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PERFORMANCE OF A SMALL SCALE BOILER BURNER IN THE FIRING OF LOW SULFUR WYOMING COAL

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Abstract

A small scale boiler burner has been constructed for the purpose of firing low sulfur Wyoming coal. The demand for low sulfur coal is increasing, because of the demanding emission regulations. Tests are being conducted to determine performance characteristics such as, flame stability criteria, and pollution emissions measurements.

Preliminary results indicate that the fraction of fuel burnt is a function of reactor temperature. Complete combustion occurs when the oxygen concentration is zero. Emissions of NO$_x$ and SO$_x$ generally increased as the burn fraction increased, however the conversion efficiency of N to NO decreased as oxygen content decreased. In contrast, the conversion efficiency of S to SO$_x$, increased at the same time indicating that the formation of SO$_x$ is more temperature sensitive than oxygen sensitive.

Introduction

Coal has become the dominant fuel for the production of electricity in the United States. Figure 1 shows that the use of coal in the production of electricity for the year 1991 was predominant, producing over 75% of the electricity generated. As such, the attendant pollutant emissions has also increased. Dominant among these pollutants are the production of sulfur oxide (SO$_x$) and nitrogen dioxide (NO$_x$) which cause acid rain and ozone depletion. Since coal will continue to be the dominant source of fuel for electricity production for the foreseeable future, additional techniques and/or methods must be undertaken in an effort to reduce gaseous emissions. Federal regulations regarding the emission of these pollutants have become particularly demanding. The current New Source Performance Standards (NSPS) for SO$_x$ and NO$_x$ are each, respectively 0.000258 Kg/MJ (0.6 lb/MMBtu). The NSPS have increased the demand for low sulfur coal, particularly Wyoming coal. As a result the cost of Wyoming coal has risen to approximately $40 per ton delivered.

The difficulties of firing low sulfur coals are as follows:

(i) low heating value compared with higher sulfur coals,
(ii) high potential for fouling and slagging,
(iii) the need for additional boiler auxiliaries.

Literature Review

The five principal classes of pollutant species emitted from combustion sources are particulates, sulfur oxides, carbon monoxide, nitrogen oxides, and organic compounds (largely hydrocarbons). The general goal of maximizing combustion efficiency and minimizing pollutants can be conflicting, since combustion efficiencies are maximized near stoichiometric conditions, where the highest temperatures are achieved. Carbon monoxide, unburned hydrocarbons, and particulates are thus minimized, but these high temperatures lead to a maximum formation of NO$_x$. Optimization therefore, can only be achieved by control of the air/fuel ratio and temperature levels.

Sulfur is found in most types of coal. During combustion, sulfur reacts with oxygen to form, primarily sulfur dioxide, SO$_x$, and to a lesser extent, sulfur trioxide, SO$_{3}$. Typically the sulfur content in coal varies between 0.4% and 2.0% by weight. There are two types of sulfur in coal: organic sulfur, which is bound to the hydrocarbon structure of the coal and inorganic sulfur, which is the remainder. The type and content of sulfur in the coal will determine the level of SO$_x$ emissions.

Nitrogen oxides are produced during combustion by (i) thermal fixation of nitrogen from combustion air, and (ii) the conversion of fuel bound nitrogen to NO$_x$. Thermal fixation becomes significant at temperatures above 1540°C (2800°F); fuel nitrogen conversion takes place at a much lower temperature and therefore is the main source of NO$_x$ in coal combustion. About 80% of the NO$_x$ in pulverized coal combustion is fuel NO$_x$ [Meyers, 1981].

Objectives

The primary objectives are to gather data in the areas of emissions and flame stability when fired with Wyoming coal.

(i) operational parameters such as burn fraction,
(ii) burner rating and reactor temperature,
(iii) pollutants production and measurement,
(iv) pollution conversion efficiency.
Experimental Setup

A schematic of the experimental setup is shown in Figure 2. The boiler burner (1) is 152 m (6 in.) in diameter and 1.575 m (62 in.) in height. The boiler burner is supported by a iron flat support stand, anchored to the cement floor. The entire boiler is constructed from stainless steel. The boiler contains three viewing ports mounted at 5.1 cm (2 in.) apart and located underneath the door (see Figure 3a). The windows are fused quartz housed in a stainless steel body. They can be removed to allow for periodic cleaning. Three sampling ports serve as locations to perform emission sampling. The combustion air is supplied by a secondary air blower (2) driven by an adjustable speed DC motor. The blower is rated to deliver up to 41 g/s (325 lb/hr). The secondary air is preheated to a minimum of 200 °C with the use of a circulation heater (3 kW) (3) before it enters the boiler (4). The fuel feed system consists of a feed hopper (5) with a capacity of 14 kg (30.8 lbs) which tapers into a rectangular cone. Compressed air is supplied through the top of the feed hopper in order to maintain a positive pressure higher than the boiler burner. An auger screw (6) runs through the conical section of the feed hopper and is driven by an adjustable DC motor (1/2 hp, 1725 rpm) (7). The auger can deliver up to 200 g/min (0.41 lbs/min) of coal into the boiler burner. The primary air (8) is supplied by the laboratory and can deliver up to 432 g/min. The purpose of the primary air is to carry the fuel (9) and to a lesser extent provide a fraction of the combustion air. The boiler burner walls are insulated on the outside with a fibrous aluminia-silica blanket (see Figure 3a) rated to operate at a maximum temperature of 1300 °C (2372 °F). Dual water jets are injected into the boiler to catch the particulates and ash, which empty into a 113.6 L (30 gallon) polyethylene tank. The products of combustion are exhausted with an induced draft fan, capable of providing a vacuum of 0.5 inches water gauge inside the boiler burner. The entire facility can be operated from a central control panel (10). The diagnostic system consists of an orifice plate for measuring the secondary air flowrate, sheathed type K and type S thermocouples (see Figure 3a) both in the boiler, the secondary air stream and in the exhaust. Rotometers are employed to measure the primary as well as hopper air flowrates. Emission measurements are performed using a Lancom 6500 emission measuring system. The system can accurately measure six gases including, SO₂, NO, NO₂, CO, CO₂, and O₂.
Burner Characteristics

