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DOE/PC/89776--T3

7th QUARTERLY PROJECT STATUS REPORT

Project Title: Effects of Calcium Magnesium Acetate on the Combustion of Coal-Water Slurries

DOE Grant #: DE-FG22-89PC89776

DOE/PC/89776--T3

DE92 000354

Principal Investigator: Yiannis A. Levendis

Project Performance Period: 1 March 1991 - 31 May 1991

Project Objectives:

The general objective of the project is to investigate the combustion behavior of single and multiple Coal-Water Fuel (CWF) particles burning at high temperature environments. Both uncatalyzed as well as catalyzed CWF drops with Calcium Magnesium Acetate (CMA) catalyst will be investigated. Emphasis will also be given in the effects of CMA on the sulfur capture during combustion. To help achieve these objectives the following project tasks were carried over this 7th three-month period.

Project Tasks:

Work on four tasks was conducted over this period: (1) Redesigning of the pyrometer electronics. (2) Theoretical analysis of the pyrometer limitations. (3) Production of pre-dried CWF agglomerates with subsequent particle heating studies and (4) Construction and testing of an apparatus to fluidize and introduce many particles in the furnace.

1 REDESIGNING OF THE PYROMETER ELECTRONICS.

Problems associated with the current configuration of the pyrometer electronics were discovered. They were mainly associated with capacitors inserted at the amplification circuitry. These capacitors were inserted in low-pass filter configurations to filter out high frequency noise (cutoff frequency $\omega = 2\pi f = \frac{1}{RC}$). However, it was determined that such circuits were creating slow time response in the system. Time responses up to 20 ms were observed. Removal of these components introduces large amplitude electronic noise in the final signal. A complete overhaul of the pyrometer electronics is currently taking place. Both linear and electronic amplifiers are being tested, in the second stage amplification, to optimize the response of the system. The schematic

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of the detector amplification circuit and the second stage linear amplifier, as well as an additional bias (offset) circuit are shown in Fig. 1.

2 THEORETICAL ANALYSIS OF THE PYROMETER LIMITATIONS.

Wien's approximation can be used to explore the limits of the resolution of the pyrometer when examining events whose temperatures are close to the furnace wall temperature (low-temperature carbon oxidation, etc.). It is desirable, in principle, to estimate the relative contributions of the emitted radiation of the particle to that reflected from the wall on the particle. Also this calculation can help to estimate the lowest particle temperature that the instrument can detect.

It should be kept in mind here that the radiation flux (photons) from all sources in the furnace that reaches the photodetectors is additive. Thus, converting fluxes in electrical signals we have: $S_{\lambda Total} = S_{\lambda r} + S_{\lambda f} + S_{\lambda p}$, where subscripts r , f and p designate room, furnace and particle, respectively. For the present system the radiation flux from the laboratory lights, $S_{\lambda r}$, was negligible. Despite efforts to eliminate the background furnace radiation, $S_{\lambda f}$, some was always present emanating from multiple reflections. This radiation is the cause of the baseline signal.

From Wien's approximation the total radiation flux originating from a particle consists of that emitted from the particle plus furnace radiation reflected on the particle surface:

$$\begin{aligned} (S_{\lambda p})_{total} &= (S_{\lambda p})_{emitted} + (S_{\lambda p})_{reflected} \\ &= \epsilon_{\lambda}(\pi d_p^2) \left[C_1 \lambda^{-5} \exp\left(-\frac{C_2}{\lambda T_p}\right) \right] \frac{\pi d_l^2/4}{4\pi L^2} \eta_L \eta_D \Delta\lambda \\ &\quad + \rho_{\lambda}(\pi d_p^2) \left[C_1 \lambda^{-5} \exp\left(-\frac{C_2}{\lambda T_w}\right) \right] \frac{\pi d_l^2/4}{4\pi L^2} \eta_L \eta_D \Delta\lambda \end{aligned} \quad (1)$$

where d_p is the particle diameter, d_l is the diameter of the lens, L is the distance between the lens and the particle, ρ is the particle reflectivity, T_p and T_w are the particle and furnace wall temperatures, respectively. Subsequently, the relative strength of the reflected and emitted fluxes can be expressed after cancelling out all common terms as:

$$\frac{(S_{\lambda p})_{emitted}}{(S_{\lambda p})_{reflected}} = \frac{\epsilon_{\lambda} \exp\left(-\frac{C_2}{\lambda T_p}\right)}{\rho_{\lambda} \exp\left(-\frac{C_2}{\lambda T_w}\right)} \quad (2)$$

