COMBUSTION AND EMISSION CHARACTERISTICS OF SAWDUST-COAL FINE PELLETS

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ABSTRACT

Pellets made from wood and coal residues at various ratios (0, 25, 50, 75, and 100% wood, and 50% wood-plus-limestone) were burned at different underfire/overfire air mixtures (20, 40, 60, and 80%) in a laboratory stationary bed burner to determine the effects of wood/coal ratio and underfire/overfire air mixture on the combustion and emission characteristics of wood-coal pellets.

The results indicated: 1) the oxygen depletion periods appeared to increase with increasing percentages of wood in the pellets and also to increase with increasing underfire air (UFA); 2) increasing wood percentages in pellets decreased flame temperature and total run time, and, thus increased the firing rate; 3) increasing percentages of wood in pellets reduced sulfur dioxide (SO_2) emissions but increased carbon monoxide (CO) and methane (CH_4) emissions; 4) increasing UFA increased the CO, CH_4, and SO_2 emissions; and 5) adding a small quantity of limestone to wood-coal pellets greatly increased the capture of sulfur in the bottom solids and thus reduced the SO_2 emission substantially.

Keywords: Underfire/overfire air, sulfur dioxide, combustion efficiency, volatile matter, firing rate.

INTRODUCTION

During the 1970s, only about 20 to 40% of all the energy consumed by sawmills was generated on-site by burning wood waste (USDA, Forest Service 1976). However, during the 1980s, the wood products industry has been using more and more of its own wood residues to generate energy for in-house use. Although about 10 to 20 million tons of unused mill residues are generated each year at primary wood processing plants (Reed 1981), less wood residue is available for generating energy (Goetzl and Tatum 1983) because the wood industry is using more efficient processing methods to stay competitive and to maintain profits.

One way to alleviate this potential problem is to combine other industrial refuse, such as coal fines, to generate energy for in-house use. Coal fines, a reject product of coal preparation plants, are a combination of fine coal, water, and other impurities. These coal fines are stored in tailing ponds, which are a large source of acid mine drainage and a visual blight to the local environment. Currently, about 86 million tons of unused coal fines are generated in the United States (Bhagwat 1987).

The advantages of combining wood residues with coal waste to produce pellets

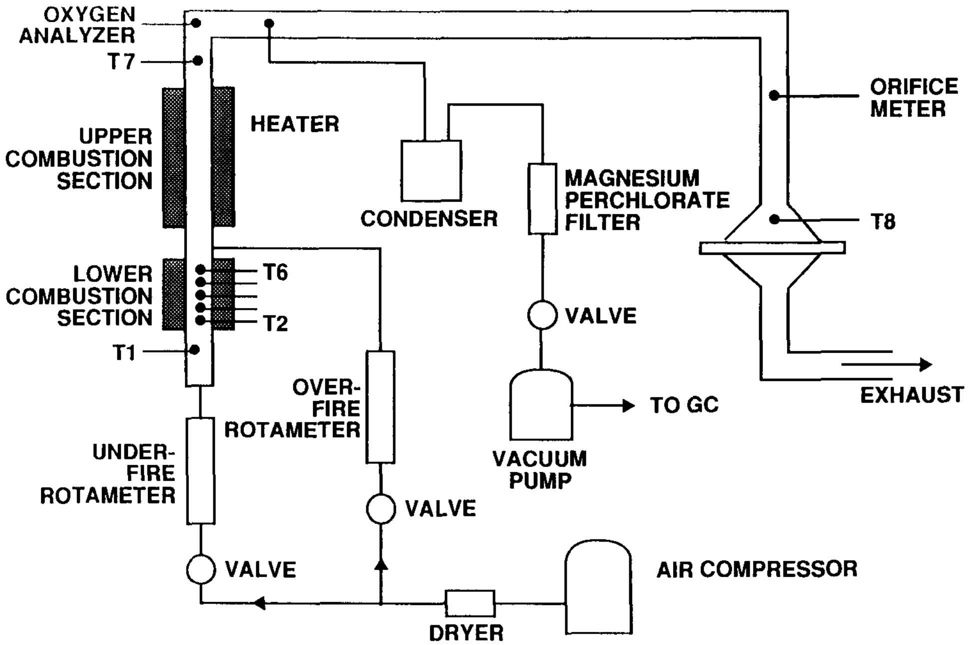

FIG. 1. The laboratory stationary bed burner.

for fuel are numerous. Such a fuel would have a higher energy value per pound, and thus delivered energy costs might be reduced because of lower handling and storage costs. The combination would reduce the pollution effects of the slurry ponds and sawdust hills on the environment. Further, such a combination of raw material to produce pellets for fuel could be especially useful in areas of the United States, such as southern Illinois, Missouri, and Kentucky, where both wood residues and coal fines from thousands of acres of tailing ponds are readily available.

