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

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Abstract

An experimental program has been completed to make detailed measurements of a pulverized coal flame with reburning and advanced reburning. Maps of species (CO, CO_2, O_2, NO, HCN, and NH_3), temperature and velocity have been obtained which consist of approximately 60 measurements across a cross sectional plane of the reactor. A total of six of these maps have been obtained. Three operating conditions for the baseline flame have been mapped, two operating conditions with reburning, and one operating condition of advanced reburning. In addition to the mapping data, effluent measurements of gaseous products were obtained for various operating conditions. This report focuses on the advanced reburning data.

Advanced reburning was achieved in the reactor by injecting natural gas downstream of the primary combustion zone to form a reburning zone followed by a second injection of ammonia downstream of reburning to form an advanced reburning zone. Finally, downstream of the ammonia injection, air was injected to form a burnout or tertiary air zone. The amount of natural gas injected was characterized by the reburning zone stoichiometric ratio. The amount of ammonia injected was characterized by the ammonia to nitrogen stoichiometric ratio or NSR and by the amount of carrier gas used to transport and mix the ammonia. A matrix of operating conditions where injector position, reburning zone stoichiometric ratio, NSR, and carrier gas flow rate were varied and NO reduction was measured was completed in addition to a map of data at one operating condition.

The data showed advanced reburning was more effective than either reburning or NH_3 injection alone. At one advanced reburning condition over 95% NO reduction was obtained. Ammonia injection was most beneficial when following a reburning zone which was slightly lean, S.R. = 1.05, but was not very effective when following a slightly rich reburning zone, S.R. of 0.95. In the cases where advanced reburning was most effective (reburning S.R. = 1.05), higher NSR values improved NO reduction but NSR was secondary to NH_3 injector location. The optimal location for injection was found to coincide with changes in the temperature field.

The mapped temperature, species and velocity data for advanced reburning showed that the largest drops in NO occurred in a region where the O_2 concentration was between 0.7 and 3.0%, NH_3 was between 0 and 2961 ppm, and temperatures were between 1274 and 1343 K. These are similar to optimal conditions known for SNCR. Significant NO reductions were seen when NSR values were near one, suggesting NH_3 was very effective at NO reduction when surrounding temperature and species conditions were favorable. Because this was only one detailed set of data, it is difficult to conclude that these conditions are optimal or need to exist for optimal NO reduction. More detailed mapping data at other operating conditions would be useful in identifying optimal advanced reburning conditions.

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1. **Executive Summary**

Excellent progress has been made during the past six months and, as of the end of September 1998, all of the objectives listed in the table below have been completed except numbers 10, 15, and 16. The three incomplete objectives involve a comparison of modeling results with the measurements. These objectives will be the focus of continued effort in the no cost extension period. During this reporting period, the advanced reburning maps have been completed and all of the LDA measurements for reburning and advanced reburning have been obtained. This report will present the advanced reburning species and temperature measurements which have proven to be of considerable interest. The LDA data has only been recently obtained but has not yet been fully analyzed and will not yet be presented. One Masters student has completed his thesis defense and graduated in this reporting period making a total of three graduate students who have been supported by this project. Additional requests for the data have been received, including a request from ABB Combustion Engineering Inc. As a result, a data book has been established containing all the data obtained in this and subsequent projects in the controlled profile reactor at BYU. The data from this project are available in hard and soft copy format. Three journal publications have been submitted and reviewed during the reporting period and indications are that they will be accepted after revisions are made.

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
17a. Map 0.5 Swirl Rebrng.																																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

2. Introduction

Reburning and advanced reburning are very promising NO_X reduction strategies which have been proven experimentally in small scale reactors and demonstrated on full scale boilers. One particularly important advantage of these techniques is the potential for retrofit on existing boilers. More information is needed, however, both empirically and fundamentally on how reburning and advanced reburning should be implemented in full scale boilers. A model for reburning has been developed for this purpose at ACERC and a model for advanced reburning is in progress (Xu et al. 1997). These models are in need of validation and further development before they may be accepted as useful tools. Over the past three years, BYU has been the recipient of a DOE grant to make detailed measurements in a coal reactor with reburning and advanced reburning. These measurements are nearing completion. Data sets now exist for a baseline coal flame at three swirls (Pickett et al., 1998, Nazeer et al., 1998a), a reburning flame at two swirls (Nazeer et. al., 1998b) and advanced reburning flame at one swirl. The data sets include major gas species (CO, CO_2, O_2, NO) and intermediates (HCN and NH_3), temperature and gas velocity (using LDA). This report will focus on advanced reburning species and temperature measurements.

