TEMPERATURE, VELOCITY AND SPECIES PROFILE MEASUREMENTS FOR REBURNING IN A PULVERIZED, ENTRAINED FLOW, COAL COMBUSTOR

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Program Manager
Franklin Shaffer

Principle Investigator
Dale R. Tree

Contracting Officers Representative (COR)
Franklin Shaffer

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Disclaimer

Abstract

Measurements of effluent NO_x, CO, and O_2 have been obtained for various reburning locations in the controlled profile reactor. The location of the reburning zone and tertiary air zone have been varied to find an optimal location for detailed reburning profile measurements. NO_x reduction of greater than 70 % has been seen with natural gas injection in and just below the primary combustion zone. Strategic injection of the natural gas for reburning reduces the residence time required for NO_x reduction but does not appear to increase the total NOx reduction capability of reburning. Modeling efforts continue in trying to match the modeling solution to the detailed baseline data taken in previous measurements. The use of more accurate measured boundary conditions did not appear to improve the model predictions greatly but the use of more detailed turbulence models was found to improve the predictions. The predictions are still far from matching the combustion measurements.

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Executive Summary

The effects of reburning on effluent NO_x have been characterized for a wide variety of reburning zone equivalence ratios and residence times. The high swirl condition (Swirl No. = 1.5) from the baseline cases was selected for the reburning tests. NO_x reductions above 70 % were realized. The highest NO_x reductions were achieved at high reburning zone equivalence ratios and long residence times in the reburning zone. There were marked improvements in NO_x reduction for longer residence times at the lower reburning zone equivalence ratios.

Modeling of the reactor with advanced combustion CFD codes has highlighted some problems with turbulence models, particularly at the high swirl number setting of 1.5. The standard k-ε model has not been able to predict the proper velocity flowfield for either reacting or non-reacting cases for flow with swirl.

Referring to the first semi-annual report of Oct. 1995 and Table 1 below, the first 6 of the 17 objectives have been met which were scheduled to have been completed in August of 1996. The project is therefore a little behind schedule but improvement should be realized over the summer as two students have virtually completed their coursework and will be able to devote more effort to their research. It is anticipated that by August, tasks 1 - 11 will be completed which were scheduled to have been done by May of 1997. One masters student, Lyle Pickett, has graduated in December with the LDA measurements being the main thrust of his thesis. A second masters student, Waseem Nazeer, will complete his work by August. He will complete the reburning species and temperature measurements while Robert Jackson, a Ph. D. student will take the reburning LDA measurements as part of his continuing work.

Table 1. Timetable for the accomplishment and assignment of milestones.

	1	9	9	5							1	9	9	6											1	9	9	7								1	9	9	8		
Task(s)	S	O	N	D		J	F	M	A	M	J	J	A	S	O	N	D		J	F	M	A	M	J	J	A	S	O	N	D		J	F	M	A	M	J	J	A
1 Baseline Map	G	G	G																																				
2 Baseline Prediction		J	J	J																																			
3 Baseline LDA						P	P	P	P	P																													
4 Model Eval.								J	J	J	J																												
5 Reburning Design	N	N	N	N		N	N	N	N																														
6 Test Reburning									N	N	N																												
7 Map with Reburning										G	G	G	G	G	G	G	G																						
8 LDA with Reburning										P	P	P	J	J	J	J	J																						
9 Converge Model														J	J	J	J																						
10 Eval. Reburning Model																			J	J	J	J																	
11 Adv. Reburning Design												S	S	S	S	S	S		S	S	S	S																	
12 Test Adv. Reburning																			S	S	S	S																	
13. Map Adv. Rbrng																						G	G	G	G	G													
14 LDA with Adv. Rbrng																							J	J	J	J	J	J											
15. Conv. Adv. Rbrng. Model																									J	J	J	J	J	J									
16. Comp. Adv. Rbrng. Model																									J	J	J	J	J	J									
17. Adv. Tamp. Meas.																																J	J	J	J	J	J	J	J

Key: G- Group Assignment J - Robert Jackson P - Lyle Pickett
N - Waseem Nazeer S - Student, Adam Clark

Two papers have been presented at the Western States Section of the Combustion Institutes spring meeting from work on the reactor since the last semi-annual report and two journal publications are underway. The publications included the LDA velocity data presented in the last semi-annual report and the baseline data set of species and temperature at the three swirl conditions.