The combustion technology of solid fuel has changed drastically over the last century. Early boilers used stationary bed burning systems. Kreisinger (1939) and Nicholls and Eilers (1934) were early pioneers in the study of stationary bed burning systems. However, only a few scientists have conducted research in this area in recent years (Carman et al. 1957; Starley et al. 1982; Yang et al. 1982).

Spreader stokers were the next innovation in boiler design in which the fine fuel particles were burned in suspension above the larger fuel burned on the grate. This system provided a higher rate of heat release because a higher fuel surface-to-volume ratio was achieved.

Some large electric utility boilers have been burning wood and coal together for years (Singer 1981). However, little research has been done to examine how the operating variables, such as wood/coal ratio, affect combustion and emission characteristics, and the ash and slug accumulation.

Although several studies on the individual combustion of wood or coal have been reported, the problems related to the simultaneous burning of these two fuels have not been fully investigated (Villesvik and Tillman 1983). Even less research has been done on the basic combustion processes of wood/coal pellets or briquettes

TABLE 1. *Composition of wood-coal pellets.*

Nominal % wood	Coal	Sawdust	Hydrolyzed wood	Binder	Limestone
			Weight (%)[1]		
100	0.0	47.5	47.5	5.0	0.0
75	23.8	35.7	35.7	4.8	0.0
50	47.6	23.8	23.8	4.8	0.0
25	71.4	23.8	0.0	4.8	0.0
0	95.2	0.0	0.0	4.8	0.0
50 + lime	44.0	22.0	22.0	4.8	7.2

[1] All percentages were calculated on a dry basis.

in a stationary bed burner, which is most commonly used by the wood industry to burn its own waste to generate energy for in-house use.

The purpose of this paper is to report the effects of wood/coal ratio and underfire/overfire air mixture on the combustion and emission characteristics of wood/coal pellets in a laboratory stationary bed burner.

EXPERIMENTAL BURNER

The experimental burner used in this study was designed and described by Helmer et al. (1988). The laboratory stationary bed burner consists of a combustion air flow system, two combustion sections, gas and particulate sampling systems, and an exhaust system (Fig. 1).

Air is supplied from an air compressor. A regulator on the tank initially reduces the pressure to about 5 psia, and final flow control is achieved with needle valves just upstream of the underfire/overfire air rotameters.

The 4-inch-deep fuel bed is held in place by fine mesh stainless steel screens. Five grounded nicrosil/nisil thermocouples (T2–T6) were placed ½ inch apart in the fuel bed to determine the ignition rate of the fuel (Fig. 1).

The fuel bed is contained in a 4-inch I.D. 304 stainless steel tube, forming the lower combustion section. Nichrome heaters wrap around the fuel bed section and minimize heat loss during combustion. The upper combustion section is 16 inches long and is made from the same 4-inch I.D. stainless steel tubing. It is wrapped around by another set of nichrome heaters. Thermocouple response is continuously recorded throughout the run by using a multipoint recorder.

A zirconia cell oxygen analyzer is mounted directly above the upper combustion section to continuously observe the oxygen concentration in the gaseous emissions. A port to extract a portion of the exhaust gases for gas chromatographic (GC)

TABLE 2. *Properties of wood-coal pellets from laboratory analysis before combustion.*

	Percent wood in pellets					50% w/lime
	100%	75%	50%	25%	0%	
Moisture content (%)	7.25	6.77	6.46	6.22	3.90	5.35
Volatile matter (%)	73.03	63.03	59.14	39.97	29.55	51.39
Ash (%)	2.30	5.89	6.71	12.44	18.34	15.55
Fixed carbon (%)	17.42	24.31	27.69	41.37	48.21	27.71
Heating value (Btu/lb)	7,839	8,682	9,034	10,458	11,218	8,747
Sulfur (%)	0.22	0.76	1.01	2.29	2.76	1.39

