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RADIATIVE PROPERTIES OF ASH AND SLAG

Tenth Quarterly Report

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ABSTRACT

Thermal radiation plays a key role in the operation and efficiency of combustion systems, accounting for over 90% of the heat transfer. The analysis of radiative heat transfer in coal-fired boilers, combustion chambers and other energy systems requires accounting for the effects of inorganic deposits on bounding surfaces and of entrained particulates, such as pulverized coal, char, and fly-ash. These effects can be predicted; however, the accuracy in predicting the radiative properties of entrained pyrolysis (ash) and deposit layers (slag) is limited by inaccurate knowledge of the physical/chemical properties of the materials over a range of material temperatures and radiative wavelengths that is representative of conditions in practical combustion systems. The objective of this project is to make laboratory measurements of the radiative properties of extracted ash and slag deposit samples and compare to model predictions.

RADIATIVE PROPERTIES OF ASH AND SLAG

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I. INTRODUCTION

Thermal radiation plays a key role in the operation and efficiency of combustion systems, accounting for over 90% of the heat transfer. The radiative heat transfer in coal-fired boilers is dominated by the properties of inorganic deposits and bounding surfaces, and of particulates, which are present in the system. The properties governing the emission, absorption, and attenuation of the radiative energy by deposits and entrained particulates are a key element in accurately predicting the radiative heat transfer. They are also necessary for in-situ determination of current deposit condition (composition, temperature) from optical measurements. The radiative properties of particles are characterized by the extinction efficiency, absorption efficiency (or emissivity) and scattering efficiency. That of deposits by the reflectance, transmittance, and absorptivity. These characteristics depend on the complex refractive index, the particle size or layer thickness and the material's morphology (porosity, inhomogeneities, grain boundaries, etc.).

This project will determine the radiative properties of deposits extracted from combustion devices. Measurements of radiative properties of materials at high temperatures are made by a technique employing a sample heating device that is coupled to a Fourier Transform Infrared (FT-IR) spectrometer to measure emission, hemispherical-directional transmission, and hemispherical-directional reflection of a sample. By this technique, the temperature at the measurement point and the spectral emittance (emissivity) of the surface can both be obtained. The complex index of refraction that is required to calculate emissivities is determined by a transmission spectroscopic technique that employs fine sample particulates suspended in KBr and CsI matrices.

During this quarter, work continued on improving the two stream model that was previously shown to result in good agreement when compared to the measured spectral emittance for a sintered slag deposit. The asymmetry parameter, g , which controls directional scattering in the model has been calculated as a function of spectral wavelength, particle size, and optical constants of the material. This is presented in Task 3.

Experiments were completed that demonstrate the measurement technique on a steel surface with varying extent of deposit coating. Spectral shifts in emittance were observed with increasing deposition. This is presented in Task 4.

II. PROGRESS SUMMARY

II.1. Task 1 - Project Implementation Plan

Completed in the third quarter and approved in the fourth quarter.

II.2. Task 2 - Measurement Technique Validation

Completed in the seventh quarter and discussed in detail in the seventh quarterly report.

II.3.a. Task 3.a - Deposit Sample Acquisition

Completed in the seventh quarter.

II.3.b. Task 3.b - Deposit Sample Characterization

Work concentrated on developing the two stream model being used to predict the spectral emittance of sintered slag deposits, which we introduced in the eighth quarterly report for this program.

The model incorporates an asymmetry parameter, g , which will influence directional scattering by the material. This parameter is being calculated as a function of wavelength, particle size and optical constants for the sintered deposit.

The asymmetry parameter, g , is given by

$$g = \frac{1}{Q_{sca}} \int_0^\pi [|S_1(\theta)|^2 + |S_2(\theta)|^2] \cos \theta \sin \theta d\theta$$

and was calculated as

$$g = \frac{1}{Q_{sca}} \sum_{n=0}^{n'} [|S_1(\theta)|^2 + |S_2(\theta)|^2] \cos \theta \sin \theta \Delta \theta$$

where $\theta = (n + 1/2)\Delta\theta$, and $n' = \pi/\Delta\theta$ ($\Delta\theta$ in radians).