3. Approach

All measurements have been obtained in the BYU/ACERC controlled profile reactor (CPR) which is a 0.5 MW, axisymmetric, down-fired, pulverized coal, reactor. The reactor was operated at approximately 0.2 MW and an overall stoichiometric ratio of 1.1. Temperature profiles were obtained using a suction pyrometer. Gas species of O_2, CO_2, CO, and NO were obtained using a water quenched suction probe and on-line gas analyzers. Concentrations of NH_3 and HCN were obtained by aqueous sampling and ion electrode analysis. Advanced reburning was achieved by injecting natural gas and ammonia into the CPR along the center line using a water cooled probe. The ammonia was initially stored in compressed tanks as approximately 25% NH_3 and 75% N_2. During injection, the NH_3/N_2 mixture (to be referred to as NH_3 injection only) was further mixed with N_2 as a carrier gas to increase the momentum of the injected flow to improve mixing. In an initial set of experiments, the location of the natural gas and ammonia injection were varied and only effluent gas concentrations were measured. This was used to investigate the effects of various injection locations, reburning zone equivalence ratios, and ammonia injection flow rates on the effluent NO concentration. From the effluent measurements, a location for each injector and flow rates for ammonia and natural gas were selected for a detailed map. Figure 1 shows the location of natural gas, ammonia, and tertiary air injection selected for the advanced reburning map with dots representing specific measurement locations for the gaseous species. Temperature measurements were obtained at the same number of locations as the gas measurements shown but were located 5 cm below each gas species location due to differences in the geometry of the sampling probe tips.

Operating conditions for reactor fuel and air feed for all conditions tested are shown in Table 2 along with reburning fuel, advanced reburning fuel and tertiary air flow rates used in the advanced reburning map to be described later. The secondary air was heated prior to the infusion of the coal. Primary air, coal and all injected gases were unheated.

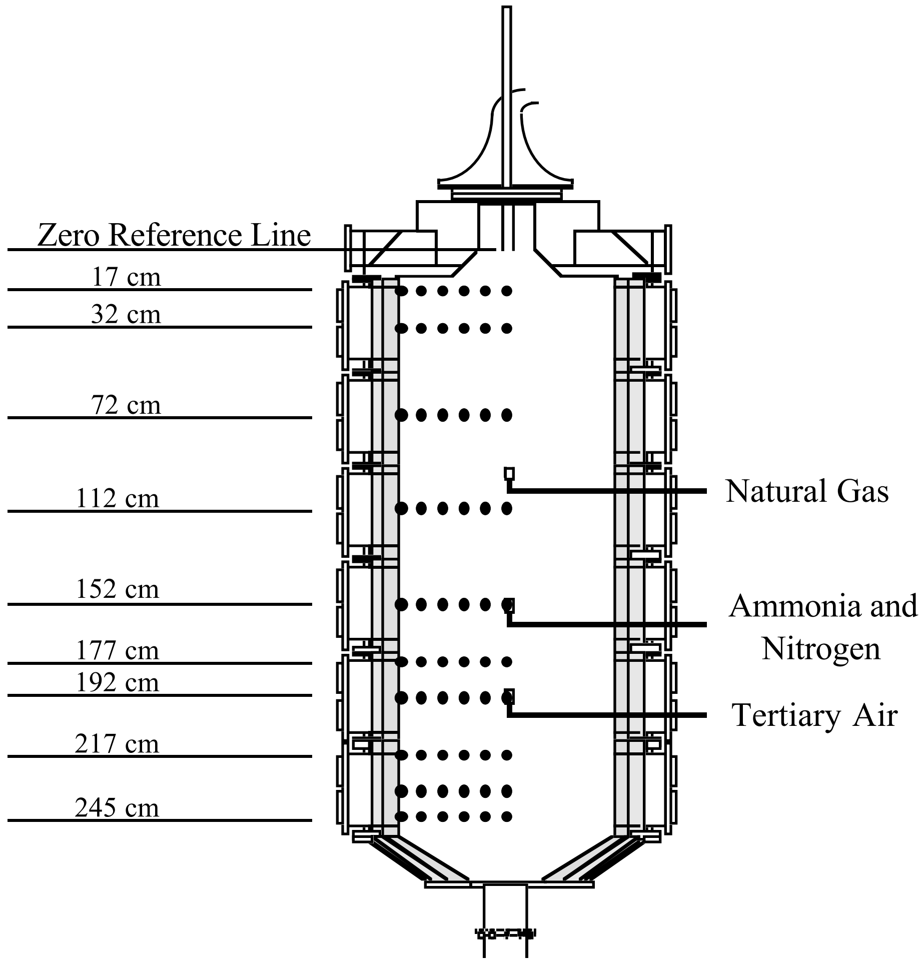

Figure 1. Advanced reburning implementation in the CPR. Injector and measurement locations.

Table 2. Operating conditions for the detailed data map.

Parameter	Flow Rate (kg/hr)	Temperature (K)
Primary Air	16.2	310
Secondary Air	176.5	600
Coal	25.6	300
Reburning Fuel (natural gas)	0.53	---
Ammonia/Nitrogen	0.65	---
Tertiary Air	18.9	---

