DOE/PC/88918-6

**REDUCTION OF NO_x AND SO₂ EMISSIONS
FROM COAL BURNING PULSE COMBUSTORS**

DOE/PC/88918--6

DE90 012523

Quarterly Technical Progress Report
for the Period January 1, 1990 - March 31, 1990

By

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May 1990

Work Performed Under Contract No. DE-FG22-88PC88918

For

U. S. Department of Energy
Office of Fossil Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania 15236

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COAL PULSE COMBUSTION RESEARCH

Quarterly Technical Progress Report for the Period
January 1, 1990 - March 31, 1990

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Prepared for

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Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania

Under Contract No. DE-FG22-88PC88918

ABSTRACT

Work accomplished during the sixth quarter of Grant No. DE-FG22-88PC88918 is presented and discussed. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

During this quarter the assembly and installation of the sorbent feed system was completed.

A series of baseline experiments was then completed to determine the NO_x and SO_2 emissions in the absence of sorbent addition or combustion staging. For the baseline tests, sound pressure levels, frequencies, exhaust gas compositions (CO_2 , CO , O_2 , NO_x and SO_2) and temperatures were measured as a function of air/fuel ratio for a fixed coal feed rate of 75 g/min. Sound pressure level was a maximum, about 160 dB, for stoichiometric conditions. Nitrogen oxides production was between 400 and 600 ppm for the entire range of air/fuel ratios investigated. The maximum concentration of NO_x (about 590 ppm) was obtained for air/fuel ratios of 1.2 and 1.3, while minimum NO_x (about 400 ppm) occurred at an air/fuel ratio of 0.8. Sulfur dioxide concentrations were near 1450 ppm for air/fuel ratios below 1.1, and they decreased steadily for larger air/fuel ratios primarily due to the dilution effect of the excess air.

Next a series of air staging tests was conducted to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the NO_x emissions. For the air staging tests, values of each of the measured quantities were obtained as a function of the primary air/fuel ratio, with the total air/fuel ratio always stoichiometric. Data was obtained from three secondary injection heights above the bed: 20 cm, 27 cm and 37 cm. Sound pressure level ranged between 154 dB at a primary air/fuel ratio of 0.5 to about 160 dB for the case without air staging, and it was little affected by injection height. Residual oxygen levels measured during these experiments indicated that combustion of the coal gases by the secondary air injection was not complete, even though the total air/fuel ratio was stoichiometric. Nitrogen oxides ranged between 400 ppm and 600 ppm with no clear effect of air staging.

Finally a series of non-pulsating tests was performed to determine the effect of pulsations on the NO_x emissions. Results of the non-pulsating tests showed much lower combustion efficiency under non-pulsating conditions. Carbon dioxide mole fractions were about 6 percent while residual oxygen was about 14 percent, indicating incomplete combustion of the coal. The non-pulsating experiments showed a significant decrease in NO_x production with decreasing air/fuel ratio. For stoichiometric conditions NO_x concentrations were about 180 ppm, which decreased to about 115 ppm at an air/fuel ratio of about 0.5. The NO_x concentrations under non-pulsating combustion were less than half (stoichiometric) to a fourth (air/fuel ratio of 0.5) of those produced under pulsating conditions. Comparison of the results of the pulsating and non-pulsating tests indicate that pulsations greatly increase the combustion efficiency for a given air/fuel ratio. Unfortunately pulsations also greatly increase the efficiency with which the fuel-bound nitrogen is converted into nitrogen oxides.

INTRODUCTION

The following report summarizes work done under DOE Grant No. DE-FG-88PC88918 during the period January 1, 1990 through March 31, 1990. This project is concerned with the reduction of sulfur dioxide and nitrogen oxides emissions from Rijke type coal burning pulse combustors by sorbent addition and combustion staging.

