A Method of Measuring the Emittance of Ash Deposits in a Coal Fired Reactor

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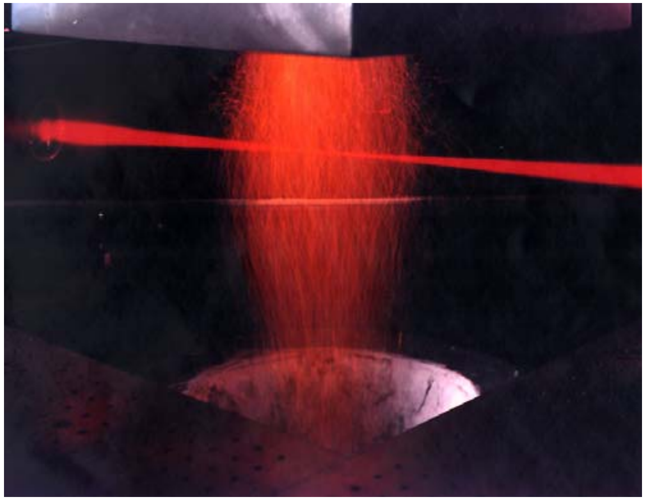
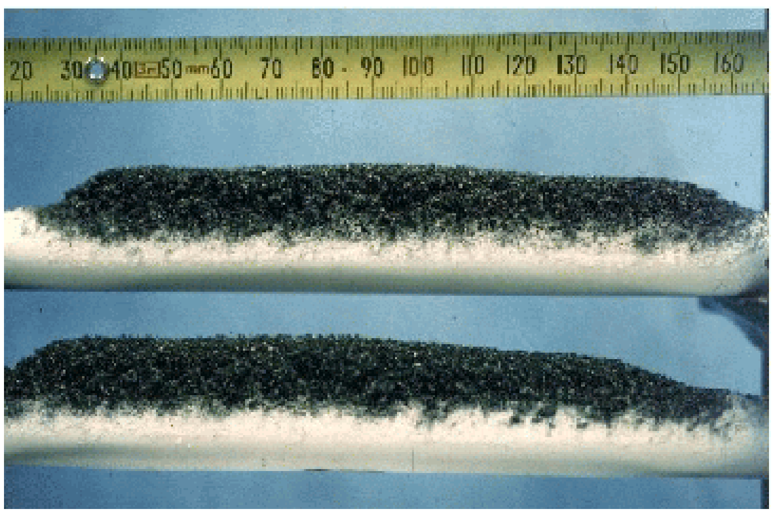
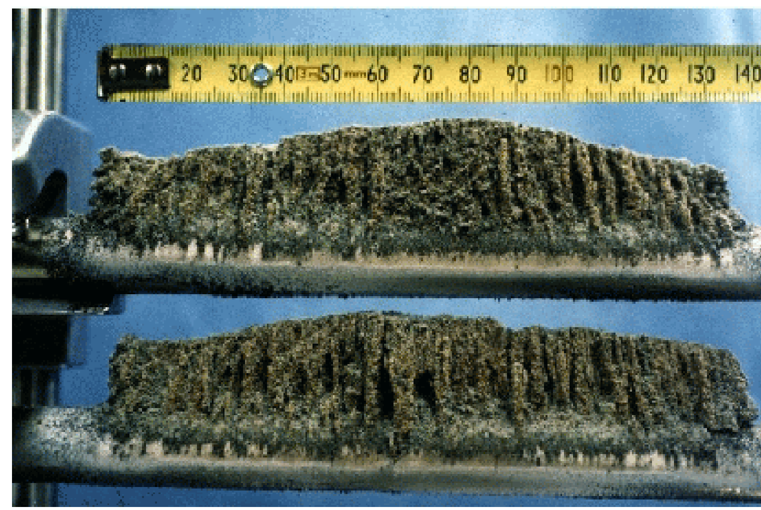


Background

In a coal fired reactor, ash is formed and accumulates on the walls of the combustion chamber. This deposited ash can significantly affect the thermal transport in the boiler.





Objectives

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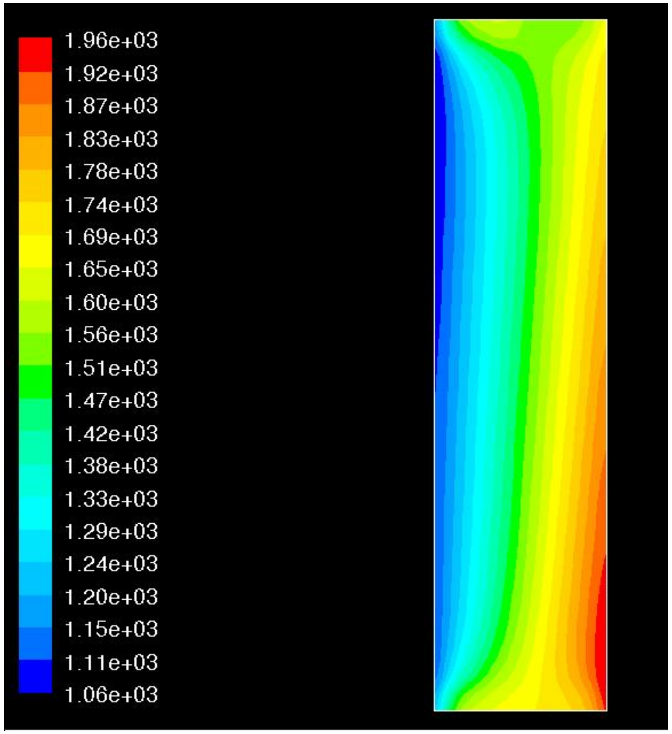
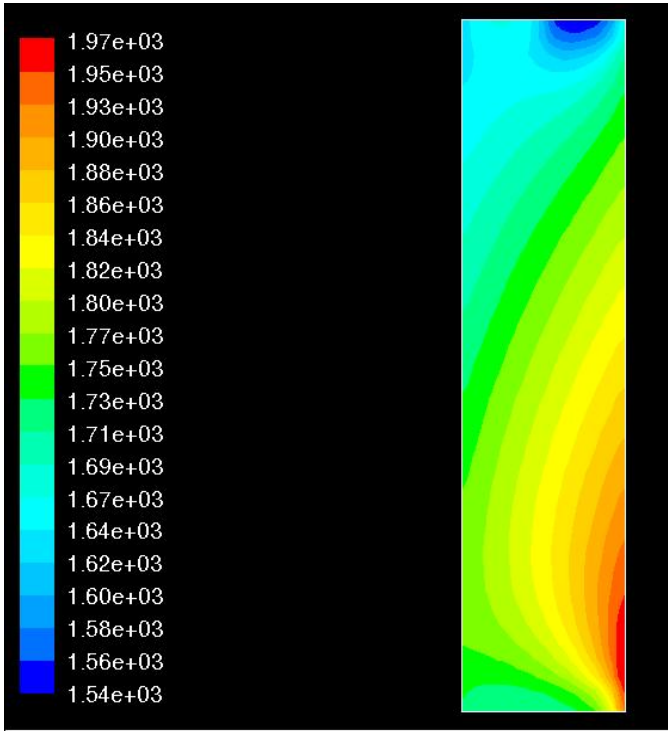
2. Develop a procedure to make accurate, *in situ* measurements of the emittance of the deposited ash.

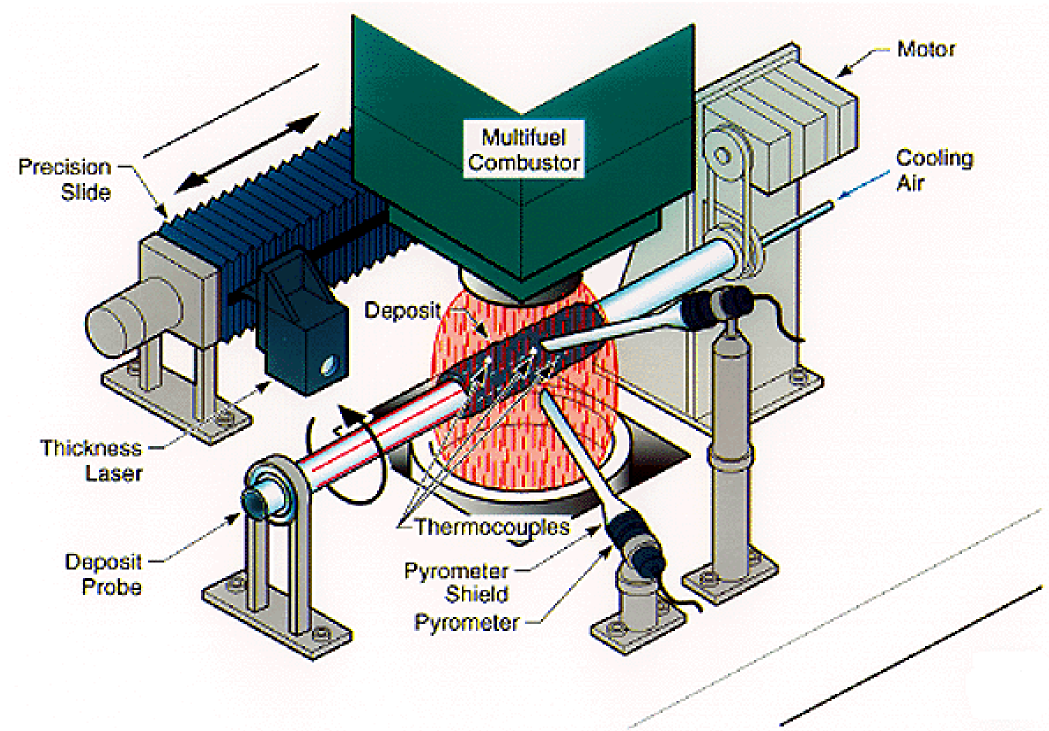
Importance

Knowledge of the properties of the ash deposits will result in better modeling capabilities and improved optimization of the design of coal fired reactors.