4. Results and Discussion

Before completing a detailed map of the reactor under an advanced reburning condition, effluent measurements of NO were obtained at numerous operating condition which varied the reburning zone stoichiometric ratio, the swirl and the nitrogen to ammonia stoichiometric ratio (NSR) in the advanced reburning zone. For these 1.5 swirl effluent species tests, the natural gas was injected at 89 cm and the tertiary air at 187 cm. The results are shown in Figure 2. The dashed lines show the NO reduction due to reburning alone decreased as the reburning zone stoichiometric ratio increased. This was expected because there was less natural gas available for NO reduction at the leaner conditions. At a reburning zone S.R. of 0.95 the addition of ammonia did little to improve NO reduction, but as reburning zone S.R. increased, the total NO reduction increased for all NSR values. Because the mixtures which were slightly lean produced greater NO reduction, the data suggest that excess oxygen or species created by small amounts of excess oxygen promote advanced reburning. No dependence on location or NSR was shown for the NH_3 addition at 0.95 and 1.0 S.R. At a S.R. of 1.05, the data show that injection at 130 cm produced higher NO reductions. The reason for this location producing higher NO reduction may be related to optimal temperatures or O_2 concentrations. Information of the species and temperature within the reactor were obtained at 0.5 swirl but not at this 1.5 swirl operating condition.

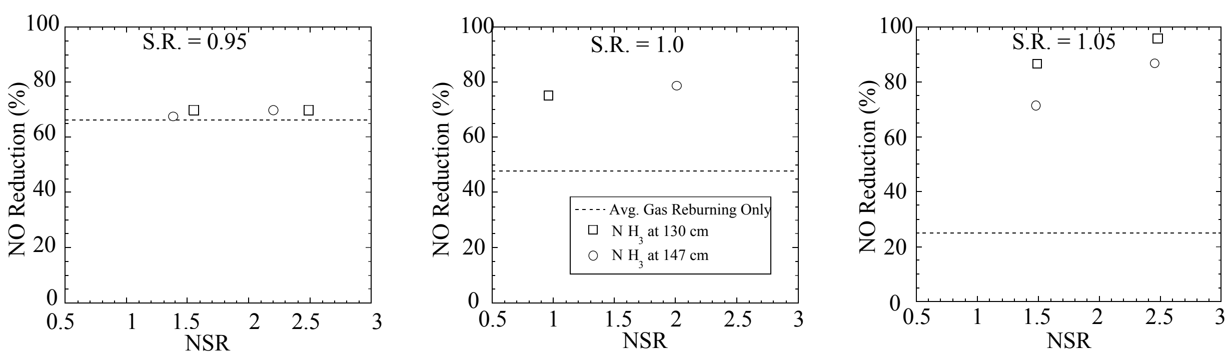

Figure 2. Effluent measurements of NO reduction for three stoichiometric ratios as a function of NSR at 1.5 swirl.

Effluent measurements taken at a swirl ratio of 0.5 are shown in Figures 3 and 4. Figure 3 includes data from various injection locations and at several NSR values where the NH_3 was injected with the assistance of additional nitrogen carrier gas. The trend of decreased NO reduction with increased S.R. for reburning alone was the same at this swirl as it was at 1.5. NO reduction due to NH_3 injection in comparison to NO reduction due to reburning alone was again seen to be negligible at a reburning zone S.R. of 0.95 but increased with increasing reburning zone S.R. The total reduction of NO did not increase as a result of NH_3 injection except at the 169 cm injection location and a reburning zone S.R. of 1.05. This implies again, as in the 1.5 swirl data, that the combination of natural gas followed by ammonia injection (advanced reburning) can provide greater NO reduction than reburning alone, but the location of the NH_3 injection is important. At 0.5 swirl, maximum NO reduction was achieved at an injection location of 169 cm while at 1.5 swirl the injection location of maximum NO reduction was 130 cm. If residence time were a limiting factor in NO reduction, the injection location furthest upstream would tend to be the best. While this was the case at 1.5 swirl it was not true at 0.5 swirl. Concntration of O_2 and other gaseous species would be expected to remain relatively constant downstream of the reburning zone suggesting that they are not responsible for the dependence of NO reduction on injector location. The temperature is however changing with reactor position as the gases flow down the reactor. The potential sensitivity of NO reduction to temperature will be investigated further in the data.