The following work will be described in this report: (1) assembly and installation of the sorbent feed system, (2) baseline tests to determine the NO_x and SO_2 emissions in the absence of sorbent addition or combustion staging, (3) air staging tests to determine the effectiveness of substoichiometric primary coal combustion followed by secondary air injection above the bed in reducing the NO_x emissions, and (4) non-pulsating tests to determine the effect of pulsations on the NO_x emissions. The report will conclude with projected work to be accomplished during the next quarter.

SORBENT FEED SYSTEM

The assembly and installation of the sorbent feed system was completed during the quarter. The sorbent feed assembly consists of a drive motor, hopper and auger mounted on support rails as shown in Figure 1. The hopper and auger have been described in Reference 1. The support rail consists of two angle-section steel beams 36 cm long placed side by side to form a single U-channel beam 5 cm wide. The motor is bolted to short angle-section beams which are welded to the support rail. The hopper is supported at its base by a 5 cm wide piece of 3 mm thick steel plate which was cut to match the hopper base and bolted to the existing holes on the hopper base. The bottom of this bracket is welded to a 5 cm long piece of angle-section beam which is bolted to the support rail. Finally, the top end of the hopper is supported by two 1.6 cm diameter aluminum rods 6.4 cm long which are bolted to the back of the hopper and to the support rail.

A tachometer system was installed on the sorbent feed auger shaft to determine the instantaneous rotational speed of the auger which is needed in order to accurately measure the sorbent feed rate into the combustor. This tachometer is similar to the one installed on the coal feed system, except that the slotted tachometer disk is smaller (10 cm diameter) and is not split into two halves. Like the slotted disk for the coal feed system, the sorbent feed disk has 60 slots. The slotted disk is bolted to a hub which fits over the auger shaft and is secured by a setscrew. A bracket mounted on the support rails holds an opto-electronic sensor whose signal is sent to the same electronic pulse counter used for the coal feed system.

The sorbent feed system was then installed on the Rijke pulse combustor. The sorbent feed assembly (motor, hopper and auger) was mounted vertically above the sorbent injection point as shown in Figure 2. The upper end of the auger was attached to the venturi section where the pulverized limestone or dolomite is entrained by a low pressure high velocity air stream. The air is supplied by the same secondary air supply used for air staging experiments. The entrained sorbent particles are then carried downward to the injector head (see Ref. 1) and enter the combustor just above the coal bed.

BASELINE TESTING

A series of baseline tests was conducted to determine the performance of the combustor without combustion staging or sorbent addition. For these tests the coal feed rate was 75 g/min and air/fuel ratios ranged from 0.6 to 1.5. These tests were conducted according to the following procedure. Beginning with an empty bed, the combustor was preheated with propane for about five minutes under non-pulsating conditions. During the preheat phase, the propane flow rate was about 25 standard liter/min (SLM) and the air flow rate was about 1020 SLM. Next the bed rotation and coal feed were started with the propane still on. After about two minutes, the coal

was burning under non-pulsating conditions, and the primary air flow was adjusted for the desired air/fuel ratio and the propane was shut off. Immediately, pulsating operation began with pressure amplitudes of about 160 dB. Pulsating operation was usually maintained for periods ranging from 15 to 25 minutes, but longer operating times were possible.

The coal used in all of the tests was a bituminous coal obtained from Georgia Power Company's Plant McDonough located near Atlanta. The coal was sieved to give a range of particle sizes between 6 mm and 12 mm in diameter. The ultimate analysis of the coal was 72.2% carbon, 5.09% hydrogen, 1.48% nitrogen, 1.26% sulfur and 6.60% oxygen. The proximate analysis of the coal as received was 5.60% moisture, 31.98% volatiles, 10.68% ash and 51.74% fixed carbon. The heating value of the coal as received was 29,060 kJ/kg.

