Journal of Heat Transfer Discussion

Measurement of Radiative Properties of Ash and Slag by FT-IR Emission and Reflection Spectroscopy[1]

S. P. Bhattacharya.[2] Markham et al. presented results on emittance measurements of ash and slag samples. As evident from the paper, the measurements were hemispherical, not normal. Therefore, all emittance figures in the paper should be interpreted as hemispherical emittance. Figure 7 of the paper shows three curves, one for the measured emittance of a fused slab and the remaining two predicted values, one at normal emergence (Eq. (7) of the paper), and the other considering an empirical void fraction of 0.15. Both the predicted values are about 10 percent different from the measured value. This difference is due to the fact that the predicted values are for normal emittance, which are compared against measured values that are hemispherical. For dielectric materials, the ratio of hemispherical and normal emittance is about 0.9 (Wall et al., 1994), and this is close to the ratio of the data in the top two curves in Fig. 7. The lead author (J. R. Markham) kindly supplied the spectral values of real (n) and absorption (k) indices of the fused sample material shown in Fig. 6 of the paper. Using these spectral n and k, spectral normal emittance and spectral hemispherical emittance of a smooth opaque slab (for which the authors calculated normal emittance, Eq. (7)) was calculated. Results are plotted in Fig. 1, which shows excellent agreement between the measured data and the predicted hemispherical emittance. In these calculations, the perpendicular and parallel components of the directional complex reflectivity are calculated first, then the arithmetic average of the two is taken considering unpolarized thermal radiation; the directional reflectivities are then integrated to get spectral hemispherical reflectivity (R_λ); and finally the spectral hemispherical emittance for an opaque slab is estimated using $\epsilon_\lambda = 1 - R_\lambda$. The procedure is after Özişik (1985) and details are available from Bhattacharya (1994). Thus it is not necessary to assume any arbitrary void fraction in order to get better agreement with the measured data. It is not clear from the paper as to the surface roughness of the fused slab, but clearly the excellent agreement between the measured and predicted hemispherical emittance values show negligible effect of the surface roughness.

Figure 8 of the paper shows the measured hemispherical emittance and predicted values for a pressed opaque wafer prepared from the ground sample. The emission characteristics clearly resembles that of powdery deposits (Wall et al., 1993). The predicted values in the paper were obtained using a simplified two-stream model and required an arbitrary choice of a constant value of 0.6 for the asymmetry factor (g). In fact, for the investigated wavelength range, 1.6–20 μm, fine particles ($\sim$2 μm) of the particular material may have asymmetry factors ranging between 0.1 and 0.8 (Bhattacharya, 1994). The albedo (ω) values in the paper were apparently taken to be spectral although it is not clear based on what particle size(s) these were calculated. However, it is known that two-stream model predictions are neither normal nor hemispherical (Brewster, 1992), because they assume an isotropic distribution of the emitted flux over the hemisphere. For powdery deposits in particular, the distribution of emitted flux is not isotropic. Although not shown here, two-stream calculations were performed using Eq. (8) of the paper with spectral values of both g (instead of a constant value of 0.6 assumed in the paper) and ω corresponding to the distributed sizes of mean diameters 1 and 2 μm. These results (Bhattacharya, 1994) are higher than the measured values reported by Markham et al. The reasonable agreement between the measured data and the predicted values in their paper using the two-stream model seems to be coincidental. It is not clear what particle size was considered in their predictions. In fact, particle size and distribution have a significant effect on any prediction. Figure 2 shows the measured emittance and several predicted hemispherical emittance values for two different mean particle sizes of 1 and 2 μm, having different distributions. While a monosize appears to match closely the measured data up to about 5 μm wavelength, the trend thereafter suggests the possible presence of a distribution of particle sizes. These calculations are based only on independent and multiple scatter in an opaque slab using a discrete ordinate method. Details of the calculation procedure are available in Bhattacharya (1994). However, for pressed slabs of fine particles, dependent effects are known to be significant, although difficult to quantify. Clearly, fundamental knowledge on dependent effects, effects of surface morphology, as well as an accurate knowledge of the size distribution are required before improved and meaningful predictions can be made.

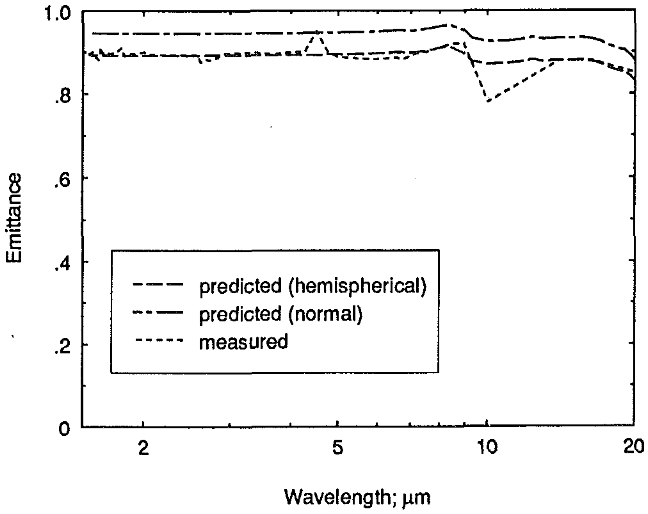

Fig. 1 Comparison of measured emittance and predicted normal and hemispherical emittance for a fused slab

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[1] By J. R. Markham, P. E. Best, P. R. Solomon, and Z. Z. Yu, published in the May 1992 issue of the ASME Journal of Heat Transfer, Vol. 114, pp. 458–464.