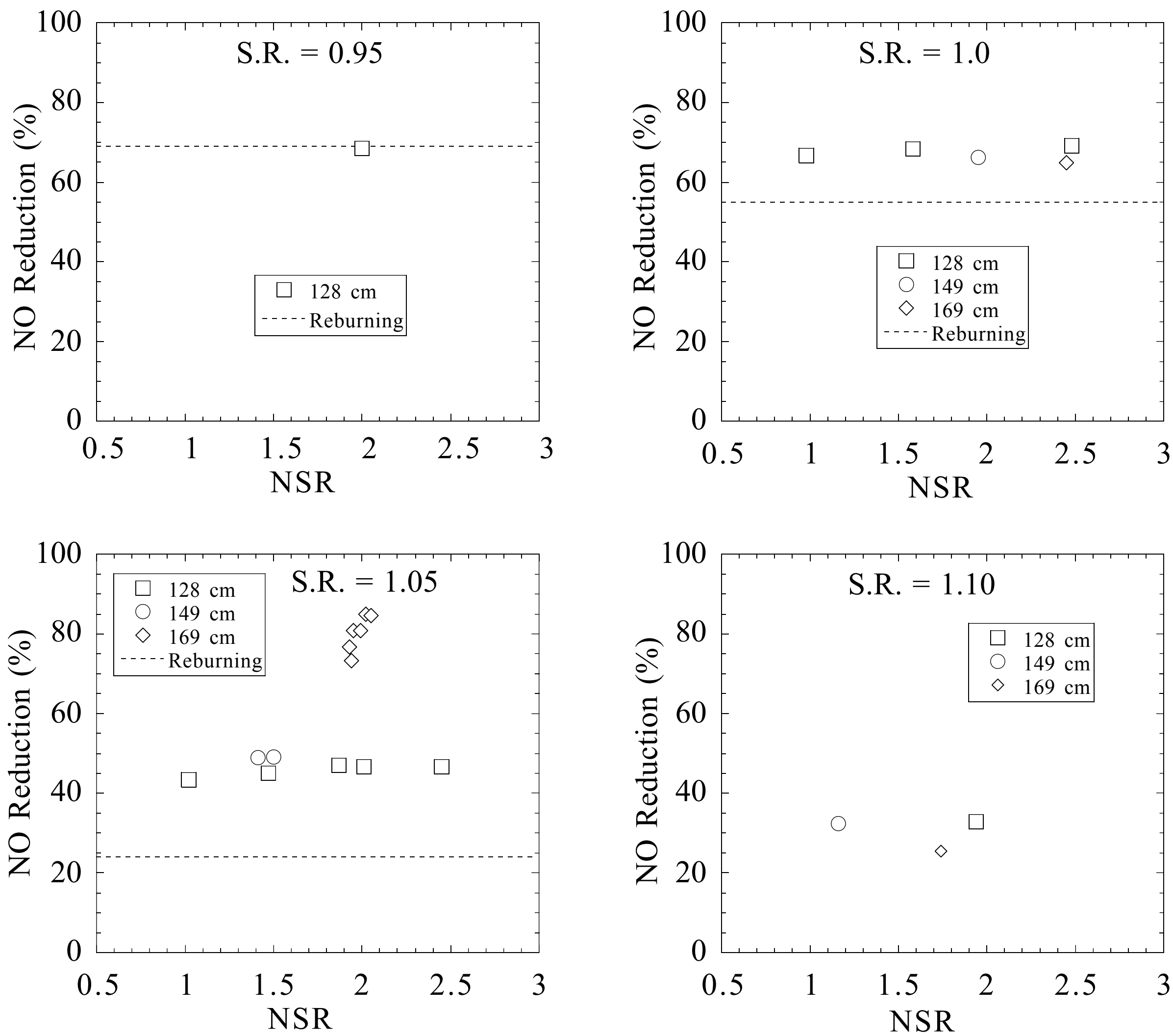

Figure 3. NO reduction for various reburning zone stoichiometric ratios as a function of NSR at 0.5 swirl.

Figure 4 shows data from two repeated reactor conditions shown in Figure 3 except in this case, the NH_3 injection was not assisted with additional carrier gas. The primary purpose of this data was to evaluate the NO reduction at a lower mixing rate of NH_3 into the product gases exiting the reburning zone. The data is similar to that with the carrier gas except that at the 1.05 reburning zone S.R., both the 149 and 169 cm injection locations produced high NO reduction, while without the carrier gas, only the 169 cm location was as effective.

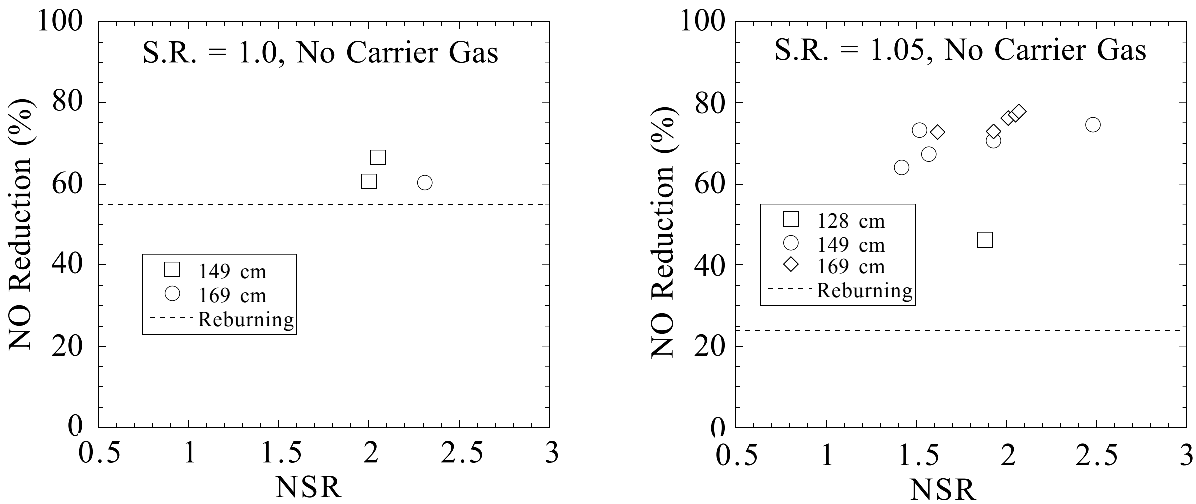

Figure 4. NO reduction for various reburning zone stoichiometric ratios as a function of NSR at 0.5 swirl where the injected NH_3 has no carrier gas.

