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Experimental investigation of ignition behavior for coal rank using a flat flame burner at a high heating rate

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The ignition behavior of pulverized coal particles was investigated as a function of different ranks and sizes using a flat flame burner at high heating rate conditions (>10^5 K/s). A high-speed camera was used to image the ignition process. Five coal types (anthracite, medium-volatile bituminous, high-volatile bituminous, subbituminous, and lignite coals) with particle sizes 150–200, 75–90, and <45 μm were tested. The released volatile matter of medium- and high-volatile bituminous coal in the size ranges 150–200 and 75–90 μm underwent homogeneous ignition. When the particle size is <45 μm, high-volatile bituminous coal underwent homogeneous ignition, while medium-volatile bituminous coal underwent heterogeneous ignition. For particle sizes in the range 150–200 μm, anthracite coal exhibited homogeneous ignition after primary fragmentation, whereas lignite coal underwent direct fragmentation and homogeneous ignition prior to ignition without primary fragmentation.

1. Introduction

Worldwide, coal continues to be one of the most widely used primary fuel sources owing to its abundance, low cost, and easy availability with respect to safety and stability. Applications utilizing coal have been under investigation for centuries; numerous types of coal technologies have been developed to produce electricity energy using a pulverized coal boiler and iron using a blast furnace. The pulverized coal boiler technology remains the most widely used to date and is expected to be the dominant method for coal combustion over the next two or three decades, especially in the field of power production. The blast furnace process is still the most widely used technology to produce iron. Its major advantages are a very high production rate and a high degree of heat utilization [1]. However, the pulverized coal boiler and blast furnace use different coal ranks. In a pulverized coal boiler, middle-rank coal is used, with a heating value of approximately 6080 kcal/kg. Pulverized coal injection (PCI) in the case of a blast furnace requires high-rank coal, whose heating value is above 7500 kcal/kg. Most power plants and iron making companies in South Korea produce power and iron using poor-quality imported non-designed coal, because of the recent increase in the price of high-rank coal. However, combustion problems occur when non-designed coal is used in a pulverized coal boiler or a blast furnace, owing to its fuel characteristics that make it difficult to obtain the optimal operating conditions. Moreover, the problem of burner damage must be considered, which occurs because of the ignition mechanisms involved in high-volatile low-rank coal. Therefore, to avoid burner damage, the ignition behavior as a function of coal rank should be investigated as fundamental data in order to take advantage of the new operating procedure of the burner.

Most practical systems deal with combustion under turbulent conditions, in which the heat release is much faster than that under laminar conditions. At very high Reynolds numbers, the flow becomes turbulent. In a turbulent flow, eddies move randomly back and forth and across the adjacent fluid layers. The flow no longer remains smooth and orderly. Even chemically non-reacting turbulent flows are highly challenging because of the above mentioned characteristics. The problems become even more complex when chemical reactions occur, since the turbulent fluid flow is further coupled with chemical kinetics, and quite often, with phase changes. For laminar flows, however, the adjacent layers of fluid slide past one another in a smooth, orderly manner. The velocity, temperature, and concentration profiles measured in a laminar flow will be quite smooth [2]. Therefore, many investigators have preferentially studied the coal combustion and ignition behaviors under laminar flow conditions before studying these under turbulent conditions, in order to solve the chemically reacting turbulent

Abbreviations: PC, pulverized coal; VM, volatile matter.

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flow. The mechanism of coal combustion on laminar flow condition has been elucidated by previous investigations. The combustion of most solid fuels involves two major steps: (i) devolatilization that occurs during the initial heating; (ii) subsequent combustion of the released volatile matter and porous solid residue (char) of the first step. Ignition occurs between these two steps. Many previous studies [3] have investigated the ignition process of pulverized coal (PC) particles, which may occur by either homogeneous ignition of the released volatile matter or heterogeneous ignition on the char surface depending on the coal rank [4–9], particle size [10], coal-feeding rate [11], heating rate [9], and ambient gas conditions, i.e., gas composition [6,7,12,13], oxygen concentration [6], and temperature [11].