1. Introduction

The overall objective of this work is to obtain a detailed data set of a realistic pulverized coal flame with reburning. The first phase of the work was to obtain a baseline set of data including species temperature and velocity. A unique feature of this data is that it includes LDA, mean and turbulent velocities at three swirl ratios. This provides a challenging and useful data set for modelling swirling flows. The next phase of the work is to obtain detailed measurements in the reactor with reburning. This has begun by measuring the overall effect of reburning on effluent NO_x for a matrix of reburning and tertiary air locations in the reactor. From this matrix, an operating condition for the detailed reburning measurements will be selected. Design and fabrication of the advance reburning injector has begun which is the third phase of this work.

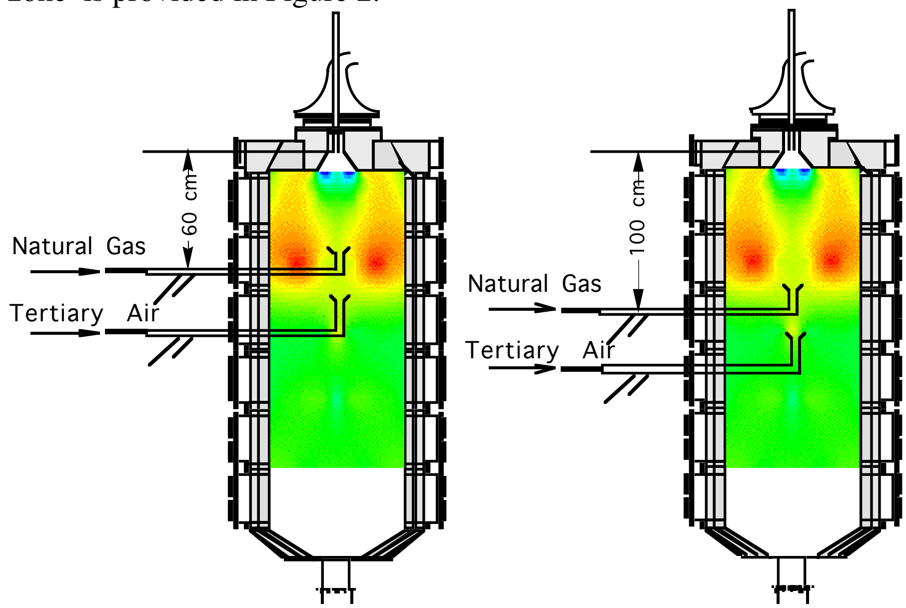
2. Results and Discussion

2.1 Effluent Emissions With Reburning

Typical reburning is achieved by creating three distinct zones within a reactor or boiler. The primary combustion zone where NO_x is formed, the fuel rich or reburning zone where excess fuel is used to reduce NO_x to elemental nitrogen and the tertiary zone where air is introduced to complete the combustion of the excess fuel added in the reburning zone. The purpose of the current series of measurements is to identify the optimal locations of the primary, fuel rich and tertiary zones to be used in the detailed profile measurements of reburning. Figures 1a and 1b show the controlled profile reactor cross section with a color contour map of measured NO concentration at 1.5 swirl obtained in previous measurements. A swirl of 1.5 has been selected for the reburning measurements because it produces a primary combustion zone which is complete near the top of the reactor allowing for a longer residence time in the reburning zone. With this 1.5 swirl condition as the baseline, locations for the fuel and tertiary air injectors are being tested.

Figures 1a and 1b show two axial locations tested for the natural gas injection at the centerline of the reactor. At positions A and B the natural gas (N.G.) is shown to be injected at an axial distance of 60 and 100 cm below the primary fuel tube inlet respectively. The fuel exits through a pintle type nozzle in the upward direction at approximately 45° to the centerline axis. The primary fuel / air jet is directed downward and radially outward toward the walls, approximately parallel to the walls of the quarl. Thus, the reburning fuel jet is expected to intersect the primary fuel jet in a cross flow at the upper location A and then flow into the region of highest measured NO_x concentration. At position B, the reburning fuel jet is directed at or just below the region of highest NO_x. Flow measurements also show this location to direct the natural gas just below the stagnation point of the primary fuel / air jet where the combustion gases recirculate toward the burner up along the centerline and along the outer reactor walls.