For each of the baseline tests, sound pressure levels, frequencies, exhaust gas compositions (CO_2 , CO , O_2 , NO_x and SO_2) and temperatures were measured as a function of air/fuel ratio (α) for a fixed coal feed rate of 75 g/min. A total of 22 baseline tests were conducted with at least two tests for each value of α . Since the measured quantities fluctuated with time during the 15-20 minute tests, data was time averaged over two or three time periods (each lasting 3-5 minutes) for each test. Plots of the measured quantities as a function of time were used to determine which one of the time averages was more typical of the test. This procedure determined a representative value for each of the measured quantities for each test. For each air/fuel ratio, the time averaged data from the appropriate tests were then averaged and tabulated. The results of the tests are shown in Table I. Plots were generated of each quantity as a function of α ; these are given in Figures 3 through 5.

Sound pressure level and frequency as a function of α are shown in Figure 3. Sound pressure level was a maximum, about 160 dB, for stoichiometric conditions ($\alpha = 1.00$). The lowest amplitude recorded was 156 dB at air/fuel ratios of 0.6 and 0.7. The pulsation

frequency increased as the air/fuel ratio was increased, ranging from about 64 Hz at $\alpha = 0.6$ to about 73 Hz at $\alpha = 1.5$. These frequencies are consistent with the fundamental longitudinal acoustic mode of the open-ended Rijke tube combustor. The changes in frequency with air/fuel ratio are due to changes in the temperature distribution and composition of the gases in the region between the coal bed and the exhaust outlet.

Table I. Averaged Sound Pressure Levels, Frequencies and Exhaust Compositions for Baseline Tests.

No. of Tests	α	SPL (dB)	Freq (Hz)	CO ₂ (%)	CO (%)	NO _x (ppm)	SO ₂ (ppm)	O ₂ (%)
2	0.6	155.9	64.5	15.4	1.12	484	NA	0.29
5	0.7	155.6	66.5	14.5	0.73	451	1420	1.36
2	0.8	159.0	65.0	16.2	1.01	398	1450	0.04
4	1.0	159.8	66.0	16.6	0.83	443	1420	0.65
2	1.1	158.3	70.0	16.5	0.42	502	1480	0.52
2	1.2	158.0	71.5	15.1	0.05	585	1270	3.16
2	1.3	157.7	72.0	10.5	0.02	592	1140	5.83
2	1.5	157.9	73.0	11.3	0.06	559	940	6.47

Carbon dioxide, carbon monoxide and residual oxygen concentrations are shown in Figure 4. Carbon dioxide levels were maximum (16.5 percent) for stoichiometric conditions, and they were above 16 percent for air/fuel ratios between 0.8 and 1.1. Carbon monoxide concentrations ranged between 0.7 and 1.2 percent for stoichiometric and fuel rich combustion, but CO levels dropped sharply when excess air was added, becoming less than 0.06 percent for $\alpha = 1.2$ or greater. For air/fuel ratios below 1.1, residual oxygen concentrations were small (less than one percent), but they increased sharply as excess air was increased, reaching 6 to 6.5 percent for air/fuel ratios of 1.3 and above.

Nitrogen oxides and sulfur dioxide concentrations are shown in Figure 5. The upper graph in Figure 5 shows that nitrogen oxides production was between 400 and 600 ppm for the entire range of air/fuel ratios investigated. The maximum concentration of NO_x (about 590 ppm) was obtained for air/fuel ratios of 1.2 and 1.3, while minimum NO_x (about 400 ppm) occurred at $\alpha = 0.8$. This graph also shows that sulfur dioxide concentrations were near 1450 ppm for air/fuel ratios below 1.1, and they decreased steadily for larger air/fuel ratios primarily due to the dilution effect of the excess air. To remove this dilution effect and allow comparison with other data, the measured NO_x and SO_2 concentrations were reduced to a 15% excess air (3% excess oxygen) basis. The reduced NO_x and SO_2 concentrations are shown in the lower graph of Figure 5. This reveals a much more pronounced effect of air/fuel ratio on the NO_x emissions from the pulse combustor. The reduced NO_x concentrations were about 250 ppm for α below 0.8, they increased rapidly as α increased from 0.8 to 1.3, and they reached about 725 ppm for $\alpha = 1.5$. The reduced SO_2 concentrations exhibited a strong increase with increasing air/fuel ratio for α less than 1.1, ranging from about 850 ppm to 1400 ppm. For higher air/fuel ratios, there was a gradual decrease in the reduced SO_2 concentration.

