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Radiative Heat Transfer in Pulverized-Coal-Fired Boilers — Development of the Absorptive/Reflective Character of Initial Ash Deposits

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ABSTRACT

Emission Fourier transform infrared (FTIR) spectroscopy data provide *in situ*, time-resolved, spectral emissivity measurements for ash deposits generated from two U.S. Powder River Basin coals under realistic combustion conditions. The first three hours of deposit growth on a tube in cross flow in Sandia's Multifuel Combustor detail the development of surface emissivity with time. Measured emissivities vary significantly with wavelength, reflecting the influence of the physical, chemical, and optical properties of the deposit. At long wavelengths ($>7\mu\text{m}$), emission bands exhibit characteristics of sulfates and silicates. The spectral emissivity measured in this region approaches a steady value, indicating that the deposit becomes opaque. In contrast, deposits are not opaque at shorter wavelengths where the measured emissivity is influenced by the properties of the underlying metal surface. Theoretical predictions of the emissivity of a particulate layer were performed and results are compared to the measured values. The theory adequately predicts the general features of spectral variation of the emissivity. The predicted trends in emissivity with particle size and deposit composition are also consistent with experimental observations. Total (Planck-weighted) emissivities are calculated from the measured spectral values for the deposits at flame temperatures. They increase with time from the clean tube value (0.2 to 0.3) to values typical of deposits formed from western U.S. coals (0.45 to 0.55). The total absorptivities are also calculated based on wall temperatures and found to be somewhat lower than the corresponding emissivities (0.30 to 0.37). In all cases, the ash deposits exhibit more reflective behavior than deposits generated from most eastern U.S. coals with emissivities of the order of 0.7 to 0.9.

INTRODUCTION

Radiative transfer is the dominant heat transfer mechanism in the furnace region of pulverized-coal-fired boilers (p.c. boilers). Radiation accounts for about 80% of the total heat transfer in the furnace region of a clean boiler, and significantly less ($\approx 10\%$) in the convective pass. Typical deposits from western U.S. coals consist of fine particles of nonabsorbing material that reflect up to 70% of incident radiation [Wall, et al., 1993 (in press)]. The reflective/absorptive properties of ash deposits are an important part of engineering calculations of heat transfer in a utility boiler. For example, reducing the wall emissivity from 0.8 to 0.4 in a utility boiler can cause an increase of 110 °C in the calculated furnace exit gas temperature [Wall, et al., 1993 (in press)]. Field experience with western U.S. coals confirms both the changes in emissivity and the increases in furnace exit gas temperature [Baxter and DeSollar, 1993]. This paper presents theoretical predictions of the spectral emissivity of coal ash deposits as a function of particle size and composition. These predictions are compared with *in situ*, time-resolved measurements of spectral emissivities from ash deposits formed in Sandia's Multifuel Combustor, among the first data of this type to be collected under simulated boiler conditions.

THEORY

Radiative Properties of Deposits

The radiative properties of coal ash deposits are a function of both the chemical composition and the physical nature of the deposit. Fine condensable salts or particulate ($< 10\ \mu\text{m}$) often contribute to initial layers of ash deposits and may be highly reflective [Wall, et al., 1993 (in press)]. As larger particles accumulate, the deposit emissivity tends to increase. The temperature gradient through the deposit may cause the outer layer to sinter, at which point it may absorb over 90% of the incident radiation, depending on its composition [Goodwin, 1986].

Deposit emissivities vary with wavelength from a low of approximately 0.2 to greater than 0.9, as will be shown later in this paper. A Planck-weighted emissivity indicates an effective average value, or total value, appropriate for many engineering applications [Baxter, et al., 1988]. This total emissivity depends on the both the spectral emissivity (which depends on surface temperature) and the temperature at which the Planck function is evaluated. In general, an arbitrary Planck-weighted radiative property r is given by

$$r_t^P(T_s, T) = \frac{\int_{\lambda=0}^{\infty} r_{\lambda}(T_s, \lambda) P(T, \lambda) d\lambda}{\int_{\lambda=0}^{\infty} P(T, \lambda) d\lambda} = \frac{\int_{\lambda=0}^{\infty} r_{\lambda}(T, \lambda) P(T, \lambda) d\lambda}{\sigma T^4} \quad (1)$$

where ϵ represents emissivity, T represents absolute temperature, λ represents wavelength, and σ represents the Stefan-Boltzmann constant. Subscripts t , s , and λ represent total, surface, and spectral, respectively.