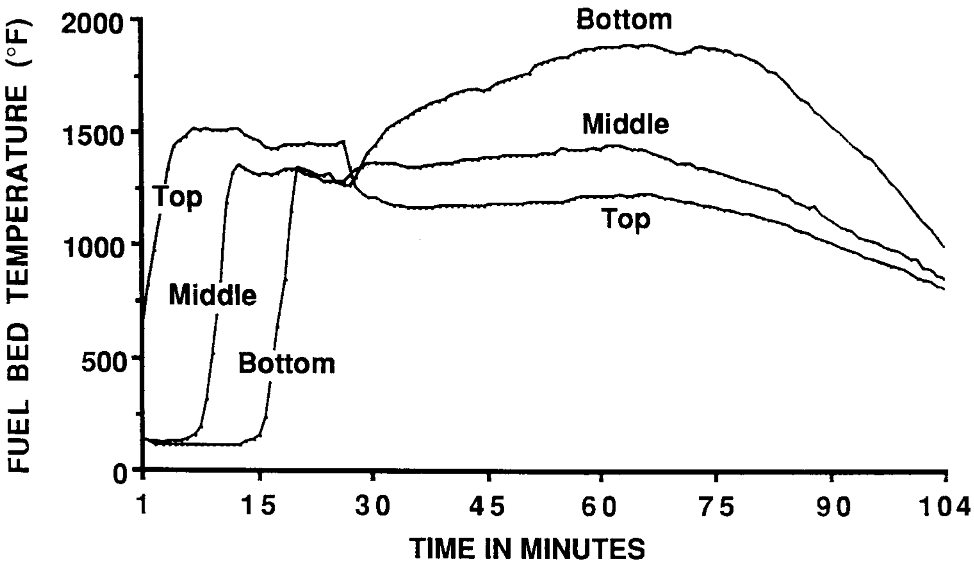

FIG. 2. Fuel bed temperature profile during combustion of 50% wood pellets at 40% UFA.

analysis is located between the zirconia cell and the orifice meter. The orifice meter is used to measure the flow rate of the exhaust gas. An exhaust particulate filter is placed in the stack right after the gases leave the building.

The GC sampling system consists of 1) a port to extract a portion of the exhaust gases, 2) a glass wool and 7-micron filter to trap particulates, 3) an ice bath condenser and a magnesium perchlorate desiccant filter to remove water vapor,

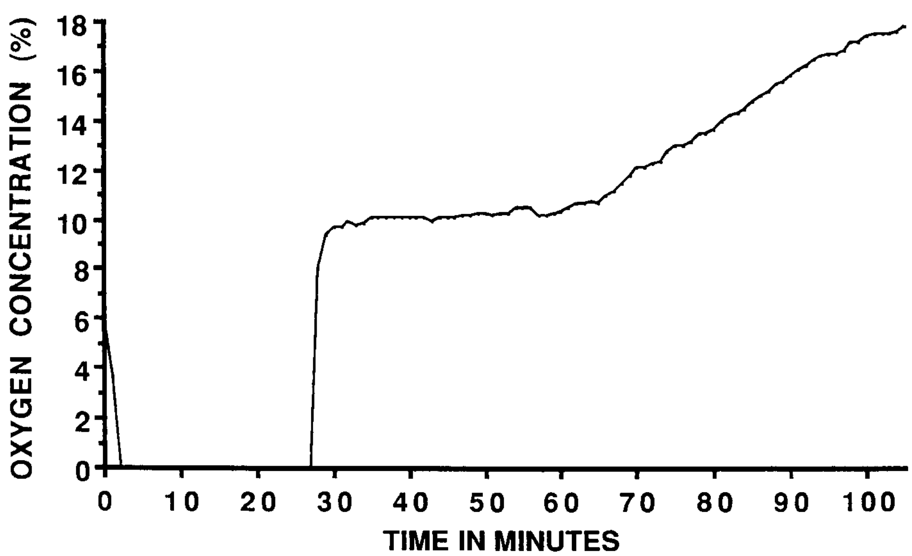

FIG. 3. Oxygen concentration in flue gas during combustion of 50% wood pellets at 40% UFA.

TABLE 3. *Oxygen depletion periods expressed as percentages of the total run times.*

Nominal % wood	Underfire air (%) 20	40	60	80
100	8.0	33.3	40.0	51.1
75	4.5	29.1	33.1	69.8
50	3.1	24.1	27.8	50.0
25	0.0	7.3	20.2	45.6
0	0.0	0.7	16.9	18.7
50 + lime	0.0	14.2	25.3	63.9

and 4) an evacuated Teflon gas sampling bag to collect gas samples during the entire run.