Gas samples were collected from the effluent using a stainless steel tube. The samples were drawn through the tube and passed through an ice bath and a water trap before entering an on-line electro-chemical gas analyzer. The sampled gases were O_2, CO, and NO_x. With the natural gas injected at location A, 60 cm below the primary tube, tertiary air injection was tested at three axial locations 82, 102 and 110 cm at four fuel flow rates while tertiary air was held constant at approximately 20 % of the primary air flow rate. With an initial value of 10 % excess air in the primary combustion zone, the addition of 20 % more air limited the reburning zone equivalence ratio to below 1.3 in order to maintain complete combustion. The overall equivalence ratio of the reburning zone was varied by increasing the natural gas flow rate, creating a reburning zone equivalence ratio which varied from the initial condition of 0.91 with no reburning to the maximum equivalence ratio of 1.31. A plot of percent NO_X reduction as a function of equivalence ratio in the reburning zone is provided in Figure 2.



(A) (B)

Figure 1. Schematic diagram of the CPR showing the location of the natural gas and tertiary air injection relative to the NOx concentration previously measured before reburning.

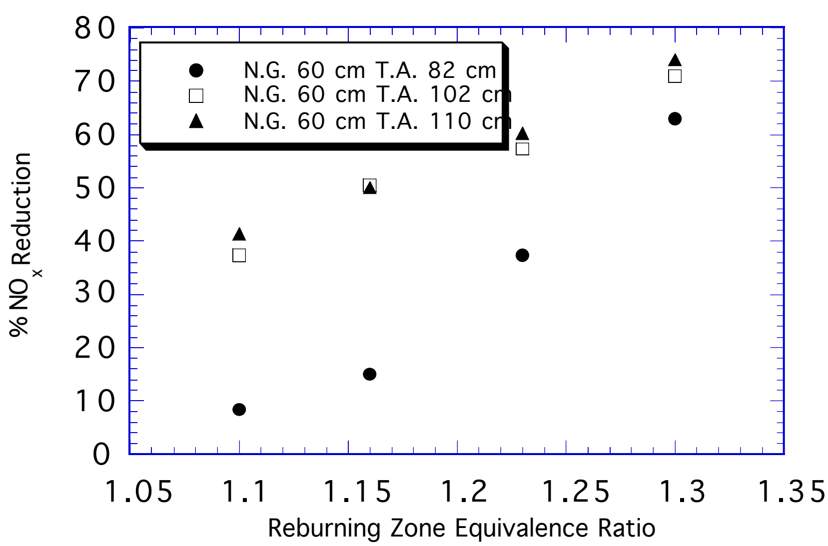


Figure 2: Effluent NO_X Reduction vs. Reburning Equivalence Ratio

The figure shows a dramatic reduction in NO_x is achieved as the equivalence ratio of the reburning zone is increased. At an equivalence ratio of 1.31 the NO_x reduction exceeds 70 %. When the tertiary air was located closest to the fuel injection location, NO_x reduction was reduced, indicating there was not enough residence time in the reburning zone or there was interference from the tertiary air in producing a fuel rich zone for reburning. At the two lower tertiary air location, the NO_x reduction was independent of the location.

With the fuel injected at location A, a typical reburning situation is not created in that the natural gas has the opportunity to inhibit the initial formation of NO_x rather than reduce the NO_x after it is formed. Thus, location A might be useful in studying strategic reburning or low NO_x burner design but is not as useful for studying reburning as might be retrofit on existing boilers. In order to address this concern, a fuel injection location was tested just below the primary formation zone of NO_x as shown by location B.

Results showing the NO_x reduction for several equivalence ratios and tertiary air location are shown in Figure 3. The fuel and air flow rates were varied as described for location A except the fuel was injected at an axial location of 100 cm and the tertiary air was injected at 120, 130 and 140 cm. The result show again a dramatic reduction in NO_x as the reburning zone equivalence ratio is increased. In this data however, the further away the tertiary air was from the reburning zone the greater the NO_x reduction. It is anticipated that as the distance of the tertiary air from the reburning zone increases, the NO_x reduction would reach a maximum as the residence time and mixing become sufficient to complete the reduction reactions. Future tests will investigate further axial locations for the tertiary air in order to find the maximum NO_x reduction location. The data at location B suggest the same high level of NO_x reduction can be achieved at this lower location but that the residence time needs to be longer. This may be due to the fact that location A inhibits NO_x formation and therefore requires less residence time or because location A mixes the NO_x and fuel more completely and at a higher temperature allowing for more rapid NO_x reduction.

