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A method to target and correct sources of unburned carbon in coal-fired utility boilers

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HIGHLIGHTS

- ▶ A general method was developed to identify sources of unburned carbon in utility boilers.
- ▶ Oxygen availability was found to play the key role in burnout rather than residence time.
- ▶ A simple strategy was designed to improve burnout by targeting air to specific regions.
- ▶ 80% of the unburned carbon is from the 6 out of the 16 coal burners.
- ▶ Coal particles larger than 140 μm contribute 70% of the total unburned carbon.

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ABSTRACT

This study presents a novel method to examine particle burnout in coal-fired utility boilers by extracting information from computational fluid dynamics (CFD) model results. The direct targeting of underlying causes enabled by this method can provide dramatic improvement in the unburned carbon in fly ash (carbon-in-ash or CIA), improving the commercial value of the ash as an additive in the production of concrete and cement and improving boiler efficiency. Data for thousands of particles are extracted and summarized for engineering characteristics such as injection burner, particle size, residence time, and exposure to oxygen. As an example of the method, unburned carbon is studied for a 200 MWe tangentially-fired utility boiler with CIA issues. The analysis, which is consistent with boiler operation data, reveals that a majority of CIA can be contributed by a disproportionately small number of sources, hence the advantage of a targeted approach. The analysis of the 200 MW boiler reveals that fewer than half of the burners contribute about 80% of the CIA and the two largest coal particle size classes contribute 70% of the CIA. Most importantly, however, the oxygen availability for the coal particles is found to be the key factor for coal burnout. Based on this result, a simple and targeted strategy to improve burnout by improving oxygen availability is designed. This method is predicted by the model to reduce CIA from 3.27% to 1.3% and NOx from 588 ppm to 503 ppm.

1. Introduction

Fly ash is a by-product of pulverized coal-fired power generation. It is often sold as an additive in the production of concrete and cement to reduce the production cost and to improve the performance of the concrete [1]. In addition, utilization of fly ash reduces the disposal cost of fly ash and abates its impact on the environment. However, the unburned carbon in fly ash can impact the performance of the concrete by absorbing the air-entraining admixtures [2–4] which are used to improve workability and freeze–thaw resistance of the concrete [5]. Therefore, the unburned carbon content in fly ash (CIA) is regulated to be under a certain limit in concrete production [6]. Also, unburned carbon in fly ash reduces boiler efficiency [7,8], increases the fuel cost, and may reduce electrostatic precipitator (ESP) efficiency [9]. Therefore, minimizing unburned carbon in fly ash is always in the interest of power utility companies. Currently, the wide application of low NOx technologies in utility boilers has caused an increase in CIA in many boilers [5,10,11]. Also, the increase in fuel blending and fuel changes in many utility companies has caused unpredictable changes in CIA for utility boilers.

Various measures have been taken to reduce CIA in utility boilers, including reducing coal particle fineness, fly ash reburning, fly ash classification and combustion tuning. These measures are usually expensive and are applied to the boiler as a whole, rather than targeting specific causes. It would be more cost-effective to reduce CIA if the specific sources of the unburned carbon could be identi-

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fied. For example, if some burners are identified as the largest contributors of the unburned carbon, measures to address the high CIA problem, such as reducing the particle fineness, would mainly focus on these burners rather than the other burners. Currently, the only measureable data for unburned carbon in ash in utility boilers is from fly ash sample analysis. The fly ash samples, which are usually collected in either the ash hoppers or the specific collection devices, typically contain a mixture of coal particles from all burners and size classes in the unit. This obscures contributions to CIA from individual burners and particle size classes.

Computational fluid dynamics (CFD) modeling technology has developed rapidly during the past two decades to the extent that it can now provide a reasonable prediction of coal combustion in utility boilers. As a result, the application of CFD to utility boilers [11–18] is growing rapidly. Some authors have used CFD to predict CIA for utility boilers. Javier et al. [11] focused on advanced char oxidation models and their incorporations with a CFD code to improve CIA predictions. Wan et al. [12] investigated the effect of coal reburning on CIA and used the CFD analysis to identify improvements that addressed the often competing objectives of low NOx and low CIA. Sathyanathan and Mohammad [20] used an empirical equation to predict overall unburned carbon for tangentially-fired boilers, including the effects of coal properties, air distribution, residence time, coal particle fineness, burner type and number but not the detailed configuration of the boiler and the burners. Stephenson [21] developed a computer model to predict the combined effects of operating conditions and coal quality on coal burnout. The temperature distribution and particle residence time calculated in a CFD simulation, incorporated with operating conditions and coal properties, was used for the predictions. These works mainly focus on the prediction of the overall CIA. The contribution of the unburned carbon in a utility boiler from specific sources has not been systematically investigated in the open literature, except for Wan et al. [12], who used CFD simulation results to analyze the contributions of the burners on the total unburned carbon in fly ash for a front wall-fired utility boiler. Their study found the unburned carbon was mainly caused by particles flowing through fuel-rich regions and/or spending insufficient residence time in the furnace.

