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**PARTICULATE BEHAVIOR IN A CONTROLLED-PROFILE PULVERIZED COAL-FIRED
REACTOR: A STUDY OF COUPLED TURBULENT PARTICLE DISPERSION AND
THERMAL RADIATION TRANSPORT**

Quarterly Technical Progress Report
for Period June 15, 1992³ to September 14, 1993

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FORWARD

This report summarizes technical progress during the seventh quarter (March 15, 1992 to June 14, 1993) of a three-year study conducted for the Department of Energy (DOE) under contract number DE-FG22-91PC91308. The principal investigators for this work are Dr. Mardson Queiroz and Dr. Brent W. Webb; Dr. Clifford Smith is the technical representative for DOE.

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ABSTRACT

During the eight quarter progress has been made in the following areas: preparation trial runs and acquisition of experimental data.

1. OBJECTIVES AND SCOPE

1.1 BACKGROUND

Improved understanding of the fundamental processes involved in pulverized-coal combustion is needed to make the energy extraction more efficient and the combustion byproducts environmentally safe. While the characterization of the local particulate behavior (concentration, size, and velocity) is important to the understanding of virtually all processes in a pulverized coal-fired furnace, it influences in a more direct way the turbulent particle dispersion and thermal radiation heat transfer. Yet the local particulate dynamics have gone relatively unaddressed, primarily because of lack of adequate instrumentation to carry out such a study. With recent advances in optical techniques such an effort is now possible. This proposal seeks to characterize the local particulate concentration, velocity, and size distribution in a well-controlled, parametrically-varied laboratory-scale reactor using a new laser diagnostic technique. This newly-developed technique is the only one currently available for the investigation of aspherical particles. The particulate data will be collected simultaneously with local gas temperature and wall radiant heat flux distributions.

1.2 OBJECTIVES

This report describes recent progress in a fundamental, three-year investigation of the coupled problem of turbulent particle dispersion and thermal radiation transport. The project's objective is to make measurements of particle size, velocity, number density, temperature and wall radiant heat flux in a parametrically-controlled reactor presently existent at Brigham Young University (BYU). Although the study proposed here is primarily designed to provide experimental data not currently available for the evaluation of turbulent particle dispersion and radiation models, comparisons of analytical predictions and the experimental data obtained will be performed, using appropriate submodels integral to comprehensive pulverized-coal combustion codes existent at BYU.

1.3 TECHNICAL APPROACH

To accomplish the above objectives, the project is divided in the following tasks:

- Design and fabrication of a modified section for the BYU controlled-profile reactor, which will allow access of several probes to be used in the proposed study.
- Design and fabrication of a two-color pyrometer and cooled probe for local particulate temperature measurement.
- Characterization of the non-reacting turbulent flow field in the reactor using the PCSV-P probe, which will serve as an input during the turbulent particle dispersion submodel validation.
- Literature review dealing with particle dispersion and radiation transport in support of the model validation effort.

- Perform the parametrically-controlled measurements in the controlled-profile reactor.
- Experimental data analysis.
- A comprehensive comparison of experimental data and model predictions.
- Final report.

2. SUMMARY OF TECHNICAL PROGRESS

2.1 CONTROLLED PROFILE REACTOR

Testing on the CPR using Pitt #8 coal was completed this quarter. Combustion characteristics of this coal required combustion to take place at an air/fuel equivalence ratio of 0.75 (fuel-rich) in order to maintain a stable flame. The reason for this difficulty in burning at higher equivalence ratios is still under investigation. Flame symmetry was established during testing using suction pyrometer measurements, and was checked at various times throughout the test. Repeatability measurements were also made. These tests showed that running on coal for four hours after warm up was necessary to ensure constant wall temperatures. The PCSV-P was used to measure radial profiles of velocities and number density distributions for particles between 0.4 and 98 microns at three axial locations in the CPR. The particle velocities were measured as the average small particle (0.4-3.5 micron) and large particle (3.5-98 micron) velocities. The analysis of the data taken during these tests has not been completed.

The coal feed system was revised again before testing. The Acrison auger feeder used to deliver the coal was calibrated according to the armature setting on the feeder motor. Variability and repeatability of this method were established by taking several manual measurements over an extended period of time. It was shown that the error associated with this method was less than 4% over one minute intervals. The small error was attributable to the excellent armature feedback supplied by the Acrison controller board.

2.2 TRANSMISSOMETER DEVELOPMENT

Transmission measurements were taken with the intrusive probe previously designed. Extinction of the beam through the diagnostic volume was so small that it was difficult to resolve. The only feasible solution was to increase the length over which the beam passed through the reactor region. Multiple passes through the diagnostic window of the existing probe was impractical due to optical alignment difficulties. Instead, a platform was constructed on either side of the CPR upon which the laser and associated optics were mounted. The beam was passed through the entire reactor and the extinction was measured on the other side. Using this method, the signal to noise ratio in the reading was substantially increased while still remaining below the limits of multiple scattering. Data was obtained on a time-resolved basis at a sampling frequency of 2000 Hz, allowing for resolution of frequency data below 1000 Hz. Aliasing of higher frequencies was eliminated by introducing an analog low-pass second order

Butterworth filter with a cutoff frequency of 1000 Hz. Several sets of time-resolved data were taken at the test condition and are now undergoing statistical and frequency analysis.

