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Pulverized coal ignition delay under conventional and oxy-fuel combustion conditions

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1. Introduction

In pulverized coal (pc) burners, high velocity streams of coal particles turbulently mix with surrounding hot gases of flame products and must ignite in tens of milliseconds. Therefore, the key ignition characteristic for burner design and operation is the ignition delay of coal streams introduced into hot surroundings. To-date, most information on ignition delay has been gleaned from experiments and modeling of individual reacting coal particles, in most cases using particles substantially larger than those that dominate practical pulverized coal behavior. Although single-particle studies are undoubtedly useful for the study of ignition and combustion of dilute particle streams, multi-particle group effects are likely important to the flame-holding process for practical burners. Therefore, an understanding of the ignition characteristics of a continuous flow of pulverized coal particles at different particle number densities is needed to address actual industrial practice. An improved understanding of particle stream ignition is important because it influences many aspects of pc burner performance, including NOx production, char burnout, flame stability, flame shape, and flame length.

Despite the recognized importance of particle loading to the pc ignition process, few studies have been conducted on ignition with a systematic, controlled variation in particle loading. In fact, whereas there have been several modeling efforts devoted to evaluating the influence of particle loading on coal ignition [1-4], only a single experimental study with continuous particle flow has been reported [5]. In that study, the ignition delay of a column of high-volatile, size-classified bituminous coal particles injected into a laminar furnace flow containing 9 vol-% O_2 was determined, over the range of 1023-1150 K, based on photographic pictures of luminous emission from the burning particles. Under these conditions, the ignition delay first decreased with increasing particle loading, reached a minimum (at a fuel mass flow rate of 3-6 g/min), and then increased with further particle loading.

In oxy-fuel combustion of pulverized coal, poor ignition quality has often been noted during pilot-scale burner trials when operating with substantial flue gas recirculation or with a synthetic oxidant with CO_2 diluent [6-9].

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Molina and Shaddix [10,11] measured the ignition delay of streams of isolated, size-classified subbituminous and high-volatile bituminous coal particles when introduced into a laminar flow furnace. The ignition delay was shown to be quite sensitive to the temperature and oxygen content of the bulk flow and to increase with the use of a CO_2 diluent. Jovanovic et al. [12] measured the visible ignition standoff length of a high-volatile bituminous coal when conducting drop tube experiments at furnace temperatures of 800 – 1350 °C and with oxygen concentrations from 10 – 100% in both nitrogen and CO_2 diluents. The standoff length initially dropped considerably with increasing oxygen content, but for concentrations of 50% O_2 or higher the decrease was fairly minor. The CO_2 diluent was found to delay ignition, particularly for environments with modest levels of oxygen.

To improve upon the existing datasets on coal stream ignition and also provide data of specific relevance to oxy-fuel combustion, this paper reports on experiments using several U.S. and Chinese coals, over a range of relevant oxygen contents. These new data give insight into the optimal particle loading for ignition and also on the influence of coal type and oxygen concentration on the ignition characteristics. They should provide useful benchmark tests for computational models used to predict oxy-fuel combustion flame characteristics in pc boilers.

2. Experimental Methods

An extensively characterized optical entrained flow reactor at Sandia National Laboratories was used for the particle stream ignition experiments. A detailed description is provided in ref. 10. Coal particles are injected through a 0.75 mm stainless-steel tube. The effect of particle loading on coal ignition was evaluated by varying the feeding rate of coal particles into burner product mixtures with N_2 as balance gas at three different oxygen concentrations (12 vol-%, 16 vol-% and 20 vol-%), while holding the water vapor concentration and CO_2 concentration constant at 11.6 vol-% and 0.3 vol-%, respectively. Steady coal feed at specified rates was provided by a coal feeding system, similar to that described by Graham [13], employing a test tube, electric drive motor, and vibrator. The coal particles were entrained by a very low flow of 0.033 slpm nitrogen gas, to minimize the thermal shielding effect of the cold entraining gas once the particles were injected in the furnace. Gas temperatures of 1320 and 1230 K were investigated. A second set of experiments was conducted in which the effect of CO_2 diluent on coal stream ignition was evaluated, over oxygen contents varying from 12 vol-% to 48 vol-%, at furnace temperatures of 1130 K and 1650 K. For this set of experiments, a single coal stream feeding rate of 0.40 g/min was used.