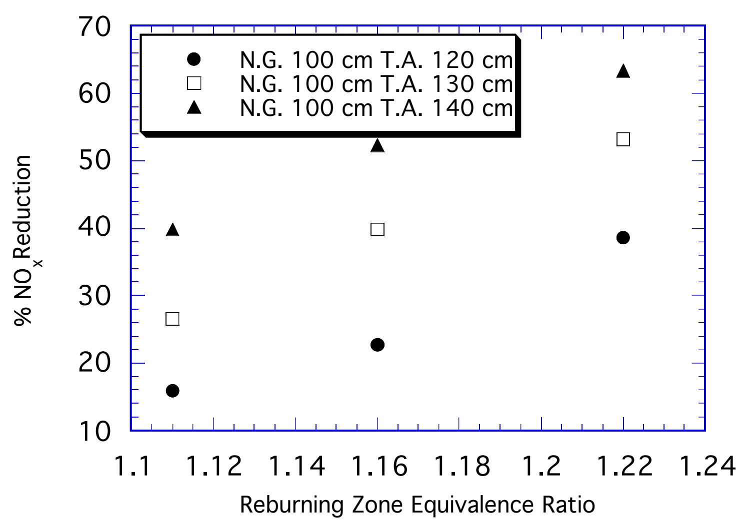


Figure 3: Effluent NO_X Reduction Vs. Reburning Equivalence Ratio

Although not a part of the originally planned work, it seems important at this point that this data set be expanded. There are numerous parameters which can be varied which would provide valuable data and insight into reburning. Fuel injection further downstream of position B, varied nozzle orifice diameters, tertiary air injection at further distance from the reburning zone, and higher tertiary air flows and thus higher equivalence ratios in the reburning zone are of interest. Also of interest are data of the unburned carbon in the ash often referred to as loss on ignition (LOI). As NO_x reduction strategies are implemented there would appear to be a fundamental trade-off between NO_x and unburned carbon. As NO_x is reduced it is always harder to burn out the carbon. Reburning is another example where this becomes important. It would be extremely valuable to learn under what conditions NO_x could be reduced without increased carbon in the ash. Because these topics are beyond the main focus of the project, much of this work will be left undone.

Future plans for this summer include profile mapping of the CPR for complete species profiles of CO_2, O_2, NO_x, CO, HCN, and NH_3. For HCN, and NH_3 analysis, water samples will be collected for each sample point and will be tested using the Ion Selective Method (ISE). Mapping of the reactor temperature and LDA velocity profile data are also planned for this summer. In addition, reburning will be tested for various axial locations for different equivalence ratios to find a point of maximum NO_x reduction.

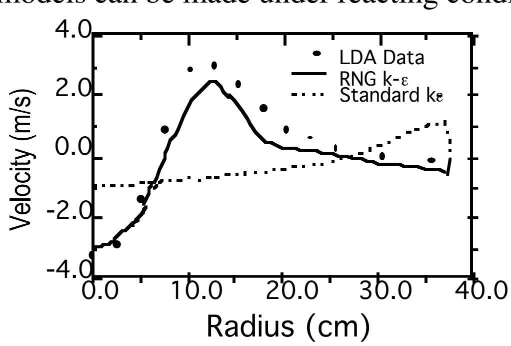
2.2 Modeling Efforts

Efforts to accurately predict the LDA measured flowfield using advanced combustion CFD codes have provided important insights. The turbulence model used has proved to have a rather large effect on the solutions. In contrast the inflow velocity profiles used as an inflow boundary condition (BC) proved to have a fairly minor impact on the solutions. Results of modeling efforts in these two areas are presented in this section.

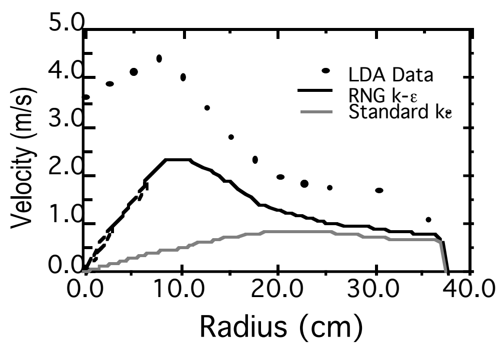
2.2.1 Turbulence Models

Two combustion CFD codes have been used to try and model the flow conditions in the CPR, FLUENT and PCGC-3. In trying to model the swirling flow cases, such as swirl = 1.5, both codes have had difficulty setting up the proper flowfield when using the standard $k-\varepsilon$ turbulence model . In addition to the standard $k-\varepsilon$ model a RNG $k-\varepsilon$ model and a non-linear $k-\varepsilon$ model have also been used. The RNG $k-\varepsilon$ model is available in FLUENT while the non-linear $k-\varepsilon$ model is available in PCGC-3. Both of these more advanced turbulence models show improvement over the standard $k-\varepsilon$ model.