MATERIALS AND METHODS

Approximately 100 lb. of northern red oak sawdust was collected from a local sawmill, and dried from green down to about 5% moisture content (MC). Also, about 100 lb. of clean coal fines having a sulfur content of 2.7% and a MC of about 10% were obtained from southern Illinois. The sawdust and coal fines were made into ½-inch-diameter pellets of various wood/coal ratios (Table 1). One kind of pellet was made with a small portion of limestone, most were made with a portion of hydrolyzed wood, and all were made with some binder.

Before the combustion tests, proximate and ultimate analyses were performed on the pellet samples at the Coal Technology Laboratory at Southern Illinois University. The properties of wood/coal pellets from laboratory analyses before combustion are summarized in Table 2.

In each combustion test, about 1,100 ml of pellets (each ½ inch in diameter, ½ inch to 1¼ inches in length) were required to fill the lower combustion section to the proper level. The lower combustion section was then rotated into place and bolted to the upper combustion section. The upper combustion section was preheated to 1,600 F, while the lower section was preheated to 400 F. As soon as the predetermined air supply was applied and the flow rates for underfire and overfire were set to the proper levels, the combustion began. Air requirements of various pellets were estimated based on a nominal fuel firing rate of 100,000 Btu/hour/ft^2 of grate area, the stoichiometric requirement for each wood/coal pellet and 40%/10% excess air for wood/coal, respectively. Sampling of the flue gas began as soon as the fuel ignited. Analysis of the gas sample by the GC represented

TABLE 4. *Total run times (min) for burning various wood/coal pellets under various UFA.*

Nominal % wood	Underfire air (%) 20	40	60	80
100	112	70	50	45
75	134	87	65	53
50	160	105	73	65
25	254	169	124	102
0	330	230	180	155
50 + lime	182	109	90	72

TABLE 5. *Combustion efficiencies (percent fuel Btu fired) of wood/coal pellets.*

Nominal % wood	Underfire air (%)			
	20	40	60	80
100	98.45	99.52	99.83	99.77
75	98.10	98.97	99.71	99.42
50	98.68	98.96	99.61	99.54
25	98.91	97.43	97.50	98.93
0	95.79	98.68	99.05	98.65
50 + lime	98.74	99.89	99.94	98.84

an average value over the entire run. The actual run time was based on the complete combustion of the fuel (when the bottom thermocouple, T2, dropped below 1,000 F, and the oxygen analyzer registered at least 17%).

The gas sample bag was removed at the end of the run for GC analysis. The particulate filter was also removed from the exhaust system (Fig. 1) and placed in an oven to dry and be weighed the next day. After the lower combustion section cooled, the bottom solids were collected, weighed, and analyzed to determine their composition.

Sulfur balances were calculated using measurements of the sulfur in the fuel, and the sulfur determined in the bottom solids. The sulfur dioxide (SO_2) measurements presented in this paper were based on the difference between the sulfur measured in the fuel before combustion and the sulfur measured from the bottom solids analyses.

Pellets from each wood/coal ratio were burned with four different percentages of underfire/overfire air flow: 20/80, 40/60, 60/40, and 80/20. Twenty-four (6 × 4) combustion tests were conducted.

RESULTS AND DISCUSSION

Pellets containing more wood have lower percentages of ash content and fixed carbon, lower heating value, and more volatile matter than pellets with more coal (Table 2). Even though the nominal 100% wood pellets have very low sulfur content compared to 100% coal pellets (Table 2), the sulfur content of 100% wood pellets was 22 times higher than the 0.01% sulfur found in the northern red oak sawdust (Helmer et al. 1988). The high sulfur content may be due to the addition

TABLE 6. *Average flame temperatures (°F) produced when burning pellets of various wood/coal ratios under various UFA.*

Nominal % wood	Underfire air (%)			
	20	40	60	80
100	1,492	1,586	1,621	1,691
75	1,633	1,674	1,664	1,757
50	1,608	1,619	1,700	1,762
25	1,617	1,671	1,778	1,834
0	1,556	1,736	1,793	1,830
50 + lime	1,605	1,736	1,747	1,850

TABLE 7. *SO_2 emissions (lb/million Btu produced) when burning pellets of various wood/coal ratios under various UFA.*

Nominal % wood	Underfire air (%) 20	40	60	80
100	0.3369	0.3629	0.3961	0.3757
75	1.2072	1.4323	1.5610	1.6161
50	1.7140	1.9312	2.1044	2.1038
25	3.7168	3.7931	3.9400	4.1813
0	3.6526	4.2849	4.5561	4.6149

of hydrolyzed wood during pelletization. Sulfuric acid is commonly used in hydrolyzing wood.