Two characteristic U.S. coals were investigated: Pittsburgh high-volatile bituminous coal and Black Thunder subbituminous coal from the Powder River Basin. In addition, for the investigation of the effect of coal particle loading, two typical high-volatile bituminous Chinese coals were also investigated: Shenmu coal from Inner Mongolia and Guizhou coal from southwest China. As particle size can have a strong influence on the ignition process, specific size cuts from commercially ground pulverized coal were investigated. Most of the measurements were performed on particles in the 75 – 105 μm size cut, generated through use of a commercial sieve shaker. Selected experiments were performed on the 54 – 74 μm and the 106 – 125 μm size fractions.

A progressive-scan monochrome CCD camera (Roper Scientific COOLSNAP fx, 1300 x 1030 pixels) was used to record images of visible light emission from ignited particles in the optical furnace. In an attempt to discriminate between gaseous volatile ignition (i.e. a definitive indication of homogeneous ignition) and ignition evidenced by thermal emission from hot soot and/or char particles (which could result from either homogeneous or heterogeneous ignition), a 431 nm bandpass filter was used in front of the camera, to capture the chemiluminescent emission from electronically excited CH radicals (i.e. CH*). To average out any irregularities resulting from instantaneous variation of coal feeding rate, the camera shutter was set to collect image data over a prolonged period of time, and multiple camera exposures were summed together.

3. Results

Digital photographs of the flow reactor experiments were acquired to provide qualitative information regarding particle stream ignition and burnout behavior. Figure 1 shows photographs for the ignition of Black Thunder coal for different coal feed rates, clearly indicating a minimum in ignition height for intermediate coal feed density. Fig. 2 shows sample results from the CCD camera analysis, confirming a minimum ignition delay for intermediate coal stream loading. At low gas temperatures, near the ignition limit, coal particle size, gas stream O_2 content, and use of CO_2 diluent are all shown to have significant influence on the ignition delay. At higher temperatures, only the particle size has a significant effect.

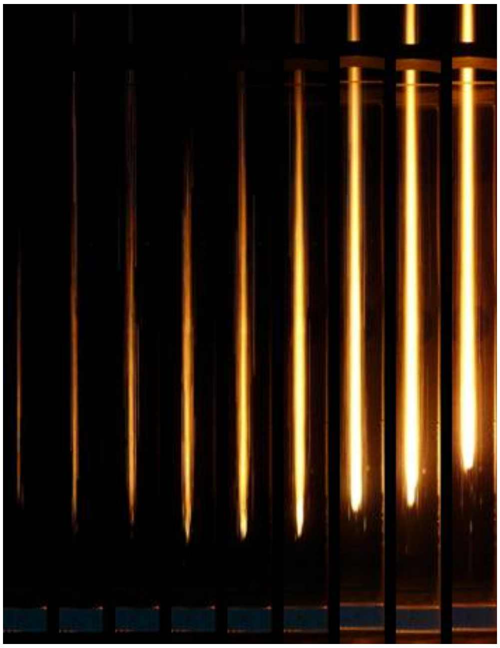

Fig. 1. Photographs of Black Thunder coal stream ignition and combustion in 12% O_2 in N_2 at 1230 K. The fuel feed rate increases from 0.005 g/min to 1.00 g/min from left to right. The coal is introduced at the bottom of the furnace and flows upwards.

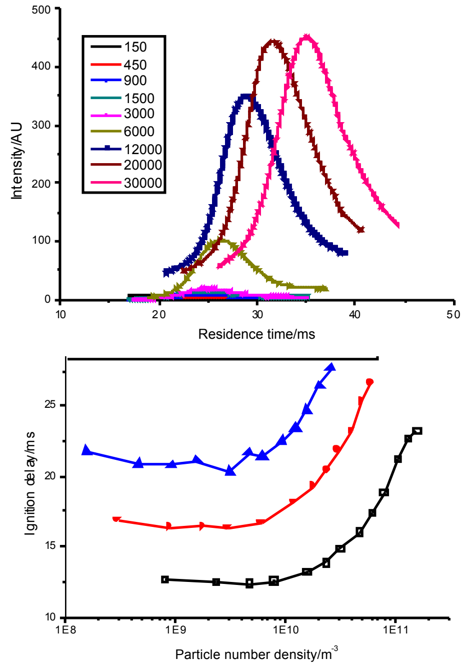

Fig. 2. Top: 431 nm emission intensity as function of residence time for Shenmu coal stream in 20% O_2 in CO_2 at 1280 K. Different curves indicate relative coal feed rate. Btm: measured ignition delay for Pittsburgh coal as function of particle loading and particle size. Black curve is for smallest particle size cut; blue for largest.

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