AIR STAGING TESTS

A series of air-staging tests was completed in which secondary air was injected at various heights above the bed (20 cm to 37 cm). The secondary air supply system and injector is shown in Figure 2. In each test the total air/fuel ratio (α_t) was stoichiometric, that is, $\alpha_t = 1.00$. Each of these tests were divided into three segments lasting about five minutes each. In the first test segment, a primary air/fuel ratio of 1.0 was used (no secondary air injection). The primary air/fuel ratio was then reduced to 0.7 in the second test segment and to 0.5 in the third test segment. Time averaged values of sound pressure levels, frequencies, exhaust gas compositions (CO_2 , CO , O_2 , NO_x and SO_2) and temperatures were obtained for each test segment.

A total of 10 air staging tests were conducted. In the first test the secondary air was injected at a height of 53 cm above the coal bed. Results of this test indicated that the secondary air should be injected closer to the bed. For the remaining tests, two tests were conducted with secondary air injection at 37 cm above the bed, three tests were run with air staging at 27 cm above the bed, and four tests were conducted with air staging at 20 cm above the bed. For each secondary air injection height and each primary air/fuel ratio, α_1 , the time averages of each of the measured quantities for the appropriate tests were averaged. The resulting values were then tabulated and plotted as a function of the primary air/fuel ratio, α_1 , for three secondary injection heights above the bed: 20 cm, 27 cm and 37 cm. These data are presented in Table II and Figures 6 through 10.

Table II. Averaged Sound Pressure Levels and Exhaust Gas Compositions for Air Staging Tests.

Air Staging Location (cm)	α_1	SPL (dB)	CO ₂ (%)	CO (%)	NO _x (ppm)	SO ₂ (ppm)	O ₂ (%)
20	0.4	151.3	12.7	0.05	597	1190	5.7
	0.5	154.1	14.5	0.20	555	1230	4.1
	0.7	156.3	15.8	0.15	535	1260	2.8
	1.0	159.9	14.1	0.58	505	1470	2.3
27	0.5	153.6	13.6	0.05	453	1170	4.5
	0.67	156.2	15.5	0.05	498	1300	3.1
	0.7	156.6	15.5	0.10	516	1210	2.7
	1.0	159.7	15.7	0.45	485	1310	1.8
37	0.5	153.8	12.7	0.10	429	1090	5.2
	0.7	155.7	15.0	0.15	454	1250	3.0
	1.0	159.2	15.3	0.35	471	1310	2.1
53	0.67	157.5	8.1	0.70	330	1320	11.5

Figure 6 shows that sound pressure levels increased nearly linearly from 154 dB at $\alpha_1 = 0.5$ to about 160 dB at $\alpha_1 = 1.0$. Secondary air injection height had very little effect on the amplitude and frequency of the pulsations.

Carbon dioxide concentrations for the air staging tests are shown in Figure 7. Except for the lowest secondary air injection point (20 cm), the CO_2 concentration increased monotonically with increasing primary air/fuel ratio. Carbon dioxide concentrations ranged between 12.5 percent and nearly 16 percent, with the lower values corresponding to $\alpha_1 = 0.5$. Except for the unexpected decrease in CO_2 concentration for secondary air injection at 20 cm, CO_2 concentrations increased only slightly between $\alpha_1 = 0.7$ and $\alpha_1 = 1.0$. The concentration of CO_2 also decreased significantly with increasing height of the secondary air injection point. Carbon dioxide concentrations measured in the air staging tests at $\alpha_1 = 1.0$ were somewhat lower than those measured in the baseline tests at stoichiometric combustion conditions. This was probably due to the dilution effect of a small amount of secondary air used to cool the injection head for the case of $\alpha_1 = 1.0$.