The temperatures at the top (T6), the middle (T4), and the bottom of the fuel bed (T2) were shown as a function of time during a typical combustion test of 50% wood pellets at 40% underfire air (UFA) (Fig. 2). The flame front took about 15 minutes to reach the bottom of the fuel bed. After about 27 minutes, the temperature of T6 dropped abruptly while T2 temperature rose rapidly. These temperature changes indicated that the fuel bed may have collapsed and the height of the fuel bed may have dropped below the top thermocouple (T6). This also may have signaled the end of combustion of volatile matter in the fuel because the timing coincided with the end of oxygen (O_2) depletion period (where the oxygen analyzer recorded 0% oxygen) and the rapid rising of O_2 concentration in the emission gases (Fig. 3). After about 90 minutes, the top thermocouple temperature began to decrease, indicating that the top of the fuel bed was starting to burn out.

The oxygen depletion periods expressed as percentages of the total run times, appeared to increase with increasing percentages of wood in the pellets and with increasing UFA (Table 3). Obviously, pellets with a greater proportion of wood contain more volatile matter that burns easily and depletes O_2 longer. The reason that the percent of O_2 depletion period increased with increasing UFA is not immediately apparent. The shortening of the total run time with increasing UFA (Table 4) may increase the percentages of O_2 depletion periods (Table 3).

The combustion efficiencies, ranging from 96 to 100%, of all types of pellets were excellent (Table 5).

$$\text{Combustion efficiency (\%)} = \left[1 - \frac{\text{unburned fuel in bottom solids (Btu)}}{\text{initial fuel placed in burner (Btu)}}\right] \times 100$$

TABLE 8. *Analysis of variance of SO_2 emissions when burning pellets of various wood/coal ratios under various UFA.*

Source of variation	df	S.S.	M.S.	F.
Wood/coal ratio	4	43.98	10.99	366.33**
Underfire air (%)	3	0.60	0.20	6.66**
Error	12	0.32	0.03	
Total	19	44.90		

** Significant at 1% level.

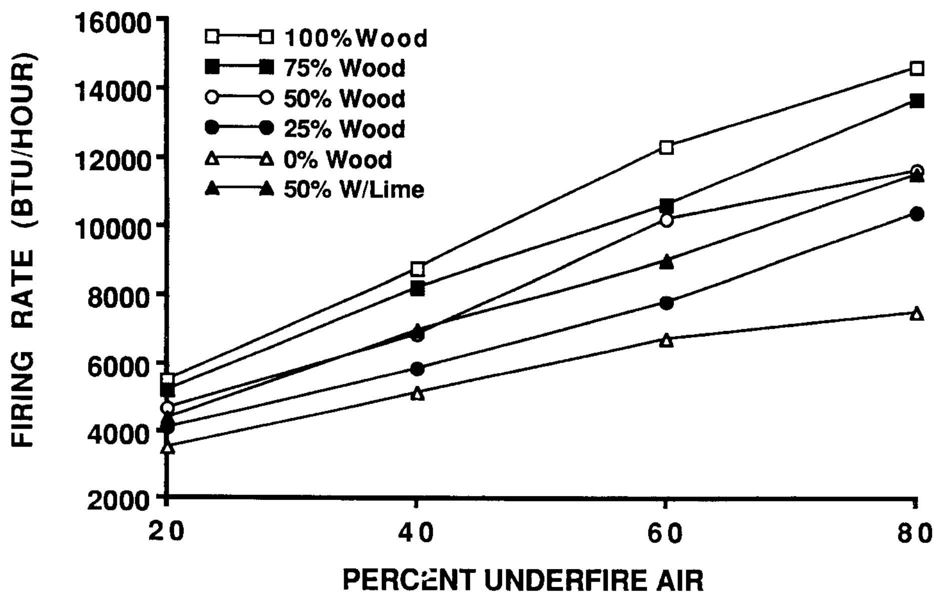

FIG. 4. Effects of UFA and wood/coal ratio on the firing rate of various pellets.

No substantial difference in combustion efficiency was detected among pellets of various wood/coal ratios and among various UFA (Table 5).