Assuming $\epsilon_\lambda \approx 0.8$ and $\rho_\lambda \approx 0.2$ and T_w equal to 1500 K the following table can be obtained for $(S_{\lambda p})_{emitted}/(S_{\lambda p})_{reflected}$ at various T_p :

$(S_{\lambda p})_{emitted}/(S_{\lambda p})_{reflected}$			
T_p (K)	$\lambda = 0.650\mu\text{m}$	$\lambda = 0.800\mu\text{m}$	$\lambda = 0.975\mu\text{m}$
1500	4.0	4.0	4.0
1550	6.4	5.9	5.5
1600	10.1	8.5	7.4
1700	22.7	16.4	12.8
2000	160.1	80.1	46.8
2500	1,464	484	204

It can be seen that at $T_p = T_w$ the particle signal will be four times the signal caused by wall reflections on the particle(!), under the above assumptions. At $T_p \gg T_w$ the contribution of the latter is negligible.

It is of interest to estimate the minimum source temperature that the pyrometer is able to resolve. The corresponding signal should be strong enough to overcome the noise level. This result can be obtained through the analysis of any given experimental profile, for example Fig. 12. A reference point in the signal is chosen, say the maximum, and its amplitude is compared to that of the minimum signal having amplitude equal to the noise level. The source temperature of the latter can be solved for by taking the ratio of the two signals as follows:

$$\frac{(S_{\lambda p})_{total,min.}}{(S_{\lambda p})_{total,ref.}} = \frac{\epsilon_\lambda \exp(-\frac{C_2}{\lambda T_{p,min.}}) + \rho_\lambda \exp(-\frac{C_2}{\lambda T_w})}{\epsilon_\lambda \exp(-\frac{C_2}{\lambda T_{p,ref.}}) + \rho_\lambda \exp(-\frac{C_2}{\lambda T_w})} \quad (3)$$

The source temperature at the peak of the signal in Fig. 12 was calculated to be 2700 K. Therefore, the minimum particle temperature that results in a signal, $(S_{\lambda p})_{total,min.}$, higher than the noise level was estimated to be: $T_{p,minimum}$ is $\approx 1650\text{K}$ at $\lambda = 0.65\mu\text{m}$ and $\approx 1600\text{K}$ at $\lambda = 0.975\mu\text{m}$ i.e 100 to 150 K above T_w . However, if the low-pass filters are removed the weakest channel of the pyrometer, i.e. $0.65\mu\text{m}$, will detect a $T_{p,minimum} \approx 2100\text{K}$ (!) because of the low signal to noise ratio. The other two channels will detect $T_{p,minimum} \approx 1650\text{K}$.

Errors in the two-color pyrometry may arise from many sources. Emittance errors may arise because char particles are neither blackbodies nor graybodies. In color py-

rometry the particle's true temperature, T , can be deduced from the apparent (color) temperature, T_{A1} using Wien's law and accounting for the emissivity of carbon, ϵ_{λ_1} , at a wavelength λ_1 :

$$\frac{C_1}{\lambda_1^5} \exp\left(\frac{-C_2}{\lambda_1 T_{A1}}\right) = \epsilon_{\lambda_1} \frac{C_1}{\lambda_1^5} \exp\left(\frac{-C_2}{\lambda_1 T}\right) \quad (4)$$

thus

$$T = \frac{1}{\frac{1}{T_{A1}} + \frac{\lambda_1}{C_2} \ln \epsilon_{\lambda_1}} = \frac{1/\lambda_1}{\frac{1}{\lambda_1 T_{A1}} + \frac{1}{C_2} \ln \epsilon_{\lambda_1}} \quad (5)$$

Similarly for the same target at a second wavelength one may write:

$$T = \frac{1}{\frac{1}{T_{A2}} + \frac{\lambda_2}{C_2} \ln \epsilon_{\lambda_2}} = \frac{1/\lambda_2}{\frac{1}{\lambda_2 T_{A2}} + \frac{1}{C_2} \ln \epsilon_{\lambda_2}} \quad (6)$$