The measured carbon monoxide emissions for the air staging tests are shown in Figure 8. Carbon monoxide concentration generally increased with increasing primary air/fuel ratio. Carbon monoxide concentration varied between about 0.05 and 0.6 percent, with the higher values for $\alpha_1 = 1.0$ (no secondary air injection). Increasing the secondary air injection height generally reduced the amount of CO in the exhaust gases. The CO concentrations measured in the air staging tests for $\alpha_1 = 1.0$ were generally lower than those measured in the baseline tests under stoichiometric combustion conditions.

Measured oxygen concentrations in the exhaust gases during the air staging tests are shown in Figure 9. Residual oxygen levels were higher for lower values of the primary air/fuel ratio, with a maximum of 5.7 percent for $\alpha_1 = 0.4$ with secondary air injection at

20 cm above the primary combustion zone. For $\alpha_1 = 1.0$, residual oxygen was about 2 percent. Residual oxygen levels increased as the secondary air injection height was increased. These residual oxygen levels indicate that combustion of the coal gases by the secondary air injection was not complete, since the total air/fuel ratio was stoichiometric. Residual oxygen concentrations in the air staging tests for $\alpha_1 = 1.0$ were somewhat higher than those measured in the baseline tests under stoichiometric combustion conditions.

The measured nitrogen oxides concentrations in the exhaust gases for the air staging tests are shown in Figure 10. Nitrogen oxides emissions ranged between 400 ppm and 600 ppm with only moderate reductions due to air staging. For secondary air injection at 20 cm above the bed, decreasing α_1 increased the NO_x concentrations, but reducing α_1 yielded slight decreases in the NO_x emissions for the higher injection points. Increasing the height of the secondary air injection point resulted in decreased NO_x emissions, especially for the smaller primary air/fuel ratios.

Although the object of the air staging experiments was the reduction of NO_x emissions, the effect of air staging on sulfur dioxide emissions was also obtained. These results are shown in Figure 11. At the lowest secondary air injection point, sulfur dioxide emissions ranged from about 1200 ppm for $\alpha_1 = 0.4$ to nearly 1500 ppm for $\alpha_1 = 1.0$. Raising the secondary injection point clearly decreased SO_2 emissions for $\alpha_1 = 0.5$ but had little effect on SO_2 concentrations for $\alpha_1 = 0.7$.

The effect of air staging on the temperature distributions in the combustor downstream of the coal bed are shown in Figure 12. Here, temperature profiles are shown for secondary air injection at 37 cm above the bed for different primary air/fuel ratios. The curve for $\alpha_1 = 1.0$ represents stoichiometric burning without air staging, where the monotonic decrease in temperature with increasing height above the coal bed is due to heat losses through the combustor walls. For the two cases with secondary air injection, the heat release in the

secondary combustion zone results in higher temperatures in this region (25 - 45 cm above the bed) than those obtained without air staging. For positions higher than 75 cm above the bed, the temperatures obtained with air staging are considerably lower than those obtained without secondary air. Since the total air/fuel ratio for all three cases is the same, this temperature deficit at the combustor exit is a further indication of the incomplete combustion and resultant smaller heat release obtained with air staging under pulsating combustion conditions.

The results of the combustion staging tests indicated that air staging was ineffective at significantly reducing the nitrogen oxides emissions. The reason for this is that lowering the primary air/fuel ratio for pulsating operation resulted in only moderate reductions in the nitrogen oxides emissions. Also it was found that incomplete combustion in the secondary combustion zone resulted in poor overall combustion efficiency.

NON-PULSATING TESTS

A series of experiments were conducted under non-pulsating combustion conditions in order to determine the effect of pulsations on the performance of the combustor, particularly regarding NO_x and SO_2 emissions. Non-pulsating operation was obtained by partially opening the viewing window at the middle of the combustor, which forced the pressure perturbation to be zero where the pressure oscillations for the fundamental acoustic mode normally have their maximum amplitude. To reduce the air leakage through this large opening, it was covered by a piece of cloth. A total of five non-pulsating tests were conducted. Each test was divided into four or five test segments of about five minutes length. Most of the tests were conducted without air staging, but in one of the tests secondary air was injected 20 cm above the bed.

