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The effects of particle size and reducing-to-oxidizing environment on coal stream ignition

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ABSTRACT

Coal particles experience a transition from a reducing to oxidizing environment in the near-burner region of pulverized coal (pc) boilers. For the first time, we report a fundamental study of ignition of a coal-particle stream experiencing a flame environment that transitions from a reducing to an oxidizing environment (termed reducing-to-oxidizing environment). High-speed videography is used to observe the particles in situ, and scanning electron microscopy is used to characterize the sampled particles. The effects of particle size on ignition are presented for four size bins (63–74 µm, 75–89 µm, 90–124 µm and 125–149 µm) for PRB subbituminous coal at two nominal gas temperatures (1300 K and 1800 K). An oxidizing environment with 20% molar oxygen composition is used as base-case. In contradistinction to single particle studies where particles are reported to ignite heterogeneously at higher temperatures, this study shows that coal streams ignite homogeneously, irrespective of particle size, in the oxidizing environment. By changing nominal gas temperature from 1300 K to 1800 K, ignition time decreases, on average, by a factor of five for each of the particle size bins. For both gas temperatures, the trend in ignition delays as particle size changes is non-monotonic. However, at 1800 K nominal gas temperature, ignition delays are independent of particle size in the reducing-to-oxidizing environment and ignition delays are doubled on average when compared to those in the oxidizing environment. It is more noticeable at the lower gas temperature of 1300 K that homogeneous ignition of coal streams is oxygen-dependent below 90 µm particle size and temperature-dependent above 90 µm. In general, ignition delay is determined by volatile release rate (controlled by the particle temperature) and the local oxygen concentration. Micrographs of particles also confirm that ignition and char burnout times are longer in the reducing-to-oxidizing environments than those in the oxidizing environments.

1. Introduction

As noted in the literature [1,2], most of the information on coal ignition behavior has been gleaned from experiments and modeling of individually reacting coal particles (i.e., single-particle ignition) [3–9]. Single particle ignition studies provide useful information on the combustion of dilute particle streams, such as minimum ignition temperature for heterogeneous ignition of particles. However, since there are no particle interactions involved in such individually reacting coal particles, the applications of information from single particle ignition experiments to practical coal furnaces are very limited [2,10]. Particle interactions are important to many aspects of pulverized coal (pc) boiler performance, including flame stability, char burnout, and NOx production [11–15]. Hence, experimental evaluation of particle-stream ignition is more relevant to pc boilers. Short ignition delays are desired in the near-burner region of a pulverized coal boiler because coal particles have very short residence times to burn completely in the boilers. For pulverized coal combustion, the relevant concern is how long it takes the coal particles to devolatilize and ignite in the near-burner region, and not the minimum steady-state temperature of ignition [1]. A better understanding of ignition for a coal particle stream can provide valuable information for designing more efficient burners, and also help address specific challenges such as flame instability and loss-on-ignition in pulverized coal boilers [16].

Despite the importance of particle interactions to pulverized coal combustion, few systematic studies have been reported on ignition of coal streams, particularly under conditions that simulate the characteristics of the near-burner region of a pc burner. On the other hand, there are many modeling efforts on coal particle stream ignition in oxidizing environments [10,17–20]. Ryan and Annamalai developed transient ignition models for dense clouds

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and dilute clouds of coal particles (100 µm in diameter) in an environment of 21% O_2 /79% N_2 by volume and a gas temperature of 1500 K [19,21]. Their findings showed that coal streams ignite homogeneously while single particles ignite heterogeneously under the same conditions. Homogeneous ignition refers to the process whereby the released volatiles ignite in the gas phase, while heterogeneous ignition refers to combustion at the particle surface [22]. Results for the ignition characteristics reveal that particles with relatively little volatile matter, which ignite heterogeneously when isolated, are found to ignite homogeneously under coal stream conditions. The minimum ignition temperature is found to increase with a decrease in particle size under isolated mode while the opposite is true under particle interactions. With increasing gas temperature, lesser changes in ignition delay are reported from the model using particle stream compared to the model using isolated particles [10,17–20]. In addition, quasi-steady and transient results obtained for coal-particle stream ignition showed that the burning rate of a single particle in the cloud is lower than the burning rate of the same particle in isolation [10,23]. These modeling efforts have provided great insights on the ignition of particle clouds and predictions of group burning rates and flame structure.