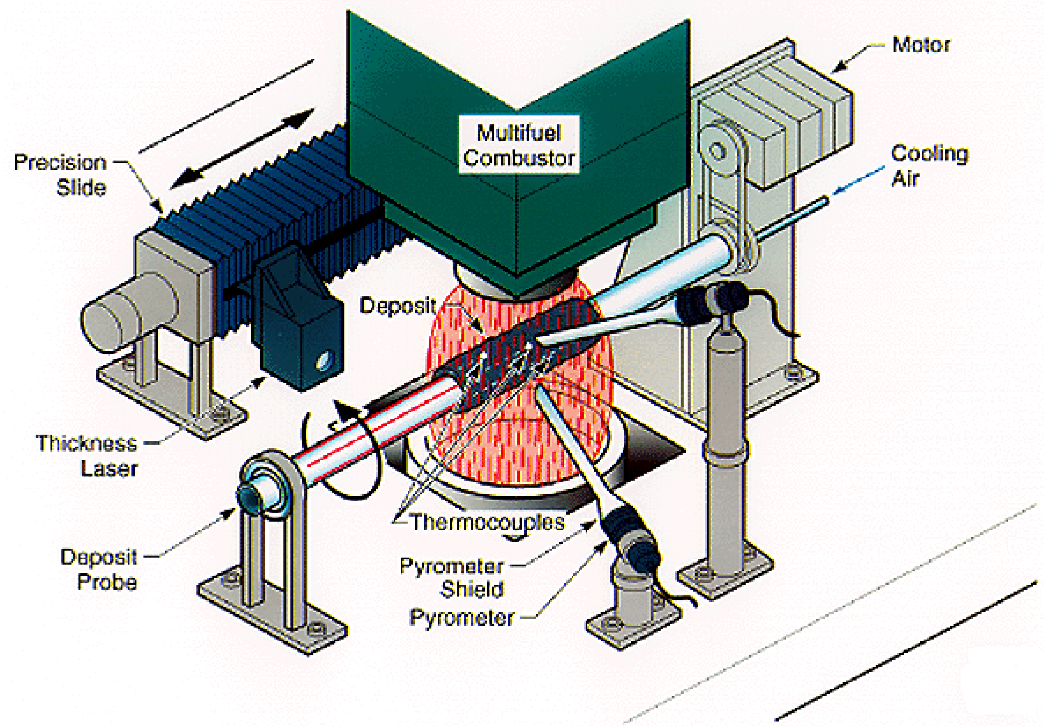
Simulating Ash Deposition



Method

An air-cooled, circular steel probe is placed at the outlet of a multi-fuel combustor. Coal is injected into the top of the furnace and the carbon in the particles is burned out before they reach the probe. The probe is rotated to ensure even accumulation of ash.