The burner is a concentric type swirl burner with downward fining and is shown in figures 3b and 4a. The primary airfuel nozzle is 1.905 cm (¾ inches) in diameter. The secondary air duct is 3.175 cm (1 ½ inches) in diameter. The entire burner is constructed from stainless steel. An impeller plate at the primary airfuel exit serves to split the thick stream of coal into thin streams and also to direct the coal into the hot recirculation zone. Radially attached swirlers provide the necessary swirl to create a recirculation zone. A swirl greater than 0.6 is necessary to create a recirculation zone (Beer and Chigier, 1972). The swirl number is a function of the burner geometry and swirl angle. For the burner in this experiment the swirl angle is 60°, and the swirl number is 1.4.

The quartz (see Figure 4b) is constructed from ceramic fiber boards rated for 1300° C continuous service temperature. The quartz has an L/D ratio of 1.8. The quartz half angle is 24°, which is nearly optimum as determined by Fricke and Leuckel, 1976.

The burner is fitted with a propane torch which serves to preheat the boiler and initiate combustion. The torch rating is approximately 1% of the total burner rating; this to ensure that the contribution of the propane torch is negligible in emission measurements as well as performance of the boiler burner. A summary of the burner characteristics can be found in table 1.

![Swirl Burner Dimensions](image)

**Figure 4a Swirl Burner Dimensions**

![Quartz Dimensions](image)

**Figure 4b Quartz Dimensions**

<table>
<thead>
<tr>
<th>Table 1 Burner Characteristics</th>
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<tbody>
<tr>
<td>Burner Rating</td>
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<tr>
<td>Particle Size</td>
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<tr>
<td>Primary airfuel nozzle diameter</td>
</tr>
<tr>
<td>Secondary air nozzle diameter</td>
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<tr>
<td>Swirl angle</td>
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<tr>
<td>Swirl number</td>
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<tr>
<td>Quartz half angle</td>
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<tr>
<td>Quartz L/D</td>
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<tr>
<td>Primary Air Velocity (cold flow)</td>
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<tr>
<td>Secondary Air Velocity (cold flow)</td>
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</table>

Experimental Procedure

The performance of the boiler burner was determined by conducting combustion experiments and determining the airfuel burned ratio, excess air, and emission measurements. The experiments were performed with different reactor temperatures and airfuel burned ratios. The emission measurements were measured with the emission monitoring system.

The coal being fired is a low sulfur sub-bituminous Wyoming coal pulverized to a size of 70% minus 200 mesh (75 μm) with the characteristics shown in Table 2.

The experimental procedure for fining was as follows:

(i) The boiler burner was preheated to the desired temperature using the propane torch.
(ii) The secondary air was preheated to a minimum of 200° C using a circulation heater.
(iii) Once the appropriate temperatures were reached in the boiler, coal was injected and the experimental data were recorded. The propane torch remained on during the experiment to compensate for heat lost in the boiler.
(iv) Data were taken for: the temperature along the centerline of the boiler at various locations, air flowrates, and composition of the flue gases. The flue gas temperature was also recorded using the emission monitoring probe mounted in the second sampling port.

<table>
<thead>
<tr>
<th>Table 2 Coal Characteristics</th>
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<tbody>
<tr>
<td>Carbon (%)</td>
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<tr>
<td>Hydrogen (%)</td>
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<tr>
<td>Oxygen (%)</td>
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<tr>
<td>Nitrogen (%)</td>
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<tr>
<td>Ash (%)</td>
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<tr>
<td>Vol. Matter (%)</td>
</tr>
<tr>
<td>Fixed Carbon (%)</td>
</tr>
<tr>
<td>Moisture (%)</td>
</tr>
<tr>
<td>Heating Value</td>
</tr>
<tr>
<td>24995 kJ/kg</td>
</tr>
<tr>
<td>Chemical Formula</td>
</tr>
<tr>
<td>A DAF, basis</td>
</tr>
</tbody>
</table>

* Determined from ultimate analysis
* Based on Chemical Formula

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Results and Discussion

Boiler performance will be discussed in terms of, burnt fraction, temperature distribution, and most importantly emission measurements.