To date, however, there have been only a few experimental studies on ignition of coal particle streams [2,24–26]. Ruiz et al. [25] conducted an experimental study in a laminar flow reactor and evaluated ignition delay for a continuous particle stream of bituminous coal injected into a 9 vol.% oxygen environment for gas temperatures between 1023 and 1150 K. Their work, which is based on photographs of luminous emission from the burning particles, showed that ignition delay first decreases with increasing particle loading, and then increases with further increase in particle loading. Liu et al. [2] conducted experiments on the ignition properties for a variety of coals at different particle loadings, using a laminar entrained flow reactor at gas temperatures between 1230 K and 1320 K. A particle size of 75–105 µm was used for their experiments and the oxygen volume percent in nitrogen was varied from 12 to 20%. They found that ignition delay is very sensitive to coal particle size, coal feed rate, and the temperature of the gas stream into which the coal stream is introduced. They also found that there is a minimum in ignition delay as coal feed rate increases. More recently, Xu and coworkers [26] studied ignition behavior of pulverized coal particle streams in different oxygen concentrations using an entrained flow reactor. They employed high-speed cameras to record the particle motion and flame behavior. They concluded that ignition delay decreases as oxygen concentration increases, and that a minimum ignition delay exists at certain coal concentration. Yuan et al. [27] investigated the ignition behavior of a coal particle stream of 65–74 µm particles using in-situ methods in an Hencken flat-flame burner. They argued that heterogeneous ignition is dominant at 1200 K gas temperature for 65-74 µm particles burning in 10 to 30 vol.% oxygen in nitrogen. Homogeneous ignition was dominant at 1500 K and 1800 K gas temperatures, and this was attributed to the shorter devolatilization time in the high-temperature environments.

While these experimental studies provide important data for model validation, they do not simulate the combustion environment that is typical of conventional pulverized coal (pc) burners, where the coal experiences a reducing environment first and then an oxidizing environment. Typical of a pc burner, the locally reducing environment in the near-burner region is created by a high density of particles undergoing devolatilization and the fast depletion of oxygen in this region [16,28]. Beyond this region, the particles move into an oxidizing environment. Such an environment is herein referred to as a reducing-to-oxidizing environment (R–O). Depending on the injected coal mass for a given coal carrier gas, combustion characteristics and ignition can be strongly affected by particles transitioning from reducing to oxidizing environments [29,30]. Thus, to provide information aimed at addressing flame stability in pc burners, it is essential that fundamental studies be conducted in an experimental platform wherein ignition of a coal particle stream can be evaluated in a reducing-to-oxidizing environment. Furthermore, data of more relevance to burner design and optimization can be obtained if fundamental ignition studies simultaneously consider coal particle streams (as opposed to single-particle studies) and the reducing-to-oxidizing environment.

Table 1
Experimental conditions.

Temperature (K)	Flame	Volumetric flow rates (SLPM)			
		CH_4	Fuel N_2	O_2	Oxidizer N_2
Oxidizing environment					
1300	Inner	0.10	–	0.90	1.74
	Outer	2.86	6.54	23.82	33.33
1800	Inner	0.35	–	1.04	1.64
	Outer	6.86	15.90	37.71	33.33
Reducing-to-oxidizing environment					
1300	Inner	0.13	–	0.23	1.86
	Outer	2.86	6.54	23.82	33.33
1800	Inner	0.27	–	0.29	1.74
	Outer	6.86	15.90	37.71	33.33

To this end, a novel “two-stage” Hencken flat-flame burner was designed. The “two-stage” refers to the design in which there are two burners in one configuration, and this allows for two flat-flame zones in the same burner. The unique feature of this design is that this burner has an inner flat-flame zone, which can be operated in a fuel-rich mode, and an outer flat-flame zone, which is operated in a fuel-lean mode. The combination creates a reducing-to-oxidizing environment for the particle stream because the particles first experience the reducing environment of the inner flat-flame zone and only later experience the oxidizing environment of the outer flat-flame zone. The burner can also be operated as a purely oxidizing environment, by ensuring the inner flat-flame zone is the same stoichiometry as the lean outer flat-flame zone. Experimental conditions including the flow rates for the inner and outer combustion gases for both the purely oxidizing environment and the reducing-to-oxidizing environment have been reported in our previous work [31] and repeated in Table 1. Characterization of the post-flame gas environment including axial and radial measurements of temperatures and oxygen concentrations and the characterization of the feeding system to ensure steady and consistent feeding with time can also be found in the literature. In addition, this study [31] also presented design information on the new two-stage Hencken burner, including the radial split of the inner flame zone from the outer flame zone.

Using this new two-stage flat-flame burner and with the aim of improving upon the limited data on ignition of coal particle streams, this paper presents new experimental findings isolating the effects of: (1) particle size, and (2) reducing-to-oxidizing environment (R–O) on ignition of a coal stream. Results are presented for two nominal gas temperatures of 1300 and 1800 K. These temperatures span a range that is typical of the near-burner region where early-stage processes of coal combustion occur [28]. Similar to the experimental works of others on coal stream ignition [2,24–26], high-speed, back-lit high-resolution videography is employed to image the particles under different combustion environments (i.e., oxidizing and R–O) for four different particle sizes. Those studies used high-speed camera videography as a real-time, non-intrusive technique for evaluating the question of residence time on ignition behavior of coal particles.

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