One explanation of the data is to assume a zone within the reactor, starting just below 149 cm and extending below 169 cm which has an optimal environment for NO reduction when NH_3 is injected. When injected at low momentum, as was the case with no extra carrier gas, the NH_3 injected at 149 cm moved downstream into the optimal region. With high injection momentum at the 149 cm injection location, the injector, which directed the gases at approximately 45^{o} upstream, forced the gases radially outward or slightly upstream, above the optimal zone. When injecting at 169 cm, the injector was centered in the optimal zone and thus either amount of injection momentum produced adequate mixing of the NH_3 with NO at the desired temperature. Throughout this region it would be expected that oxygen and other species concentrations remained relatively constant while temperature was dropping due to heat transfer to the walls. This suggests that the sensitivity of NO reduction to location is actually a sensitivity to temperature. Downstream of the ammonia injection, at the point of tertiary air injection, both temperature and O_2 concentration change. It is possible but uncertain if the tertiary air creates a desirable drop in temperature at that location which facilitates NO reduction.

The 1.5 swirl data showed the highest NO reduction when injecting the NH_3 at 130 cm which was further upstream than the 0.5 swirl case. In order to determine what temperature and species conditions existed at the point of NH_3 injection in each case, a detailed map would be needed. The objectives and resources of this work allowed only one detailed map to be obtained. Detailed mapping of baseline conditions in this reactor without reburning or advanced reburning by Nazeer et al. (1998a), however, showed that the flame at 1.5 swirl was essentially higher in the reactor than at 0.5 swirl and that the temperature dropped more rapidly. The temperature at 130 cm and 1.5 swirl was approximately 1420 K which was approximately the same temperature at 190 cm at 0.5 swirl. From the baseline data it is therefore reasonable to believe that these two optimal injection locations had similar temperatures.

The condition selected for the reburning map is shown below in Table 2. The primary consideration in selecting a condition for the map was to find an advanced reburning case by which to benchmark advanced reburning and comprehensive combustion models. Thus, it was considered important to have a significant amount of NO reduction occurring at the simplest possible advanced reburning configuration. A 0.5 swirl case was selected because it was considered to be more realistic to industrial swirl levels and because 1.5 swirl created turbulence levels and particle penetration which would be difficult to model. The 149 cm injection location was selected to allow the longest possible residence time prior to tertiary air injection while maintaining high NO reductions. The NH_3/N_2 injection without additional carrier gas was selected because it was felt that smaller NH_3 velocities would be easier to model and less dependent on the fluid modeling of the injector spray.

Table 2. Conditions and injection locations used for mapping advanced reburning.

Conditions	Swirl	Primary S.R.	Reburn S.R.	Overall S.R.	NSR
	0.5	1.10	1.05	1.15	1.7
Injector	Nat. Gas	$NH_3 + N_2$	Tert. Air		
	88 cm	149 cm	189 cm		

The mapped data were obtained during three separate test periods, two of which repeat the gaseous on-line measurements. In Test A, gaseous species and aqueous samples of the reactor were obtained. In Test B, only gaseous species were taken. Temperature data was obtained in Test C. The species and temperature are displayed below in the form of gray scale contour plots. The contours were generated by a commercial interpolation and plotting program and mirror imaged using a graphics package. This form of presentation offers the advantage of enabling the reader to visualize the combustion phenomena and rapidly identify important regions of change or high or low concentration. The contour plots, however, do not lend themselves well to an accurate determination of precise values because or the uncertainty of interpolation routines used in the plotting software. Complete tabular data for these maps are available on request with some of the most critical data in the advanced reburning zone being presented in Table 3.

Species data are shown and the two tests are compared in Figures 5 and 6. Test B contains the same number of data points but extends a little further down the reactor which may cause some difference in the way the data appears after it has been interpolated by the software. The two data sets show regions of high concentration and gradients which are generally the same in both data sets, and the magnitudes of the measurements are in fairly good agreement. Test A consistently showed a stronger axial penetration of the secondary air jet at the top of the reactor and a weaker recirculation zone. Below the NH_3 injection (149 cm) the mixing of O_2 from the tertiary air appears to be slower in Test B, but this may be due to a different set of sampling points in the two tests and the interpolation scheme of the software. The differences in the two data sets represent the variation in the reactor. The largest source of variation in the reactor was determined to be the variation of the coal feed rate. Coal was delivered using a gravity and auger feed system. Vibrators were used to avoid air pockets in the coal feed bin. Variations of 5% in the coal feed were common due to the compaction of coal in the bin over time and the batch type process used to fill the bin. The time required to obtain a species map was generally over 8 hrs, during which coal feed could vary. The coal feed was checked by turning off all but the baseline fuel and air feed and monitoring the exhaust O_2 concentration. When the O_2 concentration was not in good agreement with expected values (± 2.5%), the reburning data was not accepted and the data was retaken. This variation in the coal feed is one reason the two data sets may appear different. Another reason is the possibility of moisture of other variations in coal content. Although all the coal used was from the same mine and the same load, coal can vary in content and it is difficult to assure uniformity.