The results of the non-pulsating tests without air staging are shown in Table III and in Figures 13 through 16. The data shown are time-averaged values for the appropriate test segments. In Table III, T_1 is the gas temperature measured on the axis of the combustor 18 cm above the bed. For test numbers 1-3, the coal feed was 75 g/min, while in test numbers 4 and 5, the coal feed rate was 40 g/min.

Table III. Exhaust Gas Compositions and Above-Bed Temperatures for Non-Pulsating Tests.

Test Number	α	CO ₂ (%)	CO (%)	NO _x (ppm)	SO ₂ (ppm)	O ₂ (%)	T ₁ (C)
1	0.5	10.82	0.80	278	1412	6.50	994
2	0.5	10.10	1.01	199	1462	7.30	1082
3	0.5	5.15	0.35	114	831	14.77	1005
4	0.5	7.96	0.20	143	967	11.85	893
5	0.5	9.58	0.29	170	954	11.45	892
2	0.7	9.48	0.32	242	1064	8.76	1027
3	0.7	5.99	0.33	136	801	13.83	1034
4	0.7	6.83	0.10	125	1041	13.38	862
5	0.7	9.27	0.18	193	873	11.86	892
3	1.0	6.44	0.18	177	745	13.64	982
4	1.0	6.91	0.27	164	996	14.16	853
5	1.0	6.56	0.14	212	737	12.98	854
4	1.1	6.25	0.07	143	1043	15.15	860
5	1.1	NA	0.10	220	770	12.71	899

As shown in Table III, there is considerable variation in the measured values from one test to another for the same air/fuel ratio. This is due largely to the varying amounts of partially burned coal which fell through and around the periphery of the coal bed during the non-pulsating tests. Thus the effective air/fuel ratios varied considerably among each group of tests segments with the same

nominal air/fuel ratio. Furthermore, the effective air/fuel ratios were always higher than the nominal values shown in Table III. For this reason it was found to be more meaningful to plot the measured values of CO_2 , CO , NO_x and SO_2 concentrations as a function of the O_2 concentration rather than the air/fuel ratio. The amount of residual oxygen remaining in the exhaust gases is a function of the both the effective air/fuel ratio and the combustion efficiency. Plots of the concentrations of these four species as a function of residual oxygen concentration are shown in Figures 13 through 16.

The data shown in Figure 13 reveals that measured carbon dioxide concentrations for both pulsating and non-pulsating combustion are nearly linearly related to the residual oxygen concentration. For non-pulsating combustion, CO_2 concentrations ranged from about 5 percent to about 11 percent, while the corresponding residual oxygen concentrations varied from about 15 percent to about 7 percent. Some of the scatter in the non-pulsating data results from differences in the air/fuel ratios and coal feed rates for the different tests. For the pulsating tests, air/fuel ratios ranged from 0.6 to 1.5. The CO_2 concentrations for pulsating combustion were much higher with correspondingly lower residual O_2 concentrations. The pulsating tests with the largest concentrations of residual oxygen corresponded to those with the largest amounts of excess air. These results show that the combustion efficiency is much lower under non-pulsating conditions, indicating incomplete combustion of the coal.

The carbon monoxide concentrations measured under non-pulsating combustion conditions are shown in Figure 14. Although there is considerable scatter in the CO data, there is a definite trend of decreasing CO concentration with increasing residual oxygen for the non-pulsating tests. Similar results were obtained for pulsating combustion, but the corresponding residual oxygen levels were much lower due to the higher combustion efficiency. The decrease in CO concentration with increasing residual O_2 levels reflects the gas

phase oxidation of CO to CO₂ in the region above the coal bed when ample oxygen is present.