The total emissivity of the surface is taken as the value of Eq. 1 when both the Planck function and the spectral emissivity are evaluated at the surface temperature. It depends only on the surface temperature. In general, the spectral emissivity, ϵ_{λ} , and spectral absorbtivity, α_{λ} , are equal (Kirchoff's law). For opaque materials, the reflectivity, ρ , can be calculated by subtracting the absorbtivity from unity. Therefore, the Planck-weighted total reflectivity is found by evaluating Eq. 1 at the surface temperature and the flame temperature (or a temperature characteristic of the incident radiation) and subtracting the result from unity,

$$\rho_t^P(T_s, T) = 1 - \alpha_t^P(T_s, T). \quad (2)$$

In contrast to the total emissivity, the total reflectivity depends on both the surface temperature and the flame temperature. These Planck-weighted radiative properties are used in this investigation to approximate total radiative properties that are applicable to furnace calculations. For a large variety of materials relevant to combustion problems, the Planck-weighted properties decrease with increasing temperature [Baxter, et al., 1988; Goodwin, 1986; Wall, et al., 1993 (in press)].

The instrumentation used in this investigation does not cover the entire range of wavelengths from 0 to ∞ . The total radiative properties presented below are computed by evaluating all integrals in Eq. 1 over the range of wavelengths measured, (approximately 2.8 to 25 μm), yielding something less than σT^4 as the denominator in the last expression of Eq. 1. Between 35 and 93 percent of the total radiative heat flux from a blackbody is included in this range of wavelengths, depending on the blackbody temperature [Baxter, et al., 1988].

Prediction of Radiative Properties for Particle Layers and Slags

Deposit radiative properties depend on both deposit chemistry and composition, both of which are complex. The approach used here is to obtain first-order predictions to be compared with measured results. Deposits are treated as an opaque layer of monosized, independently scattering, isothermal, spherical particles of known optical properties [Bohren and Huffman, 1983; Wall, et al., 1993 (in press)]. While none of these assumptions is completely accurate, the first-order effects of scattering are derivable from such a model. Such particle layers backscatter (reflect) incident flame radiation into the furnace. Theoretical predictions of single particle scattering can be made using Mie theory. The size parameter ($x \equiv \pi d / \lambda$, d =particle diameter) and complex refractive index of the ash ($m = n - ik$) are the particle properties defining the interaction between the particles and the incident radiation. These single particle properties are used in conjunction with the discrete ordinates method to calculate the spectral hemispherical emissivity of the particulate layer described above [Bohren and Huffman, 1983; Wall, et al., 1993 (in press)]. In addition, the emissivity of slag layers (which were approximated as an optically smooth surface) is estimated from the complex refractive index of the slag [Goodwin, 1986; Siegel and Howell, 1981].

Spectral emissivity predictions are given in Figs. 1-2 for opaque particle layers based on the spectral optical properties of two ash types. Fig. 1 is based on data for slags ($\text{SiO}_2/\text{Al}_2\text{O}_3 \approx 2$, $\text{CaO}/\text{Al}_2\text{O}_3 \approx 0.6$, $\text{Fe}_2\text{O}_3 \approx 5\%$) [Goodwin, 1986], while Fig. 2 is based on optical properties derived for CaSO_4 [Toon, et al., 1976; Touloukian and Ho, 1989]. In Fig. 1, a region of low emissivity is apparent at wavelengths $< 5 \mu\text{m}$, where particle size strongly influences the predicted results. By contrast, ϵ_λ generally exceeds 0.9 for a smooth, iron-containing slag layer. The spectral emissivity predicted for CaSO_4 particles (Fig. 2) has qualitatively similar features, with a region of low emissivity at wavelengths $< 7.5 \mu\text{m}$, but with a more rapid increase at $7.5 \mu\text{m}$ and above to approximately 0.9.

EXPERIMENTAL APPARATUS AND PROCEDURE

Emission FTIR Spectroscopy

A diagnostic tool based on emission Fourier transform infrared (FTIR) spectroscopy has been developed to measure *in situ* properties of ash deposits in real time [Baxter, 1993; Baxter, et al., 1993 (to appear)]. In this investigation, the diagnostic is used to monitor deposits generated on a stainless steel probe in Sandia's Multifuel Combustor (MFC). The MFC is a 0.1 MBtu/hr, down-fired facility with an open test section at the furnace exit to allow optical and probe access to the flow of combustion products [Baxter, 1992; Baxter, et al., 1990]. Deposits were formed on an air-cooled cylindrical probe (1.6 cm O.D.) in cross flow. The probe was rotated continuously about its axis during each three hour test to form a nominally uniform deposit around the tube circumference.