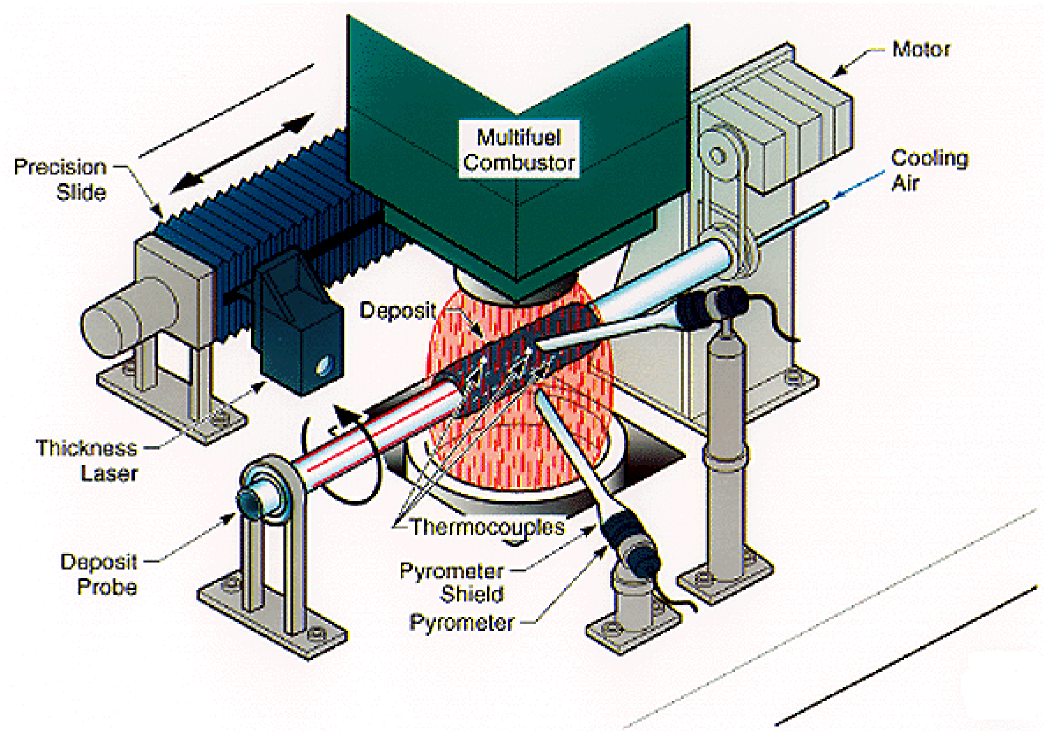
Simulating Ash Deposition



Measurable Parameters

- Flame temperature
- Ash layer surface temperature
- Probe surface temperature
- Cooling air inlet temperature
- Cooling air outlet temperature
- Mass flow-rate of air in probe
- Ash layer thickness
- Spectral radiosity of ash layer

Simulating Ash Deposition



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Definition of emittance of ash layer: $$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda E_{\lambda,b}(T_s)\,d\lambda}{\int_0^\infty E_{\lambda,b}(T_s)\,d\lambda}$$

Calculating Emittance

Using the **Planck Distribution**, $E_{\lambda,b}(\lambda,T) = \dfrac{C_1}{\lambda^5\left[\exp(C_2/\lambda T)-1\right]}$

and applying the **Stefan-Boltzmann law**, the total emittance of the ash layer is:

$$\varepsilon = \frac{1}{\sigma T_s^{\,4}} \int_0^\infty \frac{\left(\lambda^5 J_\lambda + C_1\right)\left(1 - e^{C_2/\lambda T_s}\right) + \lambda^5 J_\lambda \left(e^{C_2(T_s+T_f)/\lambda T_s T_f} - e^{C_2/\lambda T_s}\right)}{\lambda^5\left(e^{C_2/\lambda T_f} - e^{C_2/\lambda T_s}\right)\left(e^{C_2/\lambda T_s} - 1\right)} d\lambda$$

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This integral can be approximated by the following sum:

$$\boxed{\varepsilon \approx \frac{1}{\sigma T_s^{\,4}} \sum_{n=1}^{N} \frac{\left(\lambda^5 J_\lambda + C_1\right)\left(1 - e^{C_2/\lambda T_s}\right) + \lambda^5 J_\lambda \left(e^{C_2 (T_s + T_f)/\lambda T_s T_f} - e^{C_2/\lambda T_s}\right)}{\lambda^5 \left(e^{C_2/\lambda T_f} - e^{C_2/\lambda T_s}\right)\left(e^{C_2/\lambda T_s} - 1\right)} \Delta\lambda}$$

Numerical Experimentation

Purpose: Verify the use of the equation developed to calculate the total emittance of the layer of ash.