Figure 5 shows the axial temperature distribution in the boiler, measured from the burner nozzle exit. The maximum axial temperature is indicated to be approximately 43 cm (17 in) from the burner exit. The radial temperature distribution is relatively flat, varying by less than 50 K. The maximum axial temperature usually occurs in the recirculation zone boundary. This would indicate the recirculation zone is approximately 43 cm (17 in) in length.

The fraction of fuel unburned will depend on the residence time for combustion and also the reactor temperature. Figure 6 plots the burnt mass fraction of fuel versus probe temperature. Initially, as cold fuel enters a relatively cool reactor, a large percentage of the fuel will be unburned. As the fuel is burned in the reactor and probe temperature slowly increase, accompanied by an increase in the burnt fraction. When the burnt fraction approached 100%, a peak probe temperature of approximately 1070° K was produced in the reactor. It should be noted that the flame temperature at the edge of the recirculation zone (RZ) will be generally much higher. NOx and SO2 measurements were made on temperature profiles inside the RZ, measurements at the edge will be performed at a later date.

As a result of the large portion of unburned fuel, the oxygen in the flue gases will appear to be large, producing an artificially high air to fuel burned ratio. The burnt fraction can be calculated by performing an atom balance on the coal. Knowledge of the O2 content in the flue gas will allow for the use of the atom balance equations and therefore the burnt fraction of fuel can be calculated (see Figure 7). As the fraction of fuel burnt continues to increase the reactor temperature will also increase. As expected the burnt mass fraction is 100% when there is no un consumed O2 in the flue gases. As the O2 content is decreasing the excess air content is also decreasing. It is important to note that the excess air (O2) present is not the excess air delivered to the boiler in the form of primary and secondary air, but the amount of excess air (O2) present as a result of unburned fuel.

Emission measurements were taken for different air/fuel burnt ratios and temperature ranges. All emission measurements have been normalized with 3% O2 in the products as prescribed by EPA guidelines. The sampling probe for each measurement was located at the centerline of the boiler far enough down stream to ensure complete combustion. Figure 8 shows the effect of the fuel burnt fraction on SO2 and NOx emissions. As more fuel is burned, more SO2 and NOx are produced and hence NOx and SO2 emissions increase. However as more fuel is burned, O2%...
decreases and therefore the rate of increase of NOx, with burn mass fraction decreases reaching a maximum at 83% burn fraction. Alternatively, SO2 emissions continue to increase with an increase in burn mass fraction and a decrease in O2%. This indicates that the production of SO2 is a strong function of the burn mass fraction. Maximum SO2 emissions occurred when 100% of the fuel was burned. In both cases the emissions fall within the NSPS guidelines of 0002579 kg/MJ (0.6 lb/MMBtu) at their maximum, NOx and SO2 were respectively: 000197 kg/MJ (0.46 lb/MMBtu) and 000006 kg/MJ (0.14 lb/MMBtu). Temperature will have a negligible effect on emissions, particularly NOx, since its formation is dominantly fuel derived at temperatures under 1500°K (3200°F). It would be overly simple to say that the production of NOx and SO2 were simply related to A:F ratio and burn fraction. The trend of CO and CO2 production is also important.

From a knowledge of the flue gases and the ultimate analysis of the coal it is possible to calculate the conversion efficiency of sulfur and nitrogen in the fuel to SOx and NOx respectively. It appears that the conversion efficiency is related to the percent of fuel burned. Figure 9 shows the effect burn fraction on conversion efficiency. The amount of sulfur and nitrogen bound in the fuel is converted to SOx and NOx, depending on the fraction of the fuel that is burnt. The conversion efficiency of sulfur to SOx is a maximum (24%) when the burn fraction is 100%. On the other hand NOx conversion efficiency is a maximum (49.5%) when the burn fraction is a minimum at 58% (8.23% O2). The minimum or maximum burn fractions may not be the actual minimum or maximum but they merely represent the minimum or maximum value measured. The minimum SOx conversion efficiency occurs when the burn fraction is approximately 83% (3.25% O2), for NOx at 100%. The NOx conversion efficiency decreased with increased burn fraction due to decreased O2 available for the conversion of fuel N to NO. At the same time the conversion efficiency of fuel S to SOx increased for the same reason as discussed above.

Summary

A small scale boiler burner facility (35 kW) has been built and instrumented for measuring temperature distribution in the boiler, pollution emissions, and composition of the flue gases. The burner is a downward fired swirl burner with a swirl number of 1.4.

The burn fraction of fuel is a function of reactor temperature. The production of SO2 and NOx generally increase with an increase in the burn fraction, but the conversion of fuel N to NO decreases as the O2% decreases. However, fuel S to SOx conversion efficiency continues to increase as O2% decreases, probably due to increased burn fraction.

Acknowledgement

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References