According to the FLUENT User's Guide the RNG $k-\varepsilon$ model has significantly improved capabilities for handling the turbulence characteristics of the swirling flows in the present study. FLUENT was run with non-reacting flow and the results using both this RNG and the standard $k-\varepsilon$ model were compared to the cold flow velocity data (described in Oct. 1996 report). Effects of the turbulence model, especially in the top portion of the CPR, are quite dramatic. The RNG $k-\varepsilon$ solution more closely matches the LDA data as can be seen in Figure 4, which includes the radial profiles for both axial and tangential velocities at 22 cm below the primary inlet for the 1.5 swirl condition. The RNG model is able to match the shapes of both profiles, and matches absolute levels for the axial velocities. Although the magnitudes are not as accurate for the tangential velocity, the agreement is much better than with the standard $k-\varepsilon$ model. Efforts are underway to use FLUENT to model the full coal combustion case so that a comparison between these to models can be made under reacting conditions.



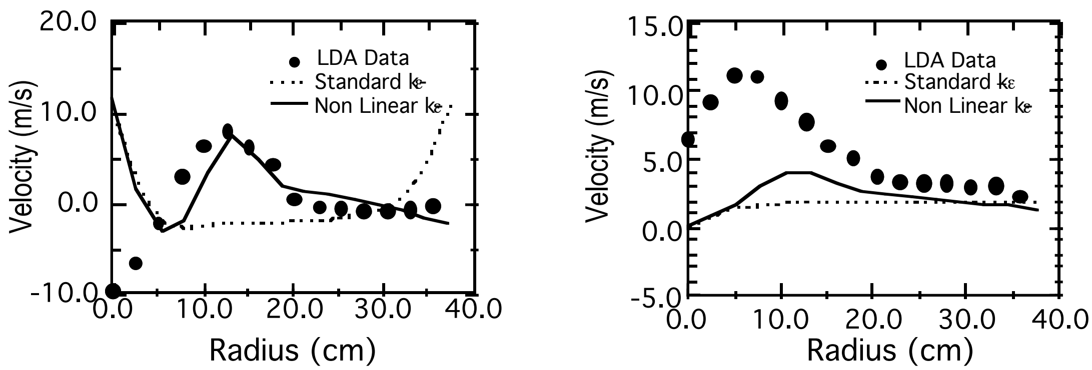
A) Average Axial Velocity



B) Average Tangential Velocity

Figure 4. Comparison of turbulence models from FLUENT with cold flow LDA data at 22 cm below the primary inlet for a swirl number of 1.5.

Reacting flow cases with coal have been modeled using PCGC-3 with both the standard k−ε model and a non-linear k−ε model . The results of these runs have been compared to the LDA data taken in the CPR under reacting conditions for the swirl = 1.5 condition. Comparisons of the velocity profiles in the upper portion of the CPR (at 22 cm below the primary exit) are included in Figure 5. While this non-linear k−ε model shows definite improvement over the standard k−ε model it still is not able to capture the true flow physics near the centerline. The recirculation, indicated by the negative axial velocities in the LDA data, is not predicted. By comparison with the RNG model predictions of the cold flow data (Figure 4) it is evident that this non-linear k−ε model does nearly as well except for this centerline region, where the RNG model did predict recirculation in the cold flow cases.

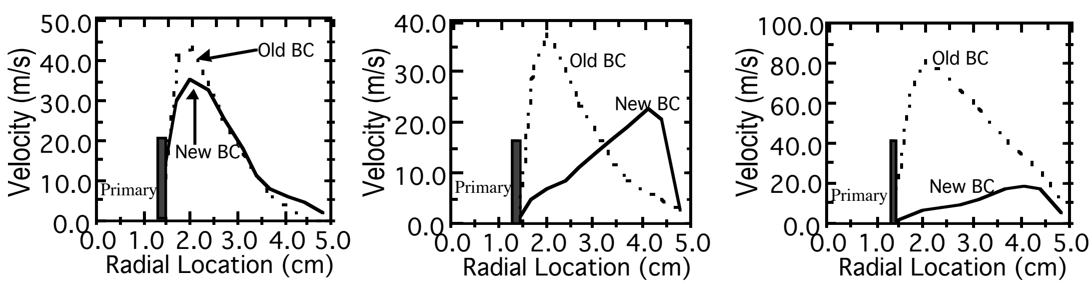


A) Average Axial Velocity B) Average Tangential Velocity

Figure 5. Comparison of turbulence models to LDA data for coal combustion cases.