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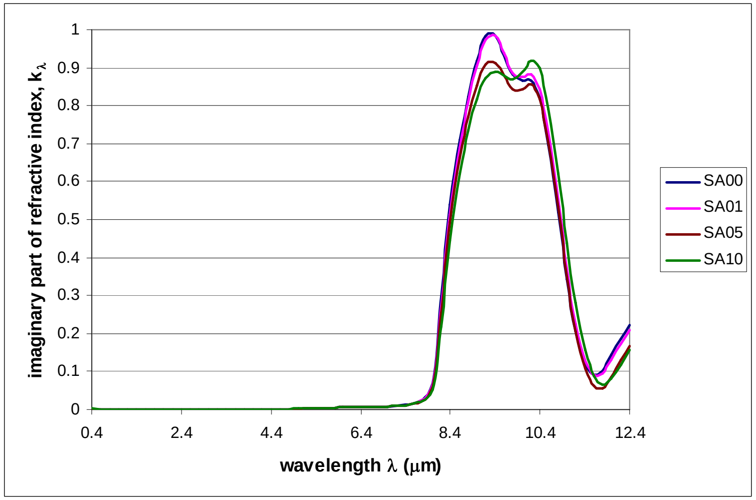
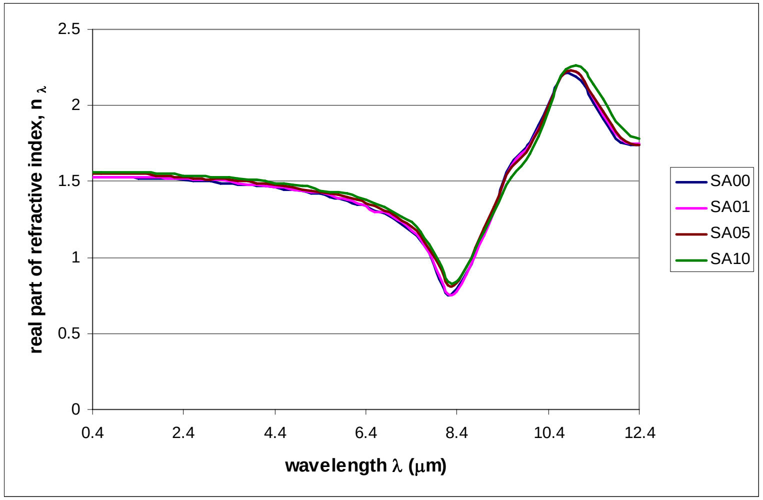
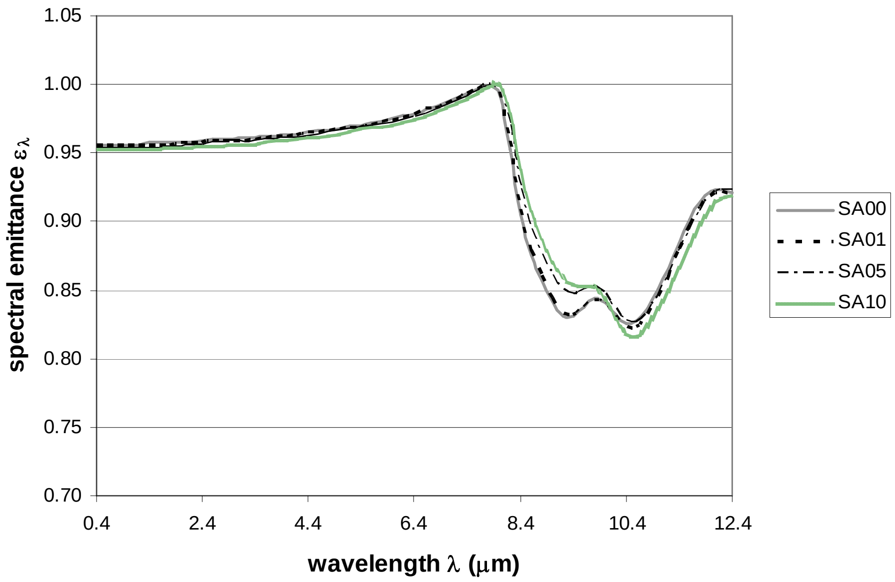
The literature contains measurements of the spectral optical constants of coal slags at room temperature with varying levels of iron content (Goodwin, *Infrared Optical Constants of Coal Slags*). These measurements were used to compute the spectral emittance of the coal slags.



