**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, 1995 to September 14, 1995

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FORWARD

This report summarizes technical progress during the sixteenth quarter (June 15, 1995 to September 14, 1995) 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 sixteenth quarter progress has been made in the area of turbulence modeling and in data reduction of heat flux measurements. A multiple-time-scale turbulence model was developed for axisymmetric, swirling flows.

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 Multiple-Time Scale Model for Turbulent Swirling Flows

The standard k - ϵ model is single-time scale turbulence model, i.e., only one time scale is used to describe both the turbulent transport of mass and momentum and the dissipation of the turbulent kinetic energy. As a result of this their predictive capability degenerates rapidly for complex flow situations such as the case of swirling flows (Kim, 1991). Swirl burners are normally used in combustion systems such as pulverized coal reactors. This is because swirling flows facilitate flame stabilization and good mixing between fuel and oxidizer. Hence in comprehensive coal combustion codes it is necessary to have a turbulence model which is capable of accurately predicting swirling flows. For this reason a Multiple-Time-Scale (MTS) turbulence model which accounts for generation, cascade and dissipation of turbulent kinetic energy was developed. This model was incorporated into the 1974 Imperial College TEACH (teaching elliptic axisymmetric characteristics heuristically) computer program (Gosman & Ideriah, 1974). The TEACH code was also modified to account for swirling flows. This was done by adding a subroutine for solving the azimuthal momentum equation with appropriate wall functions for boundary conditions. Also the source term for the radial momentum equation was modified to account for the effect of swirl. The equations for swirling flows can be found in Lilley and Rhode (1982).

The MTS model developed here is same as the one proposed by Kim and Chen (1989) and is based on simplified split-spectrum method. In this turbulence model the turbulence field is described by four partial differential equations for turbulent kinetic energy of large eddies (k_p), the turbulent kinetic energy of fine-scale eddies (k_f), the energy transfer rate (ϵ_p), and the dissipation rate (ϵ_f). It has been shown by Kim and Chen (1989) that this MTS model yields significantly improved computational results as compared to the standard k - ϵ model for a number of complex flows including swirling flows. The MTS model developed was studied for the case of backward facing step (Kim *et al.*, 1980) and coaxial swirling jets (Roback & Johnson, 1983). Figure 1 (a) and (b) illustrates the velocity vectors for the case of backward-facing step using standard k - ϵ and MTS model respectively. For a grid of 75 x 50 using an expansion factor of 1.05 for the axial grid cells the calculated reattachment using the MTS model was 7.62H, where H is the step height (0.0381 meters). This value is almost identical to the experimentally observed value of 7.6H (Avva *et al.*, 1988). For the same grid the standard k - ϵ turbulence model give the reattachment length to be 5.48H.

2.2 Convective-Radiative Heat Transfer Partitioning

From the total and radiative heat flux measurements the convective heat flux to the reactor walls was calculated. These calculations were determined using a data reduction scheme developed by Butler (1992). The convective heat flux to the probe is equal to the difference of the total and radiative fluxes measured by the probes. Using this value and the local wall and gas temperatures a convective heat transfer coefficient can be calculated. This coefficient corresponds to the convective heat transfer between the reactor gasses and the probe and is temperature dependent. In order to use it for convective heat transfer to the walls it has to be adjusted by the ratio to the 4/10ths power of the average temperature of the probe and the combustion gasses divided by the average temperature of the wall and the combustion gasses. This convective heat transfer coefficient can then be used to calculate the convective heat transfer to the walls which is the new coefficient times the temperature difference between the combustion gasses and the walls. The radiative heat flux plus the convective heat flux to the walls is the total heat flux to the walls.

The measurements of the total, convective and radiative heat flux in the reactor are shown in Fig. 2. Data shown are representative of multiple measurements made throughout the testing periods. The graph of total heat flux shows the combined convective and radiative transfer to the probe. A constant total heat flux for the top three ports is followed by a smooth decay as axial distance from the quarl increases. The radiative measurements show a constant decay of radiative heat flux with increased separation distance from the quarl. These measurements make sense in light of other measurements and visual observations. The convective part of the total heat flux is a function of the gas velocity and the temperature difference between the gas and the probe. Near the wall, where the measurements were taken, the gas temperature reaches a maximum at the third port. The flow field at this point provides high velocities to enhance heat transfer. Therefore, the convective heat flux reaches a maximum at this port and then decreases as the gas temperature decreases. The radiative heat flux is independent of the gas temperature. It is only affected by the particle and wall temperatures. At the top port the reaction zone is in direct line with the probe. The reaction is so intense that the medium is optically thick in the visible and the probe is effectively shielded from the far wall of the reactor. Therefore, it only measures heat flux from the hot reaction zone. At the lower ports the reaction zone is not optically thick, causing most of the incident radiative flux to come from the reactor walls. Since the reactor walls decrease in temperature with increased distance from the quarl, the radiative flux to the walls also decreases. The flat zone of almost constant total heat flux in the top three ports is a result of the above mentioned observations. The convective heat transfer increases in the top three ports are offset by the decreases in the radiative heat transfer. Below port 3, the lack of reaction and the cooler wall temperature causes an overall decrease in heat flux to both probes.

The heat flux to which the wall is exposed is different than the heat flux to which the probe is exposed. The probe temperature is kept near 30°C , while the average wall temperature varies linearly from 1300 K at the top of the reactor to 1100 K at the bottom of the reactor. The change in temperature gives rise to a large difference in the magnitude of the convective heat flux to the wall and to the probe. This can be seen by the difference between the line showing total heat flux to the probe and total heat flux to the wall. In the top of the reactor the wall temperature was hotter than the gas temperature causing convective heat transfer from the walls to the gas. This shows up as negative convective heat transfer to the walls. As can be seen in Fig. 2, the total heat flux to the walls is almost identical to the radiative heat flux. This indicates that heat transfer within the reactor is dominated by radiation.

LIST OF FIGURES

Figure 1. Velocity vector plot for the problem of turbulent backward facing step with step height of 0.0381 meters: (a) using standard k- ϵ model and (b) using MTS model.

Figure 2. Radiation, convection, and total heat flux measurements as a function of axial position in the reactor.

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Figure 1 (a)

Figure 1 (b)

Figure 2