2.2.2 Inflow BC

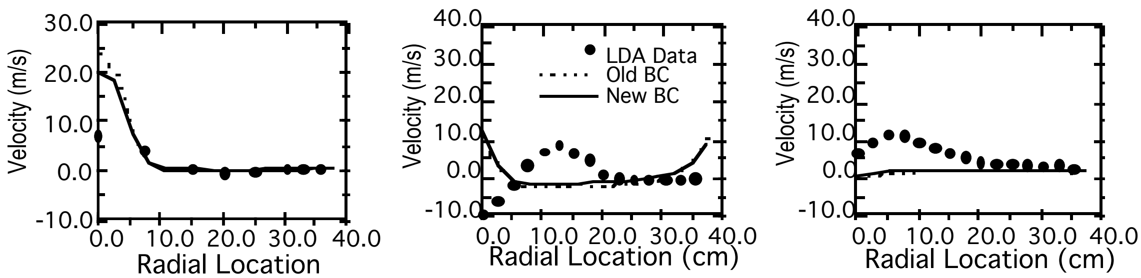
A comparison of the old and new BC velocity profiles is provided in Figure 6 for two swirl settings, 0 and 1.5. The old BC had profiles, both axial and tangential, that peaked on the inner section close to the primary. The new BC data peaks much closer to the outer radius for the higher swirl numbers, and although somewhat similar for the low swirl settings it still skewed slightly more towards the outer radius. The relatively smaller flow area for the inner radial peaks accounts for the disparity in peak velocity magnitudes. The fairly major change in velocity profiles, particularly for the higher swirl settings, seemed to have a minor impact on the solutions.



A) Axial, Sw = 0 B) Axial, Sw = 1.5 C) Tangential, Sw = 1.5

Figure 6. Comparison of velocity profiles for the old and new boundary conditions at a swirl of 0 and 1.5.

Differences due to the inflow BC in the coal combustion solutions were fairly minor. The results at 22 cm below the primary for both the zero and 1.5 swirl conditions, shown in Figure 7, are indicative of these small impacts. It is possible that the poor performance of the standard k−ε model, which was used in each of these cases, could be the limiting factor for the higher swirl cases where there is the greatest difference between the old and the new BC. More work with an improved turbulence model is warranted, but preliminary indications suggest that the solutions are not particularly sensitive to changes in the inflow BC.



A) Axial, Swirl = 0 B) Axial, Swirl = 1.5 C) Tangential, Swirl = 1.5

Figure 7. Comparison of old and new boundary conditions. PCGC-3 solutions, 22 cm below the primary fuel tube.

3. Publications

During the last 6 months two papers were published as a result of the ongoing work underway in this contract. Both papers were presented at the Western States section of the Combustion Institute's spring conference which was held at SANDIA Labs in Livermore California on the 14-15 of April, 1997. The first paper dealt with insights gleaned from the modeling efforts, described in part in section 3 of this report. The second paper concentrated on the accomplishments surrounding the LDA measurements in pulverized coal combustion. These two papers are listed below.

R. E. Jackson, L. M. Pickett, D. R. Tree, "Comprehensive Combustion Code Predictions of the Flow Field for Pulverized Coal Combustion," WSS/CI 97S-070.

Pickett, L. M., Jackson, R. E. and Tree, D. R. "LDA, Gas Species and Temperature Measurements in a Pulverized Coal Flame," WSS/CI 97s-075.

4. Conclusions

Progress continues in the effort to collect a comprehensive data set for a pulverized coal flame with reburning. In the past six months, the reburning fuel injector and tertiary air system have been tested and used to collect effluent species measurements for a matrix of reburning equivalence ratios, reburning zone locations and tertiary air locations. Reburning efficiencies of greater than 70% have been obtained. The reburning efficiency was found to increase with increasing equivalence ratio in the reburning zone. Reburning efficiency for reburning zones further down stream of the primary combustion zone are lower for the same residence time. The same amount of NO_x reduction can be achieved if the residence time is increased. The detailed map of species, temperature and velocity with reburning will be obtained within the next two months.