Figure 3 illustrates the optical layout of the emission FTIR spectroscopy system. The radiative emission from a spot approximately 5 mm in diameter on the bottom half of the probe was

collected by a set of off-axis paraboloidal mirrors and focused into the spectrometer. A commercial, rapid-scanning interferometer (Biorad FTS-40/60) was used with a liquid nitrogen-cooled, broad-band mercury-cadmium-telluride (MCT) detector and a germanium-based beam splitter. Emitted radiation from the bottom of the probe was collected to minimize the contribution of reflected furnace radiation to the total signal. The radiative emission from the probe was compared to that of a blackbody calibration source to determine the spectral emissivity of the probe or deposit surface. The measured surface temperature of the probe was typically between 450°C and 600°C, although the deposit surface temperature varied with time as the deposit grew.

Emission spectra were collected at a resolution of 2 cm⁻¹. Typically, 64 individual interferograms were co-added and deconvolved to obtain a single emission spectrum, requiring about 1 minute. Significant interference from triatomic gases (CO₂ and H₂O) in the optical path was also observed. At a resolution of 2 cm⁻¹, some of the gas-phase emission and absorption bands are isolated in the spectrum, while others are unresolved and appear as broad features. In all cases, the deposit and probe surface emission appear as broad features. The deposit emissivity can be obtained from all spectral regions except where gas-phase species dominate the signal.

Experimental Conditions

Deposits were generated at combustor wall temperatures of both 1300 °C and 900 °C. The resulting gas temperatures at the deposition probe were approximately 900 °C and 700 °C, respectively, for the two conditions. The probe surface temperature was maintained at 600±15 °C when operating at the higher temperature and at 500±15 °C for the experiments performed at the lower temperature. At these temperatures, over 90 percent of the total radiative flux from a black body is within the spectral region measured by the interferometer (2.8 to 25 μm). The coal feed rate was approximately 1.8 kg/hr for all experiments. The surface of the probe was cleaned and polished prior to each experiment.

Coal Properties

The properties of the two coals used in this investigation, Antelope and Black Thunder, are listed in Table 1. Both are U.S. subbituminous coals from the Powder River Basin. As indicated in the table, both coals contained approximately 22% moisture and have similar chemical compositions. The Antelope coal contained 5.5% ash consisting mainly of calcium, silicon, aluminum, with significant quantities of iron and magnesium. The Black Thunder coal contained 6.5% ash and a slightly greater percentage of silicon and aluminum than the Antelope, but less calcium, iron, and magnesium. The inorganic constituents of the Powder River Basin coals are primarily in the form of silica and silicates, although up to 70% of the calcium may be atomically dispersed in the coal matrix [Baxter and Dora, 1992]. Utility experience with Powder River Basin coals shows that they form sulfate-based deposits, especially in the economizer of utility boilers. Deposits containing both silicate particles and sulfates are therefore expected [Baxter and DeSollar, 1993; Baxter and Dora, 1992].

EXPERIMENTAL RESULTS

Figure 4 illustrates the time-resolved spectral emissivity from the *in situ* FTIR measurements for the Antelope coal. These spectra were obtained at a combustor wall temperature of 900°C and have been digitally filtered to remove most of the gas-phase interference. The residual interference appears as strong bands at 2.9-3.0 μm , 4.2-4.5 μm , 5.5-7.5 μm , and 14.4-15.2 μm , with emissivity values sometimes exceeding unity or less than zero.

The initial emissivity shown in Fig. 4 is that of the clean stainless steel probe taken at temperature prior to the initiation of coal flow. The emissivity appears relatively constant across the spectrum at approximately 0.2, except for the regions of gas phase interference and a slight increase at wavelengths shorter than 4 microns. An emissivity less than 0.3 is consistent with literature values for polished stainless steel [Incropera and DeWitt, 1981]. There is little change in the spectra with

time at wavelengths less than 7 μm . Ash deposits from western coals rarely contain chemical species with absorption bands in this region. The deposit emissivity appears to be influenced by the emissivity of the deposition probe. This influence was also seen in a similar test performed with a heavily oxidized mild steel deposition probe with an initial emissivity of approximately 0.8 at wavelengths less than 7 μm .