Concentrating on a set of data from a single test, Test A, the primary, reburning and advanced reburning zones can clearly be identified. Near the top of the reactor, O_2 is seen to penetrate to about 60 cm before reaching a level of approximately 3%. In this same region, CO_2 increases to 16%, and NO increases to 550 (at the centerline) to 625 ppm (near the walls). CO in this primary combustion region has narrow regions were the concentration is very high, representing unburned fuel, and other areas where CO is low suggesting O_2 availability and more complete combustion.

The reburning zone begins just below 60 cm, where the O_2 concentration drops, NO decreases by approximately 30%, and a pocket of CO is observed. NO, O_2 CO_2 and CO remain relatively constant in the bottom half of the reburning zone. At the point of NH_3 injection (149 cm), the NO begins to decrease from 500 ppm to 100 ppm. This is the advanced reburning zone. The bottom of this zone meets the tertiary air injection zone which causes a further drop in NO, probably due to dilution. The tertiary or burnout zone is apparent from the increase in O_2 concentration centered at 200 cm, just below the point of air injection (189 cm).

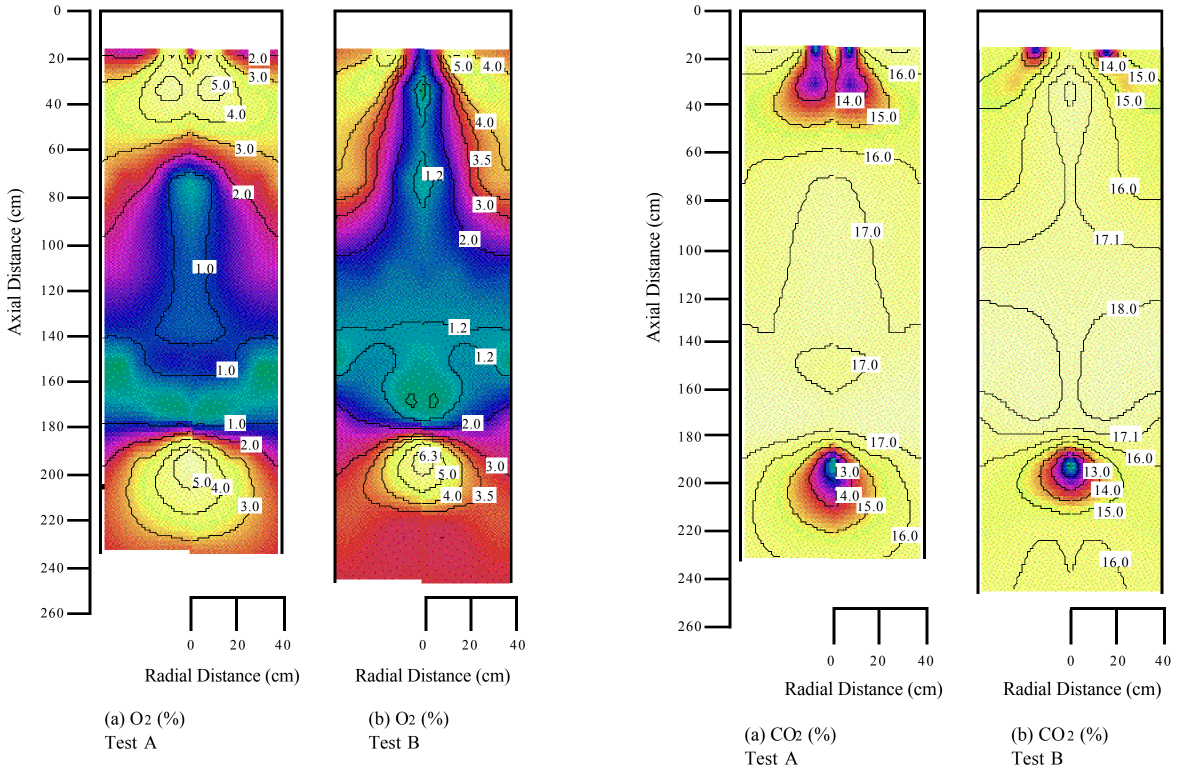

Figure 5. Concentration contour maps of O_2 and CO_2 for both tests, A and B

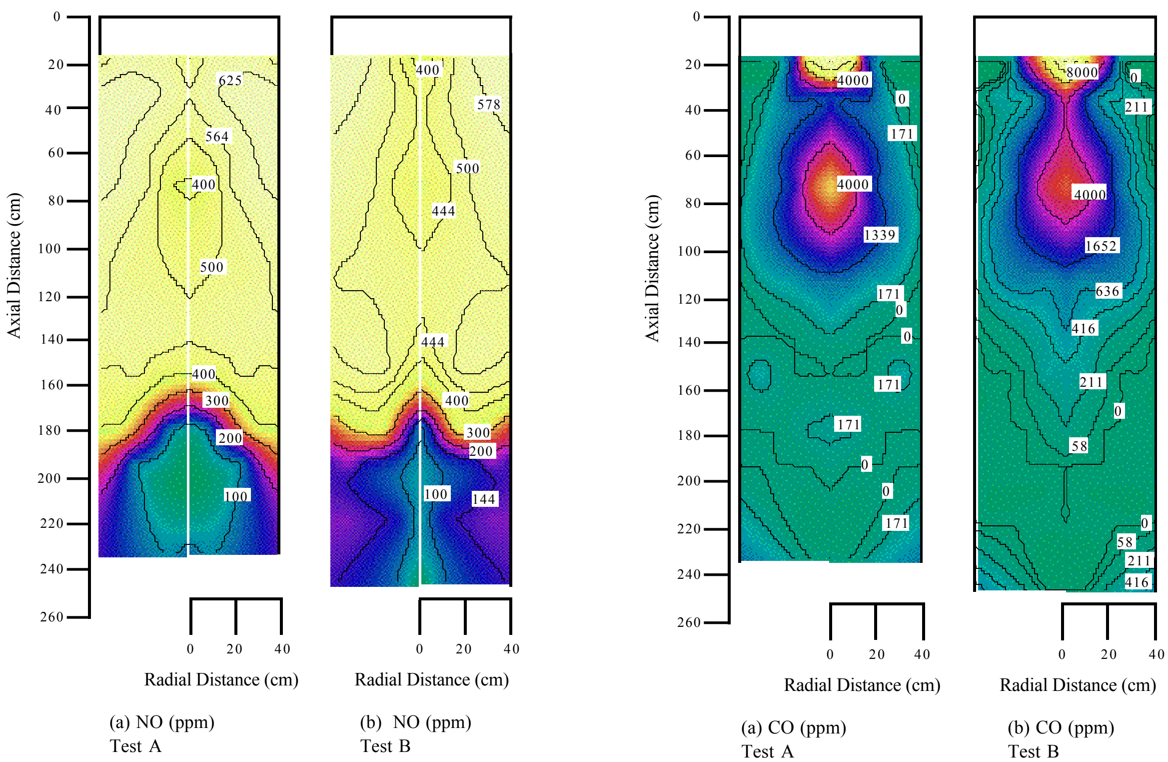

Figure 6. Concentration contour maps of NO and CO for both tests, A and B.

