \\ \ \ (1)$$

$$+ \frac{\sigma_{\omega, \omega}}{4\pi} \int I_d(S, \omega') \Phi_{\omega} (\omega' \cdot \omega) \ d\omega'$$

Where $K_d = a_d + \sigma_{\omega, \omega}$ is the extinction coefficient and in general is a function of position S.

The three terms on the right-hand side of the transfer Eq. represent respectively (a) the attenuation of intensity due to absorption and scattering, (b) the gain due to emission, and (c) the gain due to the scattering in the direction $\omega$ from all other directions. The intensity $I_d$ is defined as the energy per unit area per unit solid angle per unit wavelength and the scattering phase function $\Phi(\omega' \cdot \omega)$ is a specification of the radiation intensity scattered from the direction $\omega$ to the direction under consideration, normalised by the isotropic scattered radiation intensity, i.e. $\Phi(\omega' \cdot \omega)=1$ for isotropic scattering [13, 15, 16]. Scattering and absorption characteristics of a particle are governed by three factors: the particle shape, the particle size relative to the wavelength of the incident radiation ($p=\pi d/\lambda$), and the optical properties of the particle and the background medium. The last factor is represented by the complex refractive index $m$ defined as $(n-i\kappa)$ where $n$ is the index of refraction and $\kappa$ is the index of absorption. For particles not too closely spaced (distance between centres greater than 3r [9]), the effect of a cloud of particles can be found by summing over all individual particles [9, 13, 20, 25].

The radiative properties for a polydisperse cloud of spherical particles are expressed in terms of the extinction efficiency, scattering efficiency and phase function for a single particle. The extinction and scattering coefficients are given as

$$K_d (m, N) = \int_0^\infty \pi r^2 N(r) Q_d (p, m) \ dr \ \ \ \ (2)$$

$$\sigma_d (m, N) = \int_0^\infty \pi r^2 N(r) Q_d (p, m) \ dr \ \ \ \ (3)$$

and

$$\Phi_{\omega} (\omega' \cdot \omega) = \frac{1}{\sigma_d (m, N)} \int_0^\infty \pi r^2 N(r) Q_d (p, m) \Phi_{\omega} (\Theta, r) \ dr$$

$$\Phi_{\omega} (\omega' \cdot \omega) = \frac{1}{\sigma_d (m, N)} \int_0^\infty \pi r^2 N(r) Q_d (p, m) \Phi_{\omega} (\Theta, r) \ dr$$

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