Wood/coal ratio appeared to have a significant influence on both the combustion and emission characteristics of pellets (Tables 7 and 8). Increasing wood portion

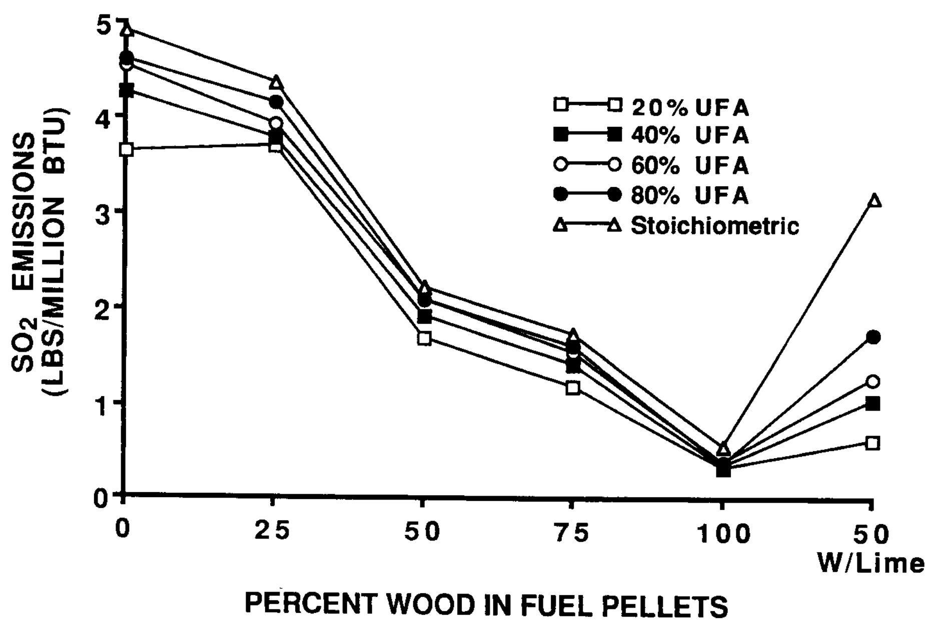

FIG. 5. Effects of UFA and wood/coal ratio on sulfur dioxide emissions.

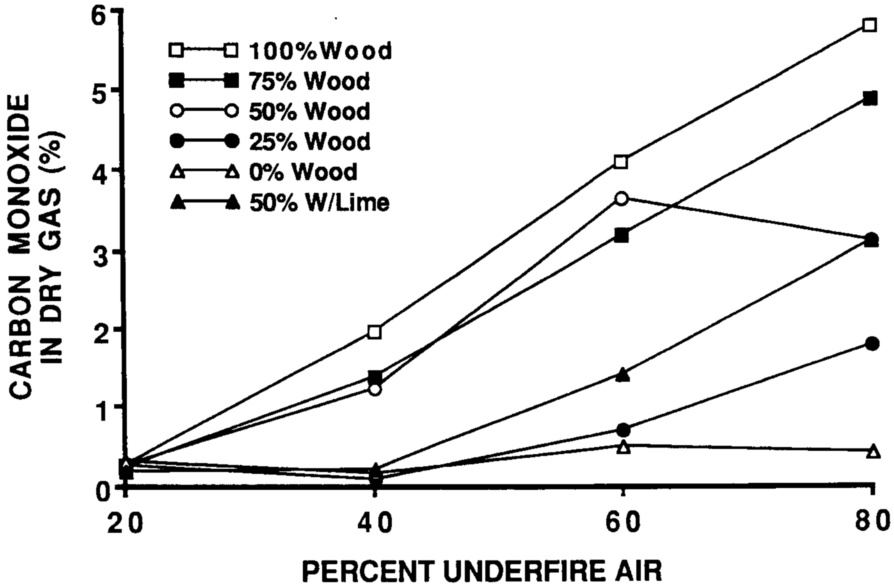

FIG. 6. Effects of UFA and wood/coal ratio on carbon monoxide formation.

in pellets showed a general trend of decreasing flame temperature (Table 6). This decrease may be because wood contains more volatile matter, which burns at lower temperatures, than coal, which has more fixed carbon (Table 2).

Increasing percentages of wood in pellets reduced the total run time substantially (Table 4) and, therefore, increased the firing rate (Btu/hour) (Fig. 4).