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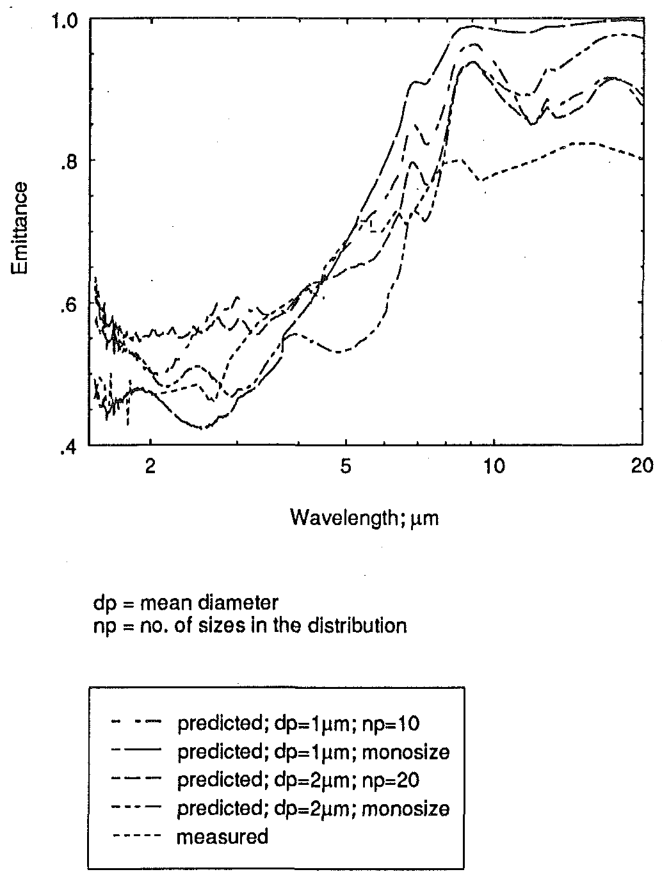

Fig. 2 Comparison of measured emittance and predicted values for the pressed wafer of ground sample, showing the effect of particle size and size distribution

There is a minor mistake in the paper, which needs to be corrected for convenience of future users of this excellent work. On page 460, first paragraph of the paper, "the incident radiation is attenuated by 1/*e*" should actually be "1/*e* of the incident radiation is transmitted in a distance of 0.8×10^{-2} mm."

References

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Authors' Closure

Much of the discussion given by S. P. Bhattacharya results from a misunderstanding of terms used in our paper. In particular, he refers to our measurements being of hemispherical emissivity, when we reported them as directional. An explanation of our measurements should clarify the terms.

For samples that exhibit a Christiansen maximum in emissivity ($\epsilon = 1$), we measure spectral radiance for a small acceptance angle for near-normal take-off. Knowing (i.e., measuring) that $\epsilon = 1$ at the Christiansen wavenumber allows a determination of ϵ_ν over the whole spectrum. We refer to this determination of ϵ_ν as normal spectral emissivity. It is clearly a directional measurement.

The method of closure is also applied in our paper; for opaque samples $\epsilon_\nu = 1 - \rho_\nu$. It is relevant to ask which spectral reflectivity, ρ_ν, should be used in the equation to yield the directional ϵ_ν referred to above. In a thoughtful experiment the sample is placed in an isothermal environment, with a small opening for normal viewing of the surface. Radiation emerging from this opening is the cavity radiation for the isothermal temperature. Evidently, the sum of normal spectral emissivity and hemispherical-directional spectral reflectivity (Siegel and Howell, 1981, p. 45) is unity. For the conditions of our measurements, the hemispherical-directional spectral reflectivity is equal to the directional-hemispherical spectral reflectivity, as usual for this experiment (Siegel and Howell, 1981, p. 67).

The value of ϵ_ν that results from the application of the equation of closure is evidently the normal spectral emissivity; and it is gratifying that the spectral values so determined by closure agree well with values of the normal spectral emissivity directly measured (for examples: Fig. 2*c* in the paper under discussion; and Markham et al., 1990). S. P. Bhattacharya is incorrect in his interpretation of our measurements.

In his discussion, S. P. Bhattacharya also indicates his discontent with our modeling effort. While the two-stream model assumes hemispherical isotropy of scattering, real-life, nonisotropic scattering can be investigated by the model if the scattering is parameterized into two-stream form, as discussed by Bohren (1987). The agreement between experiment and model calculation is readily understood in these terms: It is not a coincidence.

We encourage S. P. Bhattacharya to continue to develop his modeling techniques in this area since improved models, especially of the deposition process, would significantly improve the ability to model the heat transfer in real coal-fired furnaces. We are pleased that our spectroscopic technique to measure the radiative properties of ash and slag can provide data that can be utilized for advancement of such models. We thank the author for indicating the mistake in our paper, which should read "the incident radiation is attenuated by $1 - 1/e$ in a distance of 0.8×10^{-2} mm."

References

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