The parameter, g , is the integral of the product ($\cos \theta \times$ phase function), over angle. It is known that the integral of the phase function over angle gives unity, and this relationship was used to ensure that the integrals were being evaluated correctly, with an appropriate (i.e., not too large) value of $\Delta\theta$.

For the values of n and k calculated from ash pellet spectra and a particle size equal to $4.6 \mu\text{m}$, g values were calculated to lie between 0.14 and 0.82 (Fig. 3.1).

Plans and Objectives for Next Month

Predict the spectral emittance of deposits with the inclusion of the asymmetry parameter in the model, and compare to emittance measurements of Task 4.

Figure 3.1. The Asymmetry Parameter, g , as a Function of Wavenumbers Calculated for Ash Particles ($4.6 \mu\text{m}$).

II.4. Task 4 - Measurement of Radiative Properties of Ash Deposit Samples

This program has demonstrated that the physical characteristics of the deposits greatly influence the spectral emittance. Figure 4.1 reviews the differences observed in spectral emittance between fused, sintered, and powdery deposits for samples #1 and #7. For these opaque samples, the emittance, and hence, the reflectance of the material is clearly influenced by the texture of the sample.

To demonstrate the change in spectral emittance (and hence, in the heat absorption rate) as deposit thickness grows, hemispherical reflectivity measurements were performed on a heavily oxidized stainless steel surface after subjecting the surface to impaction with the particle and fume stream from the combustion of pulverized Illinois No. 6 bituminous coal. The steel surface temperature, as measured with a 0.005" diameter thermocouple that was bonded to the surface, was held at $1000^{\circ}\text{F} \pm 30^{\circ}\text{F}$ during the ash deposition, and at $980^{\circ}\text{F} \pm 10^{\circ}\text{F}$ during the reflectivity measurements. These temperatures are in the range typical of a boiler wall or tube surface during operation.

Figures 4.2 and 4.3 demonstrates the change in the spectral emittance (emittance = $1 - \text{reflectance}$) of the oxidized steel surface as it is increasingly coated with dusty ash deposit. Below 1500 cm^{-1} , where the strong absorption bands for coal ash in general, are located, the emittance continually increases as more material is deposited. Above 1500 cm^{-1} , there is initially a slight rise in a emittance (compare case No. 1 and No. 2 in Fig. 4.3), and then a continual decrease in emittance as the ash coating thickens and increases the reflectivity in this spectral region. The thickness of the most heavy deposition presented is estimated to be $< 200\text{ }\mu\text{m}$ thick, but is already approaching the spectral shape for emittance of the much thicker pressed wafer of dusty fly ash shown in Fig. 4.1.

Plans and Objectives for Next Quarter

The budget level of the program necessitates that this task be considered tentatively complete as to experimental data collection at this point. Further comparisons of emittance measurements to predictions generated under Task 3 are planned, however.

Figure 4.1. Measured Spectral Emittance for a) Sintered Slag Deposit (sample #1) Compared to the Material After Grinding and Pressing into a Wafer; and After Thermally Fusing the Material and b) Powdery Ash (sample #7) Compared to the Emittance After Thermally Fusing the Material.

Figure 4.2. Spectral Emittance by Measured Hemispherical Reflectance (emittance = 1-reflectance) for a) an Oxidized Stainless Steel Surface, and b-d) the Surface as Increasingly more Dusty Ash is Deposited on the Surface. The Surface Temperature for Ash Deposition was Held at $1000^{\circ}\text{F} \pm 30^{\circ}\text{F}$; and for Measurements at $980^{\circ}\text{F} \pm 10^{\circ}\text{F}$.

Figure 4.3. Effect of Dusty Ash Deposit Thickness on the Spectral Emittance (ϵ) of an Oxidized Stainless Steel Surface. Case 1 has no Ash Deposits; Case 4 has the Thickest Ash Coating. The Surface Temperature for Ash Deposition was Held at $1000^{\circ}\text{F} \pm 30^{\circ}\text{F}$; and for Measurements at $980^{\circ}\text{F} \pm 10^{\circ}\text{F}$.

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