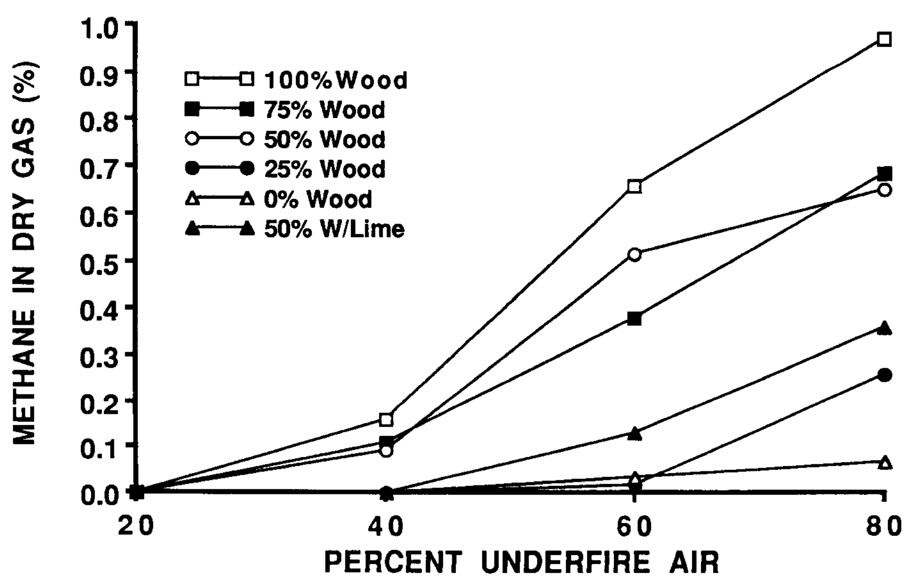

FIG. 7. Effects of UFA and wood/coal ratio on methane in the dry gas.

Increasing percentages of wood in pellets reduced SO_2 emissions (Fig. 5), presented in terms of pounds of SO_2 per million Btu of fuel input. This is the current emission parameter used by state and federal agencies to rate combustion facilities to determine if they comply with Environmental Protection Agency standards. Decreased SO_2 emissions, with increased wood in the pellets, were expected because wood has a very low sulfur content compared to coal (Table 2). However, burning wood/coal pellets appeared to reduce SO_2 emissions beyond the simple dilution effect from the addition of wood to the high-sulfur coal; all SO_2 emissions from burning pellets of various wood/coal ratios under various UFA were lower than the corresponding stoichiometric levels (Fig. 5).

Increasing wood content in pellets appeared to increase carbon monoxide (CO) and methane (CH_4) emissions (Figs. 6 and 7). However, this increase appeared to be magnified greatly by the increase of UFA because less oxygen was available above the fuel bed for converting CO and CH_4 to CO_2 and H_2O.

The underfire/overfire air mixture also significantly affected both the combustion and emission characteristics of pellets (Tables 7 and 8). Increasing UFA increased the average flame temperature (AFT) (Table 6) but decreased the total run time (TRT) (Table 4) and resulted in increased firing rate (Btu produced/hour) (Fig. 4). Increasing UFA means increased O_2 supply to the lower combustion chamber (Fig. 1), which in turn raises the combustion rate (firing rate) and shortens the TRT.

Increasing UFA increased the CO and unburned CH_4. The existence of CO and CH_4 indicated that insufficient O_2 was provided to the volatile exhaust gases above the burning fuel bed.

Increasing UFA also increased SO_2 emissions significantly (Tables 7 and 8). This shows that sulfur also has a great affinity toward O_2. Higher UFA would produce higher AFT; at elevated temperatures, a greater proportion of lignosulfonate, possibly an intermediate compound during the combustion of wood/coal pellets, would be burned and generate more SO_2 into the exhaust gases.

Adding a small quantity (7.2%) of limestone to the 50% wood/50% coal pellets greatly increased the average percentage of fuel sulfur captured in the bottom solids (62.7%) compared to the 50% wood/50% coal pellets (12.2%) and thus reduced SO_2 emissions greatly (Fig. 5).

CONCLUSIONS

Burning wood/coal pellets slightly reduced SO_2 emissions beyond the simple dilution effect from the adding of wood to the high-sulfur coal.

Both wood/coal ratio and underfire/overfire air showed significant effects on both the combustion and emission characteristics of various types of pellets.

Adding a small quantity of limestone to the wood/coal pellets greatly reduced SO_2 emissions.

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