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A comparison of radiative characteristics for fly ash and coal

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Abstract—Numerical results for extinction efficiency, phase function, albedo and asymmetry factor are presented for clouds of spherical particles illuminated by black body radiation. The refractive indices ($m = m_1 - im_2$) used were $m_1 = 1.5$ with m_2 varied from 0 to 0.024 in steps of 0.006 and $m = 1.6 - i0.6$, chosen to be representative of fly ash and coal. Averaged scattering data are given for use in radiative transfer modelling of pulverised fuel furnaces. The results are seen to depend on the product of the mean particle size and the radiation temperature. The scattering parameters of fly ash are shown to vary significantly with absorption index m_2 for small particles, but the choice of refractive index is not critical for large particles.

1. INTRODUCTION

ELECTROMAGNETIC scattering by particles affects a wide range of industrial processes. In particular, there is its influence on radiative transfer. Through this, the efficient operation of pulverised-fuel furnaces depends on the physical nature of the particles present and their number density. The relevant scattering parameters can be calculated for spherical particles using Mie theory. Buckius and Hwang [1] and Avery and Jones [2] presented results averaged over particle size distributions and radiation wavelengths at refractive indices appropriate to coal. Boothroyd and Jones [3] reported averaged scattering efficiencies for a refractive index $m = 1.5\text{–}i0.012$ representing fly ash, as recommended by Gupta and Wall [4]. Gupta *et al.* [5] showed, *inter alia*, that fly ash cloud efficiencies at discrete radiation wavelengths are strongly dependent on the particle absorption index m_2. In view of this and the current uncertainty as to the true value of m_2 [4] further scattering information for fly ash is needed.

We report here numerical results for the scattering parameters, averaged over various size distributions and a Planck function spectral distribution for particles of refractive index $m_1 = 1.5$ with $m_2 = 0$ to 0.024. Similar data evaluated for a refractive index $m = 1.6 - i0.6$, chosen to represent coal, are presented for comparison.

2. DESCRIPTION OF TERMS

For the prediction of radiative transfer in particle clouds knowledge of the extinction cross-section C_{ext}, albedo ω_0 and scattering polar diagram I_{sca} is required [6]. For certain approximations to the polar diagram, the asymmetry factor g is required [7].

In a furnace there exist distributions of both size and wavelength. In order to define any useful single property it is necessary to average over both of these. The average $\bar{F}$ of F_λ is given by

$$\bar{F} = \int_0^\infty \int_0^\infty F_\lambda N(a) E_{\beta,\lambda} \, \mathrm{d}a \, \mathrm{d}\lambda \bigg/ \int_0^\infty \int_0^\infty N(a) E_{\beta,\lambda} \, \mathrm{d}a \, \mathrm{d}\lambda$$

where $E_{\beta,\lambda}$ is the Planck function and F_λ is I_{sca} (θ), C_{abs} or C_{sca} calculated from Mie theory. The average extinction cross-section is:

$$\bar{C}_{\text{ext}} = \bar{C}_{\text{sca}} + \bar{C}_{\text{abs}}.$$

$$N(a) = \begin{cases} G_0 \exp(-a/a_0), & n = 0 \\ G_n a^n \exp(-na/a_n), & n \neq 0 \end{cases}$$

where a is particle radius and G_n is a constant. The Sauter mean radius (a_S) is $3a$ for $n = 0$ and $(n+3)a_n/n$ otherwise.

The integrals were evaluated using Gaussian quadrature [3, 8]. All the data presented were evaluated using 40-point quadrature. Tests for convergence were effected with 32-point quadrature.

The numerical procedure calculated scattering parameters for $X < 900$. Approximations were made to take account of integration points representing larger particle sizes [3].