The intent of this study is to develop a method to identify the contributions to the total unburned carbon in fly ash from different causes such as residence time, particle size, and oxygen availability using a novel analysis of the coal particle burnout information from CFD simulation results. Such a method could guide utility power companies to take cost-effective measures to reduce unburned carbon in fly ash. This analysis also challenges and refines the concept that short residence time of particles would produce high CIA by systematically taking into account the exposure to oxygen along the particle paths in the main combustion region from burner to furnace outlet.

2. Method

2.1. Computational fluid dynamics

This study re-analyzes CFD data that had been generated with the commercial CFD platform CFX-TASCflow [22]. CFD modeling solves the time-averaged conservation equations for the gas and coal particle to predict the boiler operations. An Eulerian approach is used for the gas phase while the particle phase is treated in a Lagrangian framework. Turbulence is incorporated with the standard k–ε model for closure. Coal particles experience devolatilization and char oxidation in the boiler. The pulverized coal combustion model is based on the works of Lockwood [23–25]. In particular, coal particle devolatilization is calculated using a first order single reaction model [26] and the volatile combustion is controlled by the mixing rate of the reactants [27]. Char oxidation rate is calculated by the chemical kinetic rate and the external diffusion rate of oxygen to the char surface [23]. The NOx model accounts for the thermal, prompt and fuel NOx mechanisms based on the modeling approach suggested by Chui and Hughes [19].

Thousands of coal particles from different coal burners, statistically representing different size classes according to the measured size distributions, are tracked in their travels throughout the boiler while undergoing both devolatilization and char oxidation processes [22]. Particle information including diameter, char fraction, volatile fraction, residence time, and coordinates change along their trajectories is recorded in a data file. The focus of this work is to process and present this data in a novel way, in order to gain a level of understanding beyond the usual analysis of CFD results.

2.2. The analysis method

As mentioned in Section 2.1, the individual particle information for thousands of coal particles along their trajectories is stored in a data file. To process the data, a script was written to extract the desired particle information from the data file, such as the particle information at a designated plane, particle information for a particular burner or a size class and particle information along their trajectories. The information can be used to calculate the average CIA, average particle residence time, average oxygen exposure, and the contributions on total unburned carbon of each burner or size class. Further, the information can be used to calculate the average particle temperature and oxygen mass fraction along the particle trajectories to analyze the causes of high CIA of the particles. The average oxygen mass fraction $\bar{w}_{O_2}$ along a particle trajectory from a burner to a designated location can be calculated by

$$\bar{w}_{O_2} = \left(\int_0^{t_1} w_{O_2} dt\right) \bigg/ t_1 \tag{1}$$

where w_{O_2} is the oxygen mass fraction on the particle path at time t, which is calculated by interpolating the fluid oxygen fraction around the particle onto the particle track, t is the particle traveling time, and t_1 is the total traveling time of the particle to the designated location from the burner. Similarly, the average particle temperature, $\overline{T}$, along the particle trajectory can be calculated by

$$\overline{T} = \left(\int_0^{t_1} T\,dt\right) \bigg/ t_1 \tag{2}$$

where T is the particle temperature at time t.

The average oxygen mass fraction for the particles of a particular size class is the average value for all the tracked particles of that size class; the average oxygen mass fraction for the particles of a particular burner is the average value for all tracked particles from that burner.

3. Example: 200 MWe boiler

3.1. The boiler

Fig. 1A shows the 200 MWe tangentially-fired utility boiler and its two groups of platen super heaters in the upper furnace. The coal burners (light gray squares labelled by levels A, B, C and D in Fig. 1B), the air nozzles (black squares labelled by levels AA, AB, BC, CD and DD in Fig. 1B) and oil guns (black circles labelled OA, OB in Fig. 1B), identical for each corner, are shown in Fig. 1B. The injection directions of the air nozzles, coal burners and oil guns are the same in each corner and are shown in Fig. 1C. These injection angles are designed to generate a counter clockwise rotating flow in the boiler. The boiler is firing a bituminous coal, whose coal properties including coal reaction parameters are listed in Table 1.