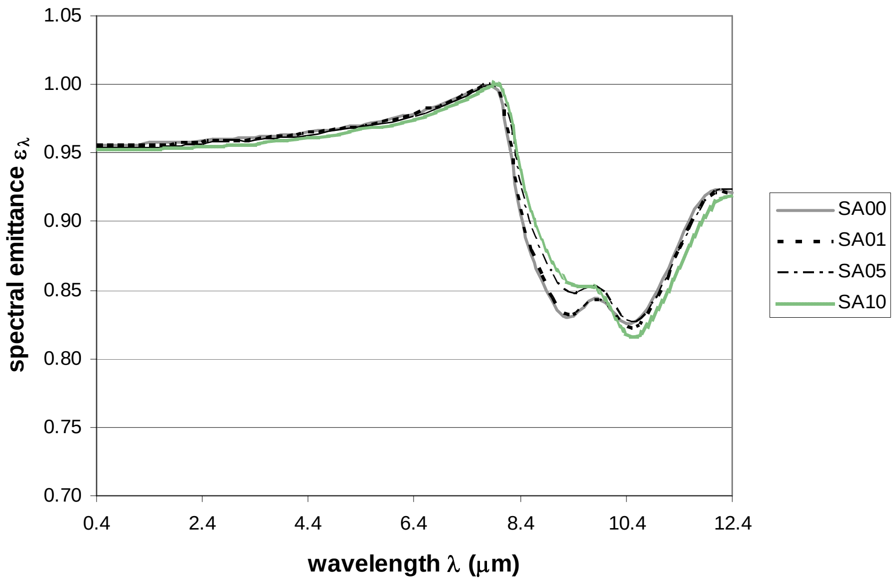


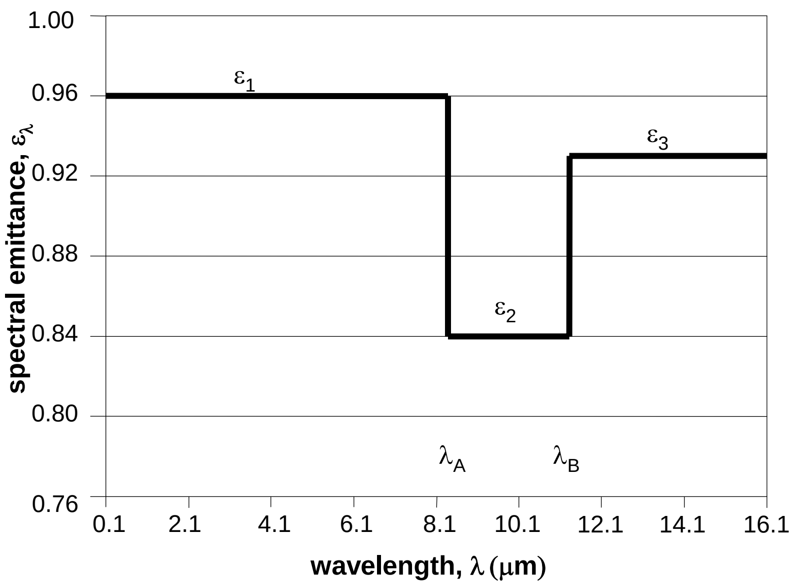
Numerical Experimentation



Spectral emittances of coal slags with 0, 1, 5, and 10 percent iron contents calculated from the optical constants.

Numerical Experimentation





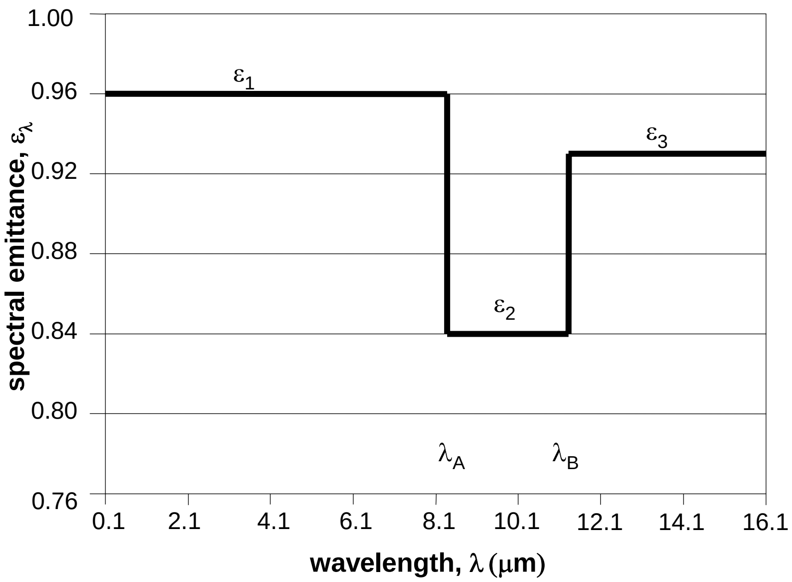
Spectral emittances of coal slags with 0, 1, 5, and 10 percent iron contents calculated from the optical constants.

Piece-wise constant approximation of the spectral emittance of the ash layer as a function of wavelength.

Numerical Experimentation

Assuming the surface temperature of the ash layer to be T_s = 923 K, the fractional function was used to compute the total emittance of the ash layer:

$$\varepsilon = \varepsilon_1 F(\lambda_A, T_S) + \varepsilon_2 \left[F(\lambda_B, T_S) - F(\lambda_A, T_S)\right] + \varepsilon_3 \left[1 - F(\lambda_B, T_S)\right] = \boxed{0.95}$$