The efficiencies are the cross-section divided by the particle's geometrical area. For example the averaged extinction efficiency Q is taken as:

$$\overline{Q_{\text{ext}}} = \overline{C_{\text{ext}}}/\pi\overline{a^2}$$

where

$$\overline{a^2} = \int_0^\infty a^2 N(a) \, \mathrm{d}a \bigg/ \int_0^\infty N(a) \, \mathrm{d}a.$$

The dependence on $a_S T$, the product of the Sauter mean radius and radiation temperature T, may be expected from the dependence of the single particle properties on the ratio a/λ. From Wien's law:

$$\lambda_{\max} \propto \frac{1}{T}$$

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NOMENCLATURE

a	particle radius [m]
a_n	modal particle radius ($n = 0, 1, 3$) [m]
a_S	Sauter mean radius [m]
$C_{abs}, C_{ext}, C_{sca}$	absorption, extinction and scattering cross-sections [m^2]
$E_{\beta,\lambda}$	Planck black body function
F_λ	$C_{abs}, C_{sca}, gC_{sca}, I_{sca}$
$\bar{F}$	average of F_λ
g	asymmetry factor
I_{sca}	scattered light intensity distribution function [$W\ m^{-2}\ ster^{-1}$]
k	wavenumber, $2\pi/\lambda$ [m^{-1}]
m	complex refractive index, $m_1 - im_2$
m_1	refractive index
m_2	absorption index
$N(a)$	particle size distribution function [m^{-3}]
n	takes values 0, 1 or 3
Q_{ext}	extinction efficiency
T	temperature [K]
X	particle size parameter, $2\pi a/\lambda$.

Greek symbols

θ	polar angle
λ	wavelength [m]
λ_{max}	wavelength at which maximum in black body curve occurs [m]
ω_0	albedo.

we have $a_S T \equiv a/\lambda_{max}$. This enables the averaged scattering data to be interpreted in terms of the most effective single particle size parameters.

The asymmetry factor is a weighted average of the polar diagram. It was calculated using $F_\lambda = gC_{sca}$ calculated directly from Mie theory [9], and also using $F_\lambda = I_{sca}(\theta)/k^2$ whence

$$\overline{gC_{sca}} = 2\pi \int_0^\pi \bar{F} \cos\theta \sin\theta \, d\theta.$$

In both cases, it was then assumed that

$$\bar{g} = \overline{gC_{sca}}/\overline{C_{sca}}.$$

As a test of this assumption, these were compared with the direct calculation

$$\bar{g} = \frac{\int_0^\pi \overline{I_{sca}(\theta)} \cos\theta \sin\theta \, d\theta}{\int_0^\pi \overline{I_{sca}(\theta)} \sin\theta \, d\theta}.$$

The three methods agreed to three decimal places and better.

3. RESULTS

It is found that the calculated results depend uniquely on the product $a_S T$ for any one size distribution. Further, while there is some slight difference, the results for the various distributions are very

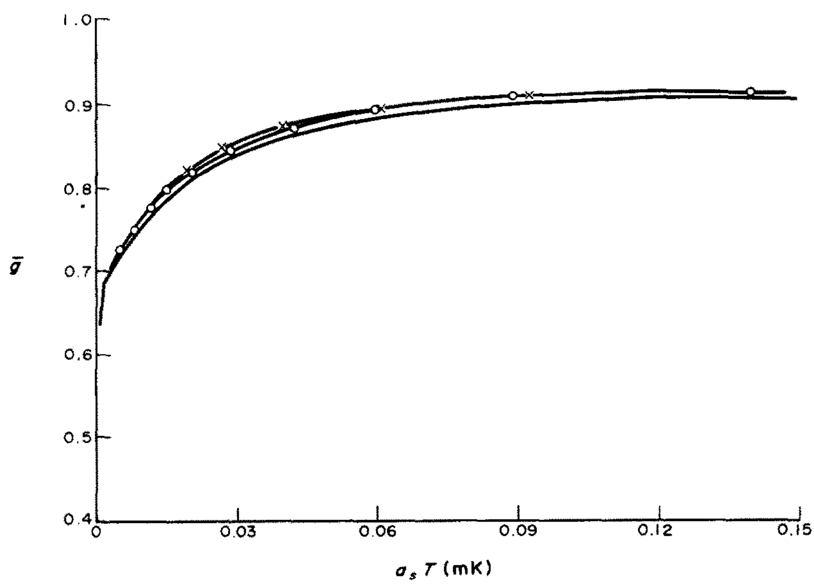

FIG. 1. Averaged asymmetry factor against $a_S T$ for $m = 1.5 - i0.006$. —— $n = 0$; —○— $n = 1$; —×— $n = 3$.