And since when $\frac{a}{b} = \frac{c}{d}$, it also $\frac{a+c}{b+d} = \frac{a-c}{b-d}$ one can deduce from Equations 11 and 12 that

$$T = \frac{2}{\frac{1}{T_{A1}} + \frac{1}{T_{A2}} + \frac{1}{C_2}(\lambda_1 \ln \epsilon_{\lambda_1} + \lambda_2 \ln \epsilon_{\lambda_2})} = \frac{1/\lambda_1 - 1/\lambda_2}{\frac{1}{\lambda_1 T_{A1}} - \frac{1}{\lambda_2 T_{A2}} + \frac{1}{C_2} \ln \frac{\epsilon_{\lambda_1}}{\epsilon_{\lambda_2}}} \quad (7)$$

For gray bodies $T_{A1} = T_{A2}$ and $\epsilon_{\lambda_1} = \epsilon_{\lambda_2}$ then for a two-color pyrometer the color temperature equals the true temperature. This assumption can be shown valid, by differentiating either Eqs. 18 or 19 for T_A with respect to the emissivity ratio, $\epsilon_{\lambda_1}/\epsilon_{\lambda_2}$. If this emissivity ratio is close to unity and the uncertainties in ϵ_{λ_1} and ϵ_{λ_2} are in the same direction, then the apparent and true temperatures are very close. The emissivity ratios for carbonaceous materials at the wavelengths employed in this work appear to be close to unity.⁴¹

In the case of the three color pyrometer, intensity ratios from the tree different combinations of wavelengths (975/800 or 975/650 or 800/650 nm) occasionally result in diverse calculated particle temperatures. This may be due to the uncertainty of the particle emissivities at those wavelengths. It is possible to compare, theoretically, the accuracy of the temperature measurement for the three different wavelength ratios in an approach outlined by Sarofim and co-workers.^{32,33} Equation 9 can be written as:

$$T = \frac{B}{\ln(R_1, R_2, \dots)} \quad (8)$$

where, $B = C_2(1/\lambda_2 - 1/\lambda_1)$ and $R_1 = S_{\lambda_1}/S_{\lambda_2}$, $R_2 = \epsilon_{\lambda_2}/\epsilon_{\lambda_1}$, etc. The fractional uncertainty of temperature can be expressed for any of the above ratios, R_x , as:

$$\frac{dT}{T} = \frac{1}{\ln(R_1, R_2, \dots)} \frac{dR_x}{R_x} = \frac{T}{B} \frac{dR_x}{R_x} \quad (9)$$

where the latter part of the equation follows by substitution from Eq. 21. Thus, the uncertainty in temperature increases linearly with temperature, everything else kept constant, and is also greater for closely-spaced wavelength pairs. Thus, the pair 975/650 appears to be the most accurate in the present pyrometer, followed by the 975/800 pair. Results of this calculation are shown in Fig. 2. Thus, the 975/650 wavelength pair is less prone to be affected by uncertainties in emissivity or other parameters by a factor of 2-3 times less than the other pairs. Furthermore, it can be seen that uncertainties are higher at higher temperatures, 3-4 times more at 3000 K than at 1000 K, for all pairs.

Errors may also arise in the calibration procedure; therefore, the standard deviation from multiple calibration runs should be recorded. Furthermore, errors may arise as a result of the environment of the pyrometer. Dust, vapors and smoke particles in long transmission paths between the source and the instrument can affect the chroma of radiation by selective absorption or scattering; moreover, particles may reflect background radiation into the optics of a two-color pyrometer and create erroneous signals. The present design is not affected by absorption of vapors, since none of the filter windows overlaps with any of the absorption bands of CO₂ or water vapor. Besides, smoke or ash particles that arise from combustion of coal volatiles, fragmentation of the residual chars and vaporization of ash should bear no influence on the pyrometric observations presented herein, since all experiments were executed in the single particle mode.

3 PRODUCTION OF PRE-DRIED CWF AGGLOMERATES WITH SUBSEQUENT PARTICLE HEATING STUDIES

Dry coal water fuel (CWF) agglomerates were generated in a thermal reactor available in our laboratory, as described in the last report. Droplets of various sizes were generated in the furnace and the dry CWF agglomerates were collected and size-classified under the microscope. CWF agglomerates containing CMA were also produced with a similar technique. The CMA concentration in that slurry was 6.4% and the coal content was 33.6%, i.e. a total of 40% solids loading. Given the sulfur

content of the coal 0.86% the Ca/S ratio was 2. In the dry agglomerate the fraction of CMA by weight is 16%. SEM micrographs of both kinds of particles are shown in Fig. 3 and 4.