The nitrogen oxides emissions measured under non-pulsating combustion conditions are shown in Figure 15. These data follow a definite trend of decreasing NO_x concentration with increasing O₂ concentration. Furthermore if a linear curve fit for the non-pulsating data is extended to very low residual oxygen levels, it agrees well with the pulsating combustion data for air/fuel ratios between 0.6 and 1.1, which is approximately the same range of α used in the non-pulsating tests. For this range in α the residual oxygen levels are a good measure of combustion efficiency, since little or no excess air is present. It thus appears that as the combustion efficiency increases, as evidenced by the decrease in residual oxygen, the production of nitrogen oxides from fuel-bound nitrogen increases.

The non-pulsating data presented in Figure 15 also show a significant increase in NO_x production with increasing primary air/fuel ratio. For non-pulsating combustion under stoichiometric conditions and large residual O₂ levels (i.e., low combustion efficiency), NO_x concentrations averaged about 180 ppm, which decreased to about 115 ppm at an air/fuel ratio of about 0.5. The pulsating data for air/fuel ratios above 1.1 also exhibit this trend of increasing NO_x emissions with increases in excess air. These results are consistent with the hypothesis that most of the NO_x is produced from fuel nitrogen and the amount produced is dependent on the availability of oxygen in the primary combustion zone. The NO_x concentrations under non-pulsating combustion at high residual O₂ (low combustion efficiency) were less than half (stoichiometric) to a fourth ($\alpha = 0.5$) of those produced under pulsating conditions with very low residual O₂ (high combustion efficiency).

Figure 16 shows the exhaust gas sulfur dioxide concentrations measured in both non-pulsating and pulsating tests as a function of residual oxygen concentration. For substoichiometric burning in the primary combustion zone, there is a pronounced trend of decreasing

SO₂ emissions with increasing residual O₂ concentrations (decreasing combustion efficiency). For the non-pulsating tests under stoichiometric and excess air conditions, the scatter in the data is large, but the SO₂ emissions appear to be somewhat larger than in the corresponding substoichiometric tests. The SO₂ data for the pulsating tests, which follow closely a straight line curve fit, fall below the extension of the linear curve fit for the substoichiometric non-pulsating data. This is due partially to the fact that the largest SO₂ values shown in Figure 16 represent nearly complete conversion of the sulfur in the coal to sulfur dioxide.

For test number 3 in Table III, two test segments were run with air staging at 20 cm above the bed under non-pulsating combustion conditions. The first test segment was conducted at a primary air/fuel ratio of 0.7, while the second test segment was conducted at $\alpha_1 = 0.5$. The results of these tests showed that carbon dioxide and residual oxygen levels in the exhaust were not significantly affected by air staging. On the other hand carbon monoxide levels were drastically reduced by air staging, indicating that some of the combustion efficiency was recovered by nearly complete combustion of the CO formed in the primary combustion zone. However the CO apparently was only a small fraction of the coal which did not burn in the primary zone. It is suspected that most of the incompletely burned material under non-pulsating conditions was fixed carbon in the coal which was lost with the ash which fell through the bed. For non-pulsating tests with air staging, the NO_x emissions were increased. For example, at $\alpha = 0.7$, air staging increased the NO_x concentration from 135 ppm to 205 ppm, which was larger than that produced under stoichiometric conditions in the primary zone without air staging. A similar result was obtained for $\alpha = 0.5$. Since this increase occurred in the secondary combustion zone where fuel-bound nitrogen is not expected to be present, it was probably due to thermal NO_x production.