The region from 140 cm down is of particular interest because it shows the conditions where the NO reduction was occurring. Before examining this region in more detail, the NH_3 and HCN species concentrations and temperature need to be considered. Contour plots for these species are seen in Figure 7. Significant amounts of HCN were found directly below the quarl outlet in the primary combustion zone but not at any other location within the reactor. There is no evidence of either NH_3 or HCN in the reburning zone. This may have been because the fuel mixed readily with the surrounding gases, and the overall S.R. in the reburning zone was lean. NH_3 was found only in the vicinity of the ammonia injection. Ammonia was found primarily on the downstream side of injection suggesting that the jet, which was directed at approximately 45^o upward, did not contain a significant amount of momentum relative to the downward flow. The temperature, which was highest at the top of the reactor, decreased more slowly in the top half of the reactor where the reburning fuel was added than the bottom half where ammonia and tertiary air were added. This was as expected because the natural gas provided an additional source of energy while the ammonia and tertiary air cooled the gasses by dilution.

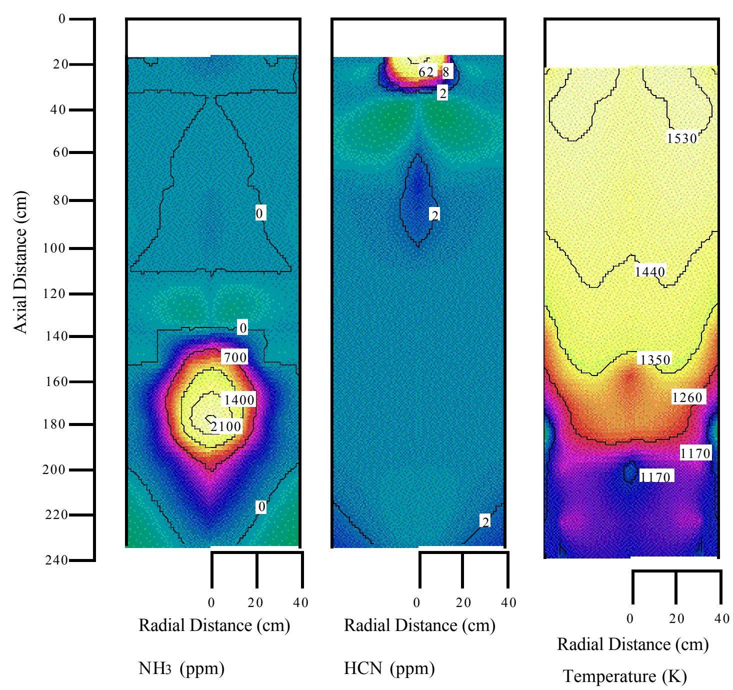

Figure 7. Ammonia, HCN and temperature profiles for advanced reburning.