4 PARTICLE HEATING EXPERIMENTS - PARTICLE SWELLING

Particle heating experiments were conducted by passing single CWF agglomerates of known size (measured under an optical microscope) through the drop-tube furnace at $T_w = 1500K$, $T_{gas} = 1450K$. The total gas flow rate was 2 lpm. Agglomerate particle size ranged between 400 and 600 μm in this experiments. The residence time of these particles in the hot zone of the furnace was estimated to be ≈ 150 to 200 ms, estimating an agglomerate average density of 0.5 g/cm³. The rate of heating was calculated to be over 10^5 degrees K/sec. Swelling factors ranging from 1.04 to 1.2 were observed, Fig. 5 and 6. Close examination of the surface shows strong evidence of melting accompanied with the formation of a hard cell with volatiles escaping through blowholes.

It was very interesting to notice that CWF treated with CMA did not show any melting or swelling effects. Formation of globules of molten mineral matter on the surface is evident, Fig. 7. This phenomenon is currently under further investigation.

5 CONSTRUCTION OF A PARTICLE FLUIDIZER APPARATUS

For future experiments in this project clouds of particles it will be necessary to introduce clouds of particles in the furnace at a constant feed rate, in the order of grams per hour. Combustion of clouds of particles will then take place at conditions similar to those of single-particle combustion. This will facilitate exploring the influence of particle temperature, kinetics and residence time in the post combustion zone on pollutant formation.

A fluidization apparatus has been constructed to fluidize the coal into the laminar flow furnace. The fluidization medium is compressed gas (air, N₂, etc.) at 1 bar gage pressure. The gas flow is measured by a rotameter and is regulated by an inlet valve. Figure 8 shows in detail the various components of this apparatus. Figure 9 shows how this system is interfaced with the furnace.

- Part A is the moving part of the syringe pump *Sage* and is in direct contact with

a glass vial (test tube) containing the powder that needs to be fluidized (coal, sorbents, etc.) and is used to move the vial upwards at a constant velocity. The syringe pump allows different velocities by which different powder fluidization rates can be achieved.

- Part B and C are couplings connected to a mechanical vibrator and their is to keep the powder in the vial at constant vibration to ensure smooth and uninterrupted flow of the particles.
- Part D is a brass piece with a *Cajon* fitting brazed at the bottom. The vial moves up linearly within the fitting sliding against the “O-ring” that exists inside the *Cajon* fitting to provide sealing.
- A 1/8 in. i.d., beveled tube serves as the feeder to the furnace. The tip of the tube has to always be slightly immersed under the surface of the powder for proper operation of this fluidizer.

To calibrate this instrument the powder that was fluidized was collected on a small beaker placed on an electronic balance (*Mettler*). At this time the calibration was done manually. The balance was used to record the weight of the powder collected at regular intervals of 1 minute. The fluidization rates were controlled by changing the rate of displacement of the vial (by regulating the syringe pump) and by adjusting the air-flow accordingly. This calibration has to be repeated for every powder used, since it is expected to be influenced by the particle size and density. Typical results obtained with 1451 bituminous coal, 45-53 μm in diameter, are shown in Figs. 10-12. The flow of coal (g/min) was plotted against time to obtain the calibration curves. At this moment we are purchasing a data acquisition card from *Mettler* in order to allow us to perform electronic data taking.

PRESENT WORK and FUTURE PLANS At present work is being conducted on (a) improving the pyrometer signal to noise ratio, (b) signal analysis, (c) development of further pyrometer calibration techniques, (d) development of a technique to observe the water vaporization times in CWF drops, and (e) production of an inventory of dry CWF drops with and without CMA from two different coal grids.

PHOTODETECTOR CIRCUIT 7181 Oriel

LINEAR AMP. CIRCUIT AD524 AD.

BIAS CIRCUIT 353 R.S.

Figure 1: Current status of the pyrometer electronics at each channel.

Figure 2: Pyrometer accuracy plot.

Figure 3: *SEM micrographs of CWF particles without CMA*

Diameter = $360\mu\text{m}$

Magnification

190

3000

mi
Sw
Sw

Initial diameter = $510\mu\text{m}$
Swelled diameter = $527.5\mu\text{m}$
Swelling factor = 1.044

Magnification

150

3000

**FIGURE-3: COAL FLUIDIZATION APPARATUS
(NOT TO SCALE)**

Figure 8: Particle fluidizer system, schematic.

Figure 9: *Particle fluidizer system, photograph.*

Figure 10: Particle fluidizer system, calibration.

Figure 11: Particle fluidizer system, calibration.

Figure 12: Particle fluidizer system, calibration.

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