FUTURE WORK

The investigation of methods to reduce NO_x emissions from the Rijke pulse combustor will be continued during the next quarter. A series of air staging tests will be conducted with total air/fuel ratios greater than unity. A series of fuel staging experiments will also be done where propane is injected at various locations in the combustor. In some of these experiments, a small amount of propane will be introduced into the primary air stream sufficiently far upstream of the coal bed to allow thorough mixing with the air before reaching the primary combustion zone. The quantity of propane introduced will be small to prevent ignition of the mixture before it reaches the primary combustion zone. These tests are based on the hypothesis that the propane will compete with the nitrogen for the available oxygen in the primary combustion zone which will reduce the nitrogen oxides emissions. In other tests, the primary combustion zone will be operated with excess air and propane will be burned in a stoichiometric zone downstream of the coal bed. These tests, which are similar to fuel staging methods used in steady combustors, are based on the theory that hydrocarbon radicals formed by the combustion of the propane reduce the NO_x produced in the primary zone to nitrogen (N_2). Only a limited number of fuel staging tests will be conducted, however, since a complete evaluation of fuel staging is beyond the scope of this project.

Investigation of the reduction of sulfur dioxide emissions in the Rijke pulse combustor by addition of sorbent materials will begin in the next quarter. For the sorbent addition experiments, limestone or dolomite will be either mixed with the coal and delivered by the coal feed system or injected in finely pulverized form through the secondary air injector. In the latter method, the pulverized sorbent material is delivered from a hopper by a vertical auger into the air entrainment system. This consists of a small venturi supplied by low pressure air. The auger feeds the sorbent into the throat of the venturi where the high air velocity and low pressure disperses the sorbent particles into the air stream. The sorbent particles are then

carried through a stainless steel line to the radial injector head located just above the coal bed. The sorbent particles then mix with the combustion gases and react with the sulfur dioxide as they are carried out with the exhaust gases. In the sorbent addition experiments, the dependence of SO₂ formation upon the method of sorbent addition (mixed with coal or injected above bed), type of sorbent (limestone or dolomite), Ca/S molar ratio, and amount of excess air will be determined.

REFERENCES

1. Powell, E. A. and Zinn, B. T., "Reduction of NO_x and SO₂ Emissions from Coal Burning Pulse Combustors," Quarterly Technical Progress Report for the Period Sept. 1, 1988 - December 31, 1988, Work performed under U.S. Dept. of Energy Contract No. DE-FG22-88PC88918, January 1989.

Figure 1. Pulverized Sorbent Feed Assembly

Figure 2. Rijke Pulse Combustor and Auxiliary Systems

Figure 3. Dependence of Sound Pressure Levels and Frequencies Upon the Air/Fuel Ratio for Baseline Tests of the Rijke Pulse Combustor.

Figure 4. Effect of Air/Fuel Ratio Upon the Concentrations of Carbon Dioxide, Carbon Monoxide, and Residual Oxygen in the Exhaust Gases for Baseline Tests of the Rijke Pulse Combustor.

Figure 5. Effect of Air/Fuel Ratio Upon the Concentrations of Nitrogen Oxides and Sulfur Dioxide in the Exhaust Gases for Baseline Tests of the Rijke Pulse Combustor.

Figure 6. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Amplitude of the Pulsations in the Rijke Pulse Combustor.

Figure 7. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Carbon Dioxide in the Exhaust Gases from the Rijke Pulse Combustor.

Figure 8. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Carbon Monoxide in the Exhaust Gases from the Rijke Pulse Combustor.

Figure 9. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Concentration of Residual Oxygen in the Exhaust Gases from the Rijke Pulse Combustor.

Figure 10. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Nitrogen Oxides Emissions from the Rijke Pulse Combustor.

Figure 11. Effect of Primary Air/Fuel Ratio and Secondary Air Injection Height on the Sulfur Dioxide Emissions from the Rijke Pulse Combustor.

Figure 12. Effect of Air Staging on the Gas Temperature Distributions Downstream of the Coal Bed.

Figure 13. Comparison of Exhaust Carbon Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

Figure 14. Comparison of Exhaust Carbon Monoxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

Figure 15. Comparison of Exhaust Nitrogen Oxides Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.

Figure 16. Comparison of Exhaust Sulfur Dioxide Concentrations for Non-pulsating and Pulsating Combustion in the Rijke Combustor.