A large change in emissivity with time occurs at wavelengths greater than 7 μm due to the changing chemical species on the deposit surface. The spectral structure derives from the presence of anhydrite, silica, and silicate in the deposit, as is discussed elsewhere [Baxter, 1993; Baxter, et al., 1993 (to appear)]. They illustrate the influence of opaque, absorbing particles on the spectral emissivity of the surface.

Figure 5 presents the spectral emissivity values of the deposit from the Black Thunder coal as a function of time. At wavelengths less than 4 μm the emissivity is very similar to that of the Antelope deposit and the clean stainless steel probe. The spectra from the Black Thunder deposit also show evidence of the presence of sulfate, silica, and silicate material. However, the spectral emissivities as a function of time are significantly different at the higher wavelengths than those of the Antelope deposit, indicative of the different chemical composition of the deposit. There is also a general increase in the deposit emissivity with time over the range of 4.8-7.5 μm .

After the combustion tests, the deposition probe (including the deposit) was cast in epoxy, cross-sectioned, and polished for examination using scanning electron microscopy (SEM) with X-ray analysis. The SEM analysis of the Antelope deposit showed an average deposit thickness of approximately 25 μm with very few ash particles larger than 10 μm in the deposit. The deposit consisted of an inner layer ($\approx$ 15 μm thick) of very small particles ($<$ 5 μm) of calcium silicate, calcium aluminosilicate, and iron which were mixed with both sodium and calcium sulfate. The sulfates appeared to be present as very small particles, but were difficult to resolve on the SEM. A few larger silicate particles were attached to the outside of this layer. The Black Thunder deposit was approximately 35 μm thick (measurements ranged from 10-60 μm), with an inner layer

similar to that of the Antelope deposit. The Black Thunder deposit contained significantly more particles larger than 5 μm in diameter, most of which were calcium aluminosilicate. The largest particles observed in the Black Thunder deposit were 30 μm in diameter. These observations support the interpretation of the trends observed in the spectral emissivities of the two deposits as a function of time.

Figure 6 presents the on-line emissivity results for the Black Thunder deposit at a wall temperature of 1300°C. The shape of the spectral emissivity of the clean probe appears similar to the emissivities measured at the lower probe and surface temperatures, although the magnitude is slightly greater (approximately 0.3). This increase may be a result of oxidation of the stainless steel surface which occurs more rapidly at the higher temperatures. The emissivities up to 40 minutes of deposition are similar to those measured at the lower probe and furnace temperature. At longer deposition times, however, the spectra are significantly different. The emissivity at 110 minutes shows no distinct sulfate and silicate peaks and the emission over the wavelength range of 5-17.5 μm is increased.

The SEM analysis of the high temperature deposit revealed an inner layer approximately 15 μm thick containing some discrete small particles of calcium silicate and calcium aluminosilicate mixed with sodium and calcium sulfate (similar to the inner layer of the lower temperature deposit). The outer layer of the deposit contained many larger particles (up to 60 μm), although most particles were less than 15 μm in diameter. The average deposit thickness was approximately 150 μm , although the thickness ranged from 30-175 μm . The larger particles were mainly calcium silicate and calcium aluminosilicate particles. A thin layer of calcium sulfate was evident on the surface of some of the larger particles. The trend in emissivity is consistent with this observed chemical composition and structure.

Total Emissivities and Absorptivities

Figure 7 illustrates the increase in total (Planck-weighted) emissivity as a function of time for the

two Black Thunder deposits. The gas-phase contributions to the spectral emissivity over the wavelength ranges 4.2-4.5 μm , 5.5-7.5 μm , and 14.4-15.2 μm were eliminated prior to the integration by linearly interpolating between the emissivity values at either side of the gas-phase emission bands. Average deposit surface temperatures calculated from the measured tube surface temperature were used to calculate the total emissivity values presented in Fig. 7. As shown in the figure, the total emissivity increased with time and the emissivity of the deposit generated at a wall temperature of 1300°C was generally higher than the lower temperature deposit.

Total deposit absorptivities were estimated for the most mature deposits of Fig. 7. The spectral incident flux was assumed to be a blackbody distribution at a flame temperature of 1800 K and the spectral emissivity measurement at 3.5 μm was assumed to apply at shorter wavelengths where experimental data were not available. The total absorptivity values of 0.30 and 0.37 are considerably lower than the total emissivities of the corresponding deposits, illustrating the influence of the spectral character of the emissivities on total radiative properties.