It is interesting to look closely at the data in the region of rapid NO destruction where measurements were made at the 152, 177, and 192 cm axial locations and 6 radial locations. Tabular data for these points are given in Table 3. NH_3 injection occurred at 149 cm just above this zone, and air injection occurred at 189 cm, near the end of this zone. Assuming a plugged flow in the downward direction, the steepest reduction in NO occurred at the centerline between 152 and 177 cm where the concentration dropped from 420 to 87 ppm. In this same interval, NH_3 increased from 1268 to 2961 ppm, O_2 was present at 0.7%, and the temperature was between 1274 and 1300 K. This means that the greatest NO reduction occurred in the presence of O_2 with a high ratio of NH_3 to NO.

At the 23 cm radial location, moving downstream from 152 to 177 to 192 cm axially, the NO decreased from 555 to 330 to 105 ppm respectively. During the first segment between 152 and 177 cm, the O_2 concentration was still relatively low between 0.9 and 1.0%, NH_3 was between 0 and 352 ppm and the temperature was between 1343 and 1265 K. In the second segment between 177 and 192 cm, NH_3 was between 352 and 224, O_2 increased from 1.0 to 3.0 % and temperature decreased from 1265 to 1213 K. The second segment shows evidence of mixing with tertiary air because of the O_2 increase. In both segments, the NH_3 levels are of the same order of magnitude as the NO. Thus, the NH_3 to NO ratio does not have to be significantly higher than one to achieve high NO reductions. The data also demonstrate that large NO reduction occurred under slightly lean (0.7 to 3% O_2) conditions at temperatures ranging from 1274 to 1343 K. These conditions are close to SNCR conditions but the temperatures and O_2 concentrations are higher than are normally thought to be optimal. It would be interesting to look at detailed maps where the ammonia was injected upstream at higher temperatures to see if NO increased initially and to determine under what conditions the NO was decreasing.

Because of the close proximity of the NH_3 injector and the tertiary air, it was uncertain from the mapped data whether or not the tertiary air helped create the temperature or species environment necessary for NO reduction. An additional effluent test was taken to determine the extent of NO reduction without tertiary air injections. The results showed a 61 % reduction when no tertiary air was used in comparison to greater than 70 % reduction with both NH_3 and tertiary air injection. This suggested that the bulk of the NO reduction was independent of the tertiary air, but in this configuration, the tertiary air was also a contributor to NO destruction. This may be a result of temperature or species concentration changes produced by the tertiary air.

Table 3. A selection of species and temperature data in the advanced reburning zone.

	Radial	0	8	15	23	30	38
Axial							
152*	NO (ppm)	420	430	440	555	490	500
	O_2 (%)	1.1	1.2	1.1	0.9	0.4	0.5
	NH_3 (ppm)	1268	1097	414	0	0	0
	Temp. (K)	1274	1326	1351	1343	1317	1248
177*	NO (ppm)	87	115	220	330	400	400
	O_2 (%)	0.7	0.8	0.8	1.0	1.0	1.0
	NH_3 (ppm)	2961	2271	1041	352	86	23
	Temp. (K)	1300	1300	1283	1265	1239	1106
192*	NO (ppm)	68	80	95	105	210	280
	O_2 (%)	6.2	4.6	3.2	3.0	2.3	1.6
	NH_3 (ppm)	1005	759	373	224	68	41
	Temp. (K)	1160	1195	1204	1213	1222	1160

* Temperature values were taken 5 cm downstream of the species measurements.

5. Summary and Conclusions

Advanced reburning has been investigated in a 0.2 MW pulverized coal flame by injecting a gaseous mixture of NH_3 and N_2 down stream of natural gas injection used as a reburning fuel. Various amounts and combinations of reburning fuel and ammonia injection were investigated through gaseous effluent measurements to determine the effect of parameters such as reburning zone S.R., advanced reburning NSR, injector location and carrier gas momentum. The results showed that while reburning and ammonia injection alone were both effective in reducing NO, the greatest reductions were realized when both were combined. Although the testing was not extensive enough to determine an optimal condition, the highest NO reductions were observed when a reburning zone S.R. of 1.05 was followed by ammonia injection. NO reduction was very sensitive to NH_3 injection location. The reason behind this sensitivity was thought to be variations in temperature at and below the injection location. Although the data support this theory, there is insufficient evidence to make this a conclusion. NO reduction was found to be sensitive to NSR under conditions where NO reductions due to advanced reburning were high, but the effects of NSR were smaller than those of injection location. Maximum NO reductions of over 95% were seen at an NSR of 2.5.

A single operating condition was selected for mapping the species and temperatures in the reactor. The map recorded CO, CO_2, NO, O_2, HCN, NH_3 and temperature at 60 locations in a cross sectional plane of the reactor. The data showed the region of most rapid NO reduction occurred directly below the ammonia injection location and that high NO reductions were occurring in regions where the O_2 was between 0.7 and 3%, the temperatures were between 1274 and 1351 K and NH_3 was between 352 and 2961 ppm. Thus the reduction occurred at slightly lean conditions and temperatures slightly higher than typical optimums for SNCR of NO. Further detailed measurements need to be obtained to determine if the NO reduction at other global operating conditions and injection locations occurs at these same local conditions.

6. References

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