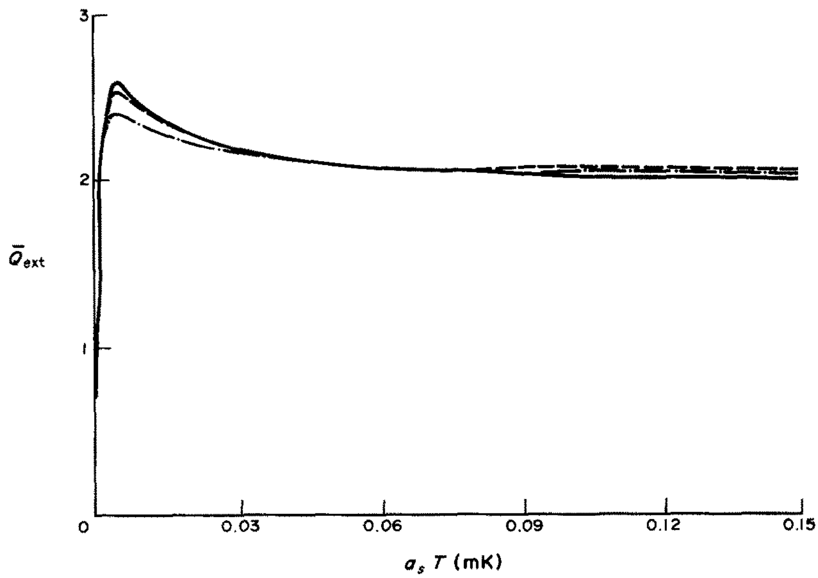

FIG. 2. Averaged extinction efficiency against $a_S T$; $n = 0$. —— $m = 1.5$; --- $m = 1.5-i0.024$; —·—· $m = 1.6-i0.6$.

close. Figure 1 is a typical example. Because of this calculations are presented only for $n = 0$, which appears to be the best representation of actual measured size distributions of fly ash. Results for other values of n always lie close to these curves.

Results for Q_{ext} are shown in Fig. 2. As $a_S T$ increases the averaged extinction efficiencies show the same trends as Mie efficiencies with increasing a/λ, and approach a value of 2 demonstrating the well-known extinction anomaly.

In Fig. 3 albedos for fly ash are compared with that representative of coal. It can be inferred that for clouds where the preponderant particles are small, coal is strongly absorbing whereas fly ash scatters strongly. It will also be noted that in this region small changes in the imaginary part of the refractive index of fly ash cause significant differences in the amount of scattering. As $a_S T$ increases the influence of the refractive index is diminished.

Results for $\bar{g}$ are shown in Fig. 4. In all cases the scattering becomes progressively more forward directed for larger particles. This is also seen in Fig. 5, where scattering polar diagrams are shown. It may be noted that increasing the imaginary index for fly ash over a narrow range from zero quickly reduces backscattering.