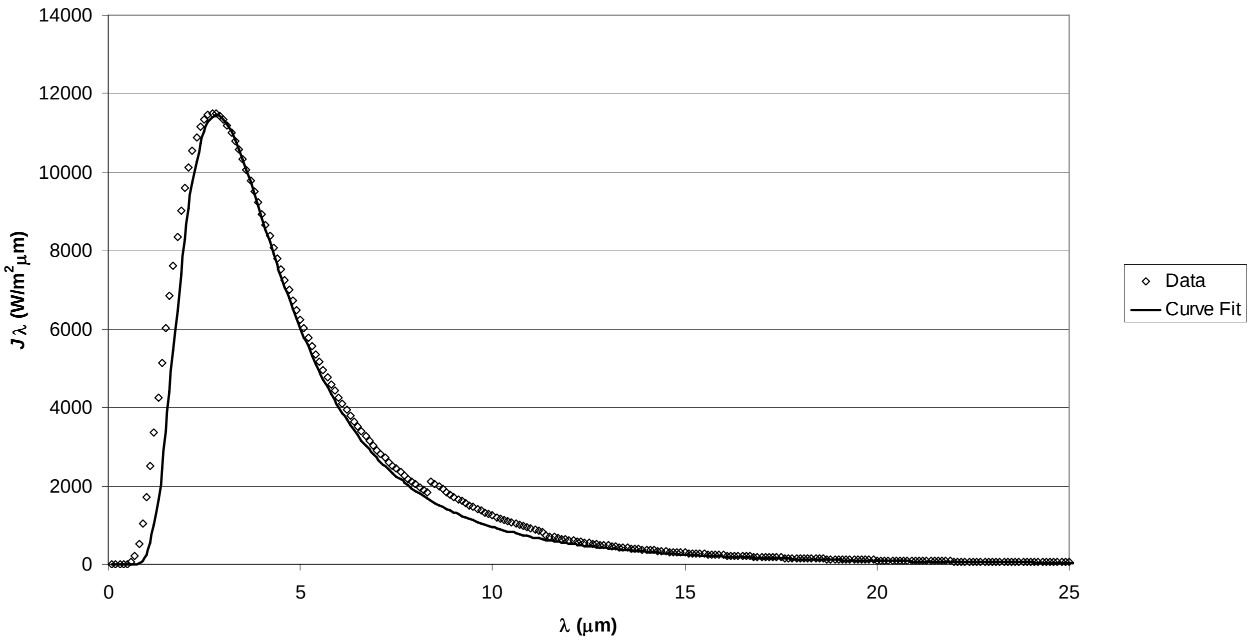


Numerical Experimentation

Simulated experimental measurements of the spectral radiosity were calculated using the following equation:

$$J_\lambda = \varepsilon_\lambda E_{b,\lambda}(T_s) + (1 - \varepsilon_\lambda) E_{b,\lambda}(T_f)$$

where T_s = 923 K and T_f = 1580 K.

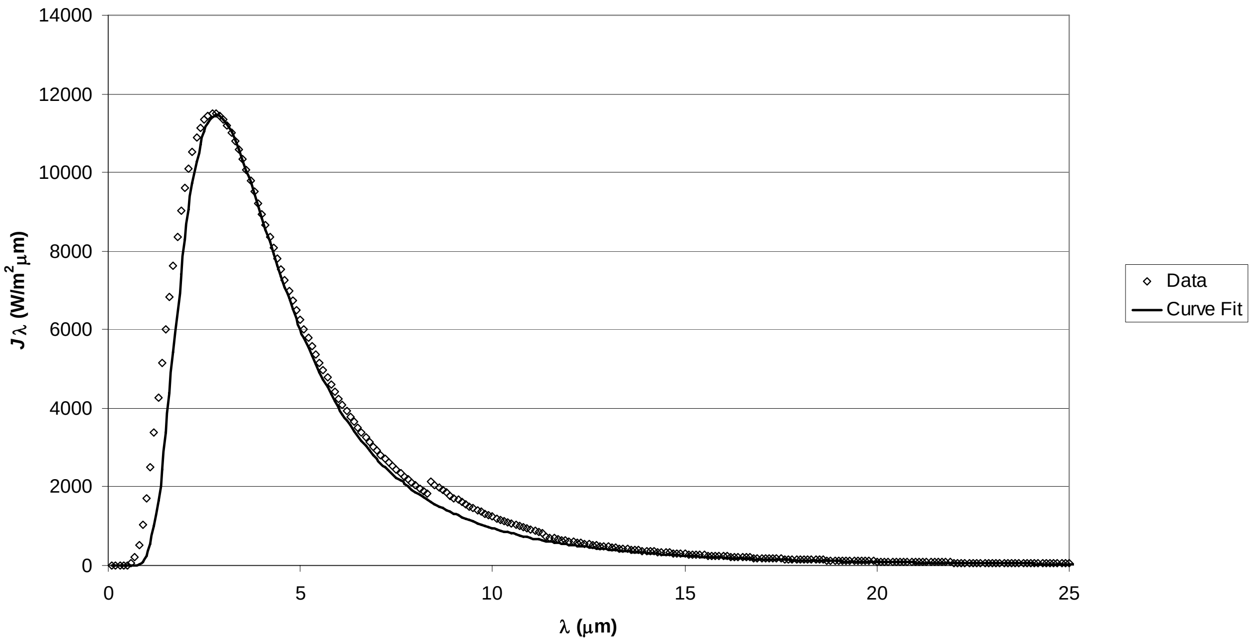


Numerical Experimentation

$$\varepsilon \approx \frac{1}{\sigma T_s^4}\sum_{n=1}^{N}\frac{\left(\lambda^5 J_\lambda + C_1\right)\left(1-e^{C_2/\lambda T_s}\right)+\lambda^5 J_\lambda\left(e^{C_2(T_s+T_f)/\lambda T_s T_f}-e^{C_2/\lambda T_s}\right)}{\lambda^5\left(e^{C_2/\lambda T_f}-e^{C_2/\lambda T_s}\right)\left(e^{C_2/\lambda T_s}-1\right)}\Delta\lambda$$

The numerical integration was performed over a range of $0.1\mu m \le \lambda \le 39\mu m$ with a resolution of $\Delta\lambda = 0.1\mu m$.