Comparison of Experimental Measurements with Theoretical Predictions

The spectral emissivities predicted for the sulfate particles at wavelengths greater than 7 μm (Fig. 2) most closely resemble spectra presented in Fig. 4 for the Antelope deposit, consistent with experimental observations of sulfates in the deposit. There is a prominent emission band between 8 and 10 μm , while the emissivity at wavelengths greater than 10 μm has a value of approximately 0.6. The magnitude of the emissivity increases with time at wavelengths greater than 7 μm , although the strong sulfate character remains. At early times, the deposit is not opaque and emission is collected from both the tube and the deposit, resulting in a relatively low emissivity. As the deposit grows, its opacity increases and the effect of the tube on the spectral emissivity is diminished. However, the deposit is less likely to be opaque at shorter wavelengths (1-4 μm) where the complex index of refraction of the ash is considerably lower. Therefore, the

emissivity of the tube is expected to play a more significant role at short wavelengths, consistent with experimental observations.

The emissivity measurements of the Black Thunder deposit (shown in Fig. 5) are generally higher at a given time than those of the Antelope deposit. The Black Thunder deposit was thicker than the Antelope deposit and appears to be more opaque. The Black Thunder deposit also shows evidence of the presence of sulfates, although the emissivity at wavelengths greater than 9 μm more closely resembles that predicted for a silicate deposit. There is also an increase in emissivity with time in the region of 4.8-7.5 μm . A rise in emissivity in this spectral region is predicted to occur with increasing particle size, as shown in Fig. 1. This rise is consistent with the SEM analysis that revealed that the Black Thunder deposit contained more large aluminosilicate particles than the Antelope deposit.

No significant difference in the emissivity at 110 minutes and 179 minutes is observed at wavelengths greater than 8 μm in the spectra from the high-temperature Black Thunder deposits (Fig. 6). The magnitude of the spectral emissivity in this region varies between 0.8 and 0.9, in reasonable agreement with the calculated values for the same region. The deposit is optically thick in this region, excluding any contribution from the probe to the deposit emissivity. Any additional changes in the emissivity would be due to changes in the size of particles which form the deposit, the deposit composition, or the physical state of the deposit. The emissivity of the deposit appears to increase with time throughout the experiment in the region from 5-8 μm , consistent with the presence of larger particles in the deposit. SEM examination confirmed the presence of larger particles in the outer layer of the deposit.

CONCLUSIONS

In situ, time-resolved measurements of the spectral emissivity of ash deposits are reported for two U.S. Powder River Basin coals using emission FTIR spectroscopy. Trends in observed deposit emissivity with composition, thickness, and temperature are consistent with SEM/EDX measurements and predicted results. At long wavelengths ($> 7 \mu\text{m}$), features in the emission spectra were observed due to the chemical composition of the deposit. As the deposit thickened and matured, the emissivity approaches a constant value, indicating that the deposit had become opaque. In contrast, deposits are not opaque at short wavelengths, and the measured emissivity is influenced by the properties of the underlying probe surface. An increase in the spectral emissivity at wavelengths of 4.8-7.5 μm is observed as larger particles were incorporated into the deposit, consistent with theoretical predictions. Total emissivities, calculated from the measured spectral values for each deposit, increase with time from the clean probe value (0.2-0.3) to values of 0.45-0.55. The total absorptivities are also calculated (0.30-0.37) and found to be lower than the corresponding emissivities.

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REFERENCES

Baxter, L. L. (1992). "Char Fragmentation and Fly Ash Formation During Pulverized Coal Combustion." *Combustion and Flame*, **90**, 174-184.

Baxter, L. L. (1993). "In Situ, Real-Time Emission FTIR Spectroscopy as a Diagnostic for Ash Deposition During Coal Combustion". In *Engineering Foundation Conference on The Impact of Ash Deposition on Coal-Fired Plants*, . Solihull, England:

Baxter, L. L., and DeSollar, R. W. (1993). "A Mechanistic Description of Ash Deposition During Pulverized Coal Combustion: Predictions Compared to Observations." *Fuel*, **72**(10), 1411-1418.

Baxter, L. L., and Dora, L. (1992). "The Combustion Behavior of a Blend of Eastern and Western Coals: Comparisons Between a Blend and Its Individual Components." *ASME Paper No. 92-JPGC-FACT-14*.