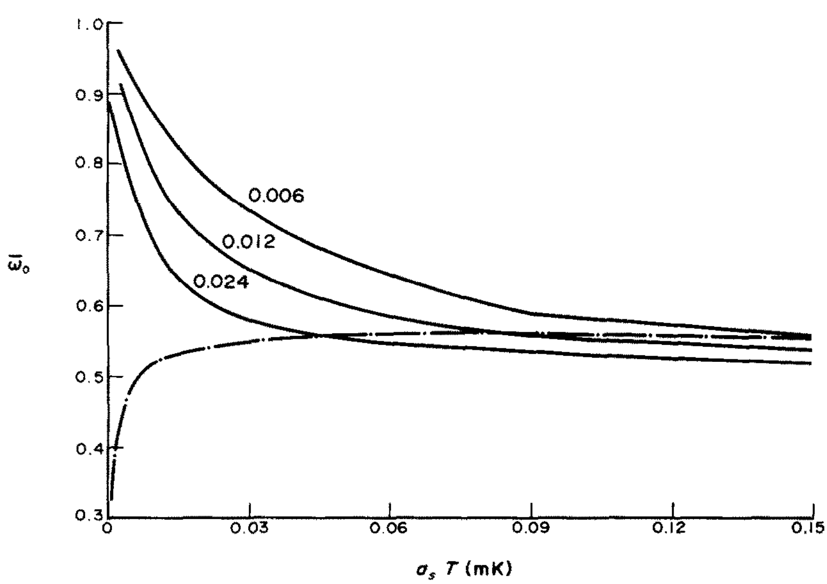

FIG. 3. Averaged albedo against $a_S T$; $n = 0$. —— $m = 1.5$ and m_2 as shown; —·—· $m = 1.6-i0.6$.

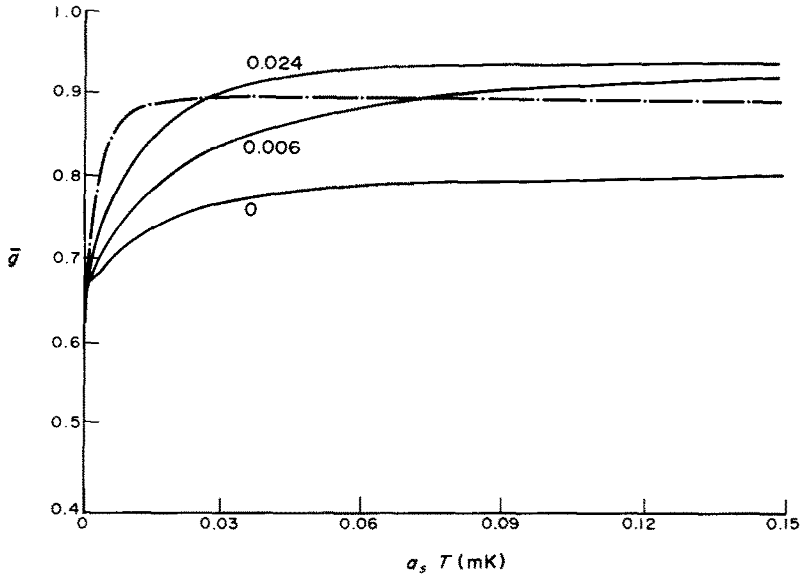

FIG. 4. Averaged asymmetry factor against $a_S T$; $n = 0$. —— $m = 1.5$ and m_2 as shown; —·—· $m = 1.6 - i0.6$.

4. CONCLUSIONS

The results show that homogeneous spherical particles of coal and fly ash with $a \sim \lambda$ have significantly different scattering properties. The fly ash will scatter much more than coal which is strongly absorbing. Also, in predicting the radiative behaviour of these fly ash particles the choice of absorption index is critical. However, larger coal and fly ash particles have similar properties. For some size distributions, large particles present in even relatively small numbers could dominate because the amount of light scattered increases approximately as the square of particle radius. Except at low temperature, the choice of refractive index is not critical for predicting scattering properties relevant to furnace particulates.