2.3 PARTICLE TEMPERATURE MEASUREMENTS

Particle temperature measurements have been taken using a two-color pyrometer with wavelengths of 1.27 and 1.6 microns. The original diagnostic volume, 10 cm in length, was modified to extend all the way across the reactor. Readings taken with this larger diagnostic volume produce larger signals lower in the reactor where there are cooler temperatures. Readings were also taken with the smaller diagnostic volume to give spatial resolution. Temperature data was taken on a time averaged and a time resolved basis. The analysis of the data will include calculations of mean temperatures, standard deviations, power spectral densities, and probability density functions.

2.3 RADIATION AND PARTICLE DISPERSION MODELLING

Sloan (1985) studied the performance of the $k-\epsilon$ model for strongly swirling flows. His results indicate that the prediction of the $k-\epsilon$ model is generally poor in the near burner region. Simulations performed by Costa *et al.* (1990) for a swirling, pulverized-coal flame also indicated the predictive deficiency of the $k-\epsilon$ model in the near burner region. However, they managed to obtain relatively better predictions by reducing the swirl number for the simulation. The $k-\epsilon$ model is also used in PCGC-2 to solve the gas-phase equations. Since the particle dispersion model is coupled with the gas-phase equations, any deficiency in gas-phase predictions will affect the dispersion predictions. Therefore, in order to establish the effect of swirl number on gas-flow predictions as well as on the dispersion statistics, simulations for the reacting flow cases were performed for two different swirl numbers. The swirl number used for these simulations included the experimental swirl number of 1.4 and a reduced swirl number of 0.8. The reduced swirl number of 0.8 was selected after extensive investigations.

The results discussed here are for the reacting base case (Hcase1). Figure 1 (a) and (b) shows the predictions of gas flow pattern along with the particle trajectories for swirl numbers 1.4 and 0.8, respectively. These plots show that the main features of the flow predictions are a strong internal reverse-flow zone (induced by the swirl imparted to the secondary air) and an external recirculation zone (caused by the sudden enlargement of the furnace chamber). The strength and size of the internal reverse-flow zone predicted by the $k-\epsilon$ model for a swirl number of 1.4 is definitely greater compared to a swirl number of 0.8. This results in a relatively less penetration of the primary jet containing the coal particles into the internal reverse-flow zone for the higher swirling case. Also, the predictions show that the particles are dispersed further away towards the reactor wall for the larger swirl number. The strength of the internal reverse-flow zone is also depicted in Figure 2, which compares the gas axial velocities for the two different swirl number predictions inside the penetration zone. The figure shows that the magnitude, and hence

the strength of the recirculation velocity, is higher for the high swirling case. These high negative velocities reduce the axial penetration of the primary jet along with the coal particles for the larger swirl number. There does not appear to be any significant difference between the external recirculation zones predicted for the two cases (Figure 1 (a) and (b)).

The first set of comparisons between the experimental data and the predictions consists of comparing the measured small particle velocity data with the predicted gas axial velocity. The probe used during the experimental study was rotated through a known angle to align the flow channel of the probe with the mean flow, it was necessary to estimate the axial velocity component in order to carry out these and any further velocity comparisons with the predictions. The axial velocity was computed as the product of the measured velocity times the cosine of the angle made by the probe with the vertical direction.

Figure 3 (a) and (b) show the comparison between the experimental small particle axial velocity with predicted gas axial velocity for swirl numbers 1.4 and 0.8 at two different axial locations. The axial location of 0.3 meters is around the penetration zone, whereas the axial location of 1.9 meters is at a location farther downstream. It is evident from Figure 3 (a) that predictions for the two different swirl numbers differ significantly in a region close to the reactor centerline. As for the comparison with the experimental data, the lower swirl number case (0.8) appears to agree with the experiments from the centerline up to a region just before the predicted gas flow reverses its direction. It should be noted at this point that the experimental probe used for this study was intrusive in nature and was not capable of recording velocities in the reverse direction. Bonin (1992) has estimated the effect on probe intrusion on the measurement of gas-phase velocity. He used a hot film anemometer to measure the gas velocities for both swirling and non-swirling flows with and without the PCSV-P cooling jacket. His results showed that the impact of probe intrusion on measurements can be as high as fifty percent. For further details of this study one should refer to the above-mentioned reference. Therefore, the probe intrusion and the inability of the probe to record negative velocities are important factors to consider while making such comparative evaluations. The axial distance 0.3 meters is outside the penetration zone and within the internal reverse-flow zone for the swirl number of 1.4, and hence, its predictions differ very significantly with those observed experimentally. This observation suggests that the penetration could be under predicted for the 1.4 swirl number case.

Figure 3 (b) shows that the experimental data and the predictions for both cases relate fairly well farther downstream. This is a region where there is no reverse flow for swirl number 0.8 case and a small region of reverse flow near the centerline for the 1.4 swirl number. The comparisons agree very well, considering the restrictions imposed by the probe intrusion effect.

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Figure 1. Predicted gas flow pattern along with the particle trajectories for two different swirl numbers (1.4 and 0.8).

Figure 2. Gas axial velocity comparison for Hcase1 between two different simulation swirl numbers (1.4 and 0.8), at an axial distance of $x = 0.13$ m.

Figure 3. Comparison between the predicted gas axial velocity and the experimental data for small particle velocity for two different simulation swirl numbers (1.4 and 0.8) for Hcase1 at axial distances of (a) 0.3 m and (b) 1.9 m.

4. APPENDIX

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