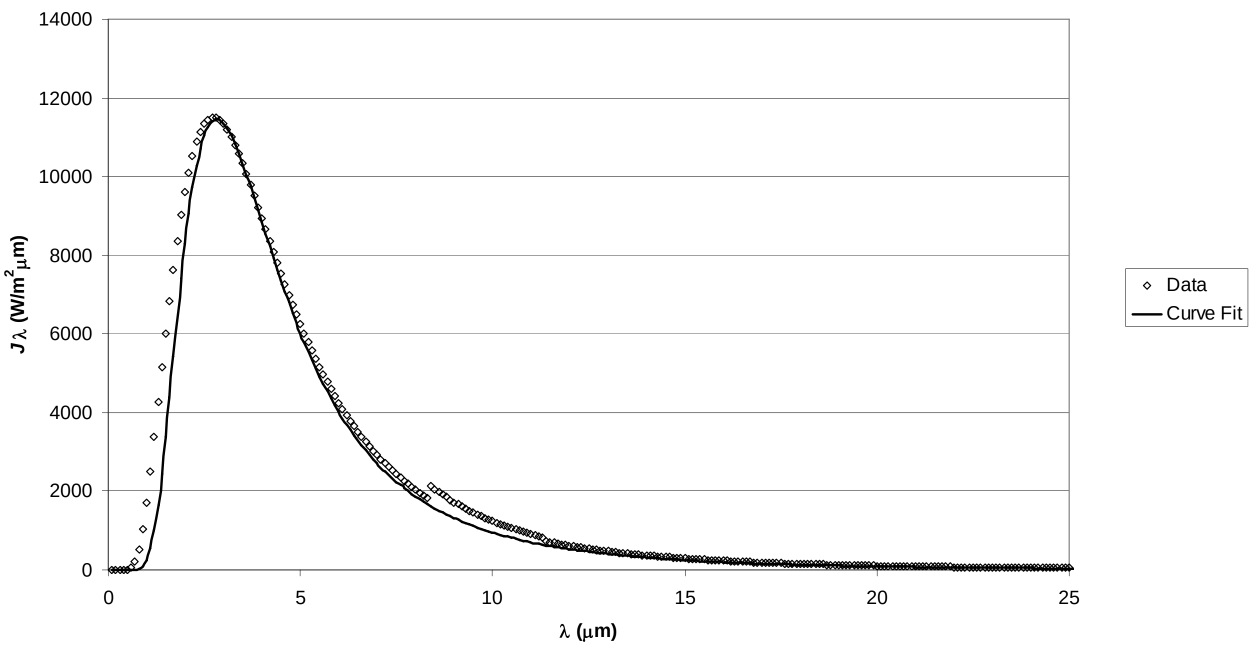
The resulting emittance was $\varepsilon = 0.95$.



Numerical Experimentation

In order to reduce the number of required measurements of the spectral radiosity, a nonlinear least squares method was used to fit a curve to the simulated data:

$$J_\lambda(\lambda) = \frac{2.91\times10^8}{\lambda^5\left(\exp(14.0/\lambda)-1\right)}$$



Numerical Experimentation

$$\varepsilon \approx \frac{1}{\sigma T_s^{\,4}} \sum_{n=1}^{N} \frac{\left(\lambda^5 J_\lambda + C_1\right)\left(1 - e^{C_2/\lambda T_s}\right) + \lambda^5 J_\lambda \left(e^{C_2 (T_s + T_f)/\lambda T_s T_f} - e^{C_2/\lambda T_s}\right)}{\lambda^5 \left(e^{C_2/\lambda T_f} - e^{C_2/\lambda T_s}\right)\left(e^{C_2/\lambda T_s} - 1\right)} \Delta\lambda$$

The numerical integration was performed again, this time over a range of $0.1\mu\text{m} \leq l \leq 18\mu\text{m}$ and with a resolution of $\Delta\lambda = 1.5\mu\text{m}$ resulting in a total emittance of $\boxed{\varepsilon = 0.95.}$

This matches the total emittance calculated from the spectral emittance profile and verifies the use of the above equation in estimating the emittance of the layer of ash.

Sensitivity to Measurement Error

Varying levels of random error were introduced into the temperature and radiosity measurements to see their effect on the calculated emittance.

Percent error in calculated emittance with the introduction of measurement error.

Error in T \ Error in J_λ	0%	±1%	±5%	±10%	±20%
0	0	±0.22%	±1.30%	±2.07%	±4.30%
±1 K	±0.54%	±0.37%	±1.60%	±2.61%	±4.14%
±2 K	±1.08%	±0.40%	±1.15%	±2.74%	±3.93%
±5 K	±2.70%	±0.66%	±1.16%	±3.60%	±4.39%

Conclusion

These results show that this method can tolerate relatively high errors in both the temperature and spectral radiosity measurements. Therefore, it is concluded that the proposed method can be used to accurately estimate the emittance of the layer of ash that forms on the probe.

Future Work

Planned future work includes the development of similar procedures to measure the thermal conductivity of the ash layer and to develop relationships between these properties and the structure of the ash. The experimental apparatus necessary to experimentally validate the proposed method is currently under construction.