Ignition behaviors based on the particle size and coal type under low heating-rate conditions have been studied By Chen et al. [9], who examined the ignition of anthracite, bituminous coal, and lignite by thermogravimetry (TG) and differential thermal (DT) analyses, with PC sizes ranging from 37 to 4000 μm. They proposed that with an increase in the coal quality (from lignite to bituminous to anthracite), the ignition type changed from homogeneous to hetero-homogeneous to heterogeneous, respectively. Moreover, the ignition behavior of bituminous coal changed from a hetero-homogeneous to homogeneous process with increasing coal particle sizes, whereas in anthracite and lignite coal, the behavior did not change with change in the range of the particle sizes examined. However, Chen et al. [9] conducted their study under low heating-rate conditions(<10^1 K/s). Therefore, the investigation of reactors with heating rates similar to that of PC boilers is required. McLean et al. [4] used a flat flame burner designed for high heating rates (>10^5 K/s) and a shadowgraph to observe the condensed matter surrounding the coal particles with a mean mass size of 65 μm corresponding to the ignition of bituminous coal—suggesting that homogeneous ignition initially occurs. The shadowgraph technique offers the advantage of detecting the soot cloud. Molina and Shaddix [13] used CCD (Charged-Coupled Device) camera images with LFR to capture excited CH^* emissions from the coal flame to determine the ignition point. These results showed a significant ignition delay in char compared to coal particle ignition, using coal from the same seam and under similar experimental conditions as the McLean study [4]. Shaddix and Molina [12] also used a CCD camera with a very short exposure time (20 μs) to investigate the ignition and devolatilization behavior of single particles of bituminous and subbituminous coals by changing the ambient gas conditions. The results showed that highly volatile bituminous coal ignited with a high-temperature soot cloud; in contrast, this cloud was not obvious during the ignition of subbituminous coal. All the aforementioned studies describe how coal rank and particle sizes affect PC particle ignition at various conditions; however, the ignition phenomenon of PC particles, in a wide size range, at very high heating rates (>10^5 K/s) as a function of coal rank is yet to be thoroughly investigated.

Herein, we report our investigations on the ignition behavior of PC particles of different ranks and sizes using a high-speed camera at high heating-rate conditions (>10^5 K/s) in a flat flame burner which is developed for setting up a similar heating rate of large industrial scale. Five types of coal were examined, namely anthracite, medium-volatile bituminous, high-volatile bituminous, subbituminous, and lignite coals.

2. Experimental method

Five coal types of different ranks were investigated in this study; Table 1 shows their properties. Coal rank was defined using the ASTM method. Low-rank coals, which are lignite, subbituminous coals, and high-volatile bituminous coals, are classified according to the heating value and not the volatile content. Further, the basis of the volatiles content when comparing high rank coals which are medium volatile, low volatile bituminous coals and anthracite are compared on a dry ash-free basis (Table 1). Experiments were carried out in an entrained-type flat flame burner at Pusan Clean Coal Center, South Korea. A schematic of this system is shown in Fig. 1. The burner was designed with a honeycomb structure and a circular cross section in order to ensure symmetry in temperature and gas-composition conditions along the horizontal plane. A quartz tube with a rectangular cross section was set above the burner to isolate the inner reacting zone and decrease the heat loss. A non-premixed flat flame was created using CO and H_2 as a fuel and O_2 as an oxidizer to provide a high-temperature condition above the burner. N_2 was also used to control the temperature, oxygen concentration, and velocity of post flame gas flows. The PC particle inlet was designed at the center of the burner using N_2 as a carrier gas. The calculated composition of the post flame gas is shown in Table 2. The gas-temperature profile along the burner centerline was measured with a 125 μm type R thermocouple and corrected for radiation losses. The corrected gas temperature as a function of the height above the burner is shown in Fig. 2. In a blast furnace, pulverized coal particles are injected into the hot blast from a lance with a small diameter. The temperature and oxidant gas of the hot blast are 1300–1500 K and air, respectively [14]. In a pulverized coal boiler, the coal particle that passes through the burner nozzle encounters a 1700 K flame zone [15]. Therefore, the experimental conditions were chosen as 21.6 mol% O_2 and 1600 K.

PC particles were fed into the burner at a feeding rate of <1 mg/min to ensure a single-particle feeding condition and to guarantee that the reacting zone conditions would not be affected by the heat of combustion of the PC particles. The ignition behavior of the PC particles was captured via a Photron FASTCAM SA4 high-speed camera. Because the ignition process occurs at the speed of 10^1 ms (including gas-phase and heterogeneous reactions under high heating-rate conditions), a frame rate of 10,000 frames/s was selected. In order to capture the PC particles before ignition when no light is released, a backlight using a Photron HVC-UL device was oriented toward the high-speed camera.

3. Results and discussion

3.1. Effect of coal rank: homogeneous and heterogeneous ignition behavior

The effect of coal rank for particles in the size range 150–200 μm are shown in Fig. 3. Coal particles are injected into the burner, and they are preheated by the flame in the downstream direction. Then, volatile matter is evolved, and ignition occurs on the particle surface or the gas phase. After almost all the volatile matter is evolved, char combustion becomes dominant. Finally, ash is produced after the char combustion is complete. The mass of the coal particle decreases with an increase in the residence time during the combustion progress. As mentioned in the Introduction section, PC particle ignition can occur via either gas-phase combustion of the released VM (homogenous ignition) or heterogeneous combustion of the particle surface (heterogeneous ignition). Bituminous (coals A, D) and subbituminous coals (Adaro coal) showed a typical combustion behavior as seen in Fig. 3. As the coal particle heated up after injection into the burner, homogenous ignition occurred after the gas-phase VM was released from the particle. As more gas-phase VM was released, the corresponding combustion flame became bigger and surrounded the particle. The solid coal particles remained black prior to the extinction of the