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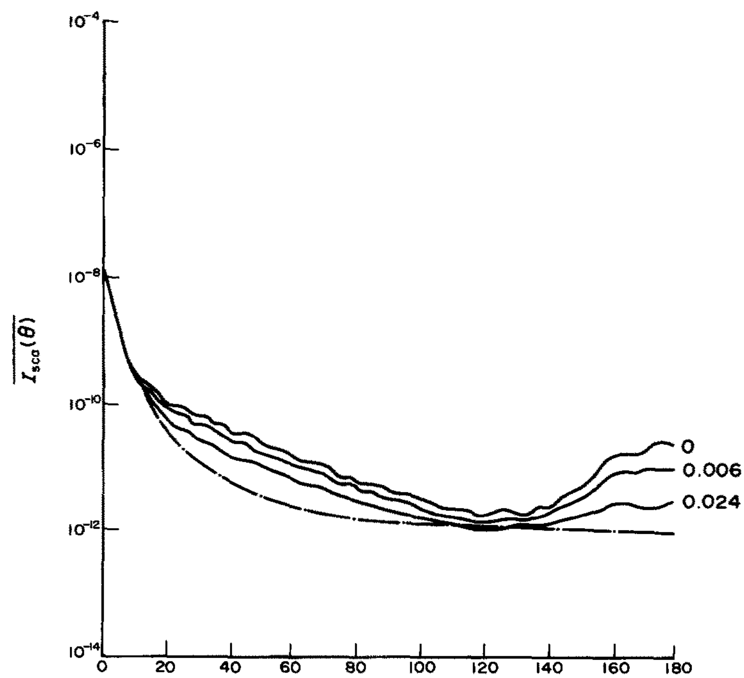

(a)

FIG. 5. Averaged scattered intensity against angles; $n = 0$. —— $m = 1.5$ and m_2 as shown; —·—· $m = 1.6 - i0.6$. (a) $a_0 = 5\ \mu m$; (b) $a_0 = 30\ \mu m$.

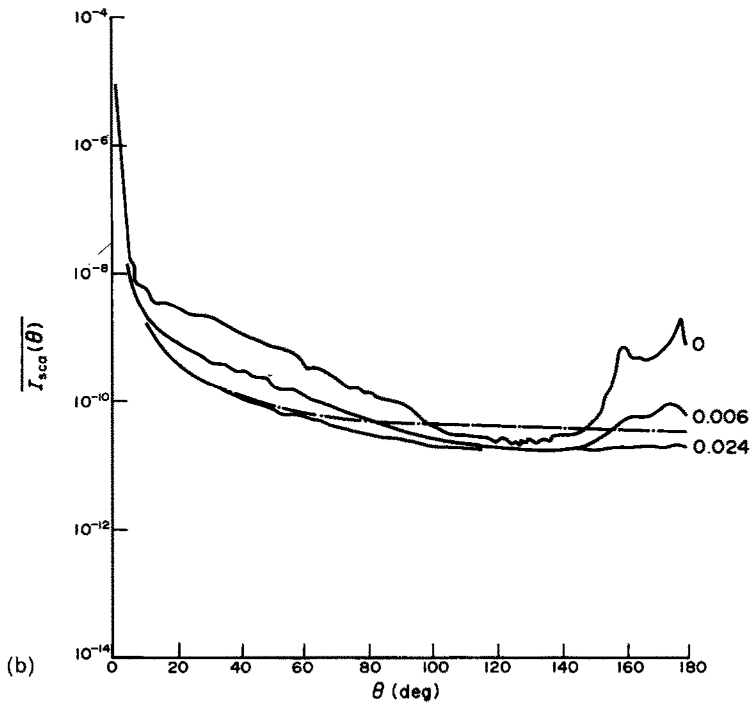

FIG. 5—*continued.*

REFERENCES

1. R. O. Buckius and D. C. Hwang, Radiation properties for polydispersions: application to coal, *J. Heat Transfer* **102,** 99–103 (1980).
2. R. K. Avery and A. R. Jones, Scattering of grey body radiation by clouds of spherical particles, *J. Inst. Energy* **55,** 78–85 (1982).
3. S. A. Boothroyd and A. R. Jones, Radiative scattering data relevant to fly ash, *J. Phys. D, Appl. Phys.* **17,** 1107–1114 (1984).
4. R. P. Gupta and T. F. Wall, The complex refractive index of particles, *J. Phys. D, Appl. Phys.* **14,** L95–L98 (1981).
5. R. P. Gupta, T. F. Wall and J. S. Truelove, Radiative scatter by fly ash in pulverized-coal-fired furnaces: application of the Monte Carlo method to anisotropic scatter, *Int. J. Heat Mass Transfer* **26,** 1649–1660 (1983).
6. L. P. Bayvel and A. R. Jones, *Electromagnetic Scattering and its Applications.* Applied Science, Barking, U.K. (1982).
7. H. C. van de Hulst, *Multiple Light Scattering,* Vols 1 and 2. Academic Press, New York (1980).
8. M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions.* NBS, Washington, DC (1972).

UNE COMPARAISON DES CARACTERISTIQUES RADIATIVES DES CENDRES VOLANTES ET DU CHARBON

Résumé—Des résultats numériques pour l'extinction, la fonction de phase, l'albédo et le facteur d'asymétrie sont présentés pour des nuages de particules sphériques recevant un rayonnement de corps noir. Les indices de réfraction ($m = m_1 - im_2$) utilisés avec $m_1 = 1{,}5$ et m_2 variant de 0 à 0,024 par pas de 0,006 et $m = 1{,}6$–i0,6, sont choisis pour représenter les cendres voltantes et le charbon. On donne des valeurs de diffusion mayonnes pour utiliser les modèles de transfert radiatif dans les foyers à combustibles pulvérulents. Les résultats dépendent du produit de la taille moyenne de particule par la température de rayonnement. Les paramètres de diffusion de la cendre volante varient sensiblement avec l'indice d'absorption m_2 pour des petites particules, mais le choix de l'indice de réfraction n'est pas critique pour des grosses particules.

VERGLEICH DER STRAHLUNGSEIGENSCHAFTEN VON FLUGASCHE UND -KOHLE

Zusammenfassung—Es werden numerische Ergebnisse der Extinktionseffizienz, der Phasenfunktion, des Albedo und des Asymmetriefaktors für eine Wolke kugelförmiger Partikel, die durch schwarze Strahlung beleuchtet wird, vorgestellt. Die verwendeten Brechungszahlen ($m = m_1 - im_2$) betragen $m_1 = 1{,}5$, wobei m_2 von 0 bis 0,024 bei Schrittweiten von 0,006 variiert wurde. Als repräsentativer Wert für Flugasche und -kohle wurde $m = 1{,}6 - \mathrm{i}0{,}6$ gewählt. Für die Modellbildung des Strahlungsaustausches in Staubfeuerungsanlagen werden gemittelte Streuungsdaten mitgeteilt. Es zeigt sich, daß die Ergebnisse vom Produkt aus mittlerer Partikelgröße und Strahlungstemperatur abhängen. Es zeigt sich weiterhin, daß die Parameter für Flugasche bei kleinen Partikeln signifikant vom Absorptionsindex m_2 abhängen. Jedoch ist für große Partikel die Wahl der Brechungszahl nicht kritisch.

СРАВНЕНИЕ РАДИАЦИОННЫХ ХАРАКТЕРИСТИК ЛЕТУЧЕЙ ЗОЛЫ И УГЛЯ

Аннотация—Представлены численные результаты для коэффициента экстинкции, фазовой функции, альбедо и коэффициента асимметрии для скоплений сферических частиц, освещенных излучением абсолютно черного тела. Значения показателей преломления ($m = m_1 - im_2$) составляли: $m_1 = 1{,}5$ при m_2, изменяющемся от 0 до 0,024 ступенчато с шагом 0,006, и $m = 1{,}6 - i0{,}6$, выбранные в качестве характерных для летучей золы и угля. Осредненные данные по рассеянию используются при моделировании радиационного переноса в печах с распылением топлива. Результаты зависят от произведения среднего размера частицы и температуры излучения. Показано, что параметры рассеяния для летучей золы сильно зависят от m_2 для малых частиц и слабо—для больших.