Baxter, L. L., Fletcher, T. H., and Ottesen, D. K. (1988). "Spectral Emittance Measurements of Coal Particles." *Energy & Fuels*, **2**, 423-430.

Baxter, L. L., Hencken, K. R., and Harding, N. S. (1990). "The Dynamic Variation of Particle Capture Efficiency During Ash Deposition in Coal-Coal Fired Combustors". In *Twenty-Third Symposium (International) on Combustion*, (pp. 993-999). Orleans, France:

Baxter, L. L., Richards, G. H., Ottesen, D. K., and Harb, J. N. (1993 (to appear)). "In Situ, Real-time Characterization of Coal Ash Deposits Using Fourier Transform Infrared Emission Spectroscopy." *Energy & Fuels*.

Bohren, C. F., and Huffman, D. R. (1983). *Absorption and Scattering of Light by Small*

Particles. New York: John Wiley & Sons.

Goodwin, D. G. (1986) "Infrared Optical Constants of Coal Slags." Ph.D. Dissertation, Stanford University.

Incropera, F. P., and DeWitt, D. P. (1981). *Fundamentals of Heat Transfer*. New York: John Wiley & Sons.

Siegel, R., and Howell, J. R. (1981). *Thermal Radiation Heat Transfer*. New York: Hemisphere.

Toon, O. B., Pollack, J. B., and Khare, B. N. (1976). *Journal of Geophysical Research*, **81**, 33.

Touloukian, Y. S., and Ho, C. J. (Ed.). (1989). *Thermal Radiative Properties of Nonmetallic Solids*. New York: Plenum.

Wall, T. F., Bhattacharya, S. P., Zhang, D. K., Gupta, R. P., and He, X. (1993 (in press)). *Progress in Energy and Combustion Science*.

Table 1

Proximate, ultimate, heating value, and ash analyses of the coals used in this study.

Proximate and heating values are given on a dry, ash-free basis.

	Black		Ash Oxide	Black	
	Antelope	Thunder		Antelope	Thunder
Moisture (%)	22.9	21.3	SiO ₂	25.03	30.31
Ash (% dry)	5.51	6.46	Al ₂ O ₃	11.36	16.27
Prox. (% daf)			Fe ₂ O ₃	8.18	5.04
FC	54.2	42.0	TiO ₂	0.66	1.27
VM	45.8	58.0	CaO	28.88	21.07
Ultimate (% daf)			MgO	5.60	4.74
C	72.4	74.8	Na ₂ O	1.57	1.41
H	5.2	5.4	K ₂ O	0.25	0.35
O	20.9	18.3	P ₂ O ₅	0.81	0.91
N	1.1	1.0	SO ₃	17.65	17.46
S	0.4	0.5	undeter.	0.01	1.17

Heating Value	13562	13119
(daf - Btu/lb)		

Figure Captions

Fig. 1: Predictions of spectral hemispherical emissivity (ϵ_λ) for opaque particulate deposits as a function of particle size. The uniform ash composition is that of a calcium aluminosilicate with 4.65% Fe_2O_3 .

Fig. 2: Spectral emissivity predictions for an opaque layer of CaSO_4 particles using the following optical properties:

$$1.08 \leq \lambda \leq 7.47 \mu\text{m}$$

$$\lambda > 7.4 \mu\text{m}$$

$n=1.5$, k for CaSO_4 crystals

Curve 1. n and k of $(\text{NH}_4)_2\text{SO}_4$ crystals

(for all curves)

Curve 2. $n = 1.5$, $k = 0.5$

Curve 3. n of

$(\text{NH}_4)_2\text{SO}_4$ crystals, $k = 0.5$.

Fig. 3: Optical layout of emission FTIR diagnostic for *in situ*, real-time monitoring deposit emissivity.

Fig. 4: Spectral emissivity measurements for ash deposits generated from the Antelope coal as a function of time during the first 3 hours of deposition. Furnace wall temperature = 900°C .

Fig. 5: Spectral emissivity measurements for ash deposits generated from the Black Thunder coal as a function of time during the first 3 hours of deposition. Furnace wall temperature = 900°C.

Fig. 6: Spectral emissivity measurements for ash deposits generated from the Black Thunder coal as a function of time during the first 3 hours of deposition. Furnace wall temperature = 1300°C.

Fig. 7: Calculated total emissivity as a function of time for deposits generated from the Black Thunder coal at wall temperatures of 900 and 1300°C. Calculated using Eq. 1 with constant surface temperatures of 500 and 600°C, respectively.

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