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Combustion behavior profiling of single pulverized coal particles in a drop tube furnace through high-speed imaging and image analysis

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ABSTRACT

Experimental investigations into the combustion behaviors of single pulverized coal particles are carried out based on high-speed imaging and image processing techniques. A high-speed video camera is employed to acquire the images of coal particles during their residence time in a visual drop tube furnace. Computer algorithms are developed to determine the characteristic parameters of the particles from the images extracted from the videos obtained. The parameters are used to quantify the combustion behaviors of the burning particle in terms of its size, shape, surface roughness, rotation frequency and luminosity. Two sets of samples of the same coal with different particle sizes are studied using the techniques developed. Experimental results show that the coal with different particle sizes exhibits distinctly different combustion behaviors. In particular, for the large coal particle (150–212 μm), the combustion of volatiles and char takes place sequentially with clear fragmentation at the early stage of the char combustion. For the small coal particle (106–150 μm), however, the combustion of volatiles and char occurs simultaneously with no clear fragmentation. The size of the two burning particles shows a decreasing trend with periodic variation attributed to the rapid rotations of the particles. The small particle rotates at a frequency of around 30 Hz, in comparison to 20 Hz for the large particle due to a greater combustion rate. The luminous intensity of the large particle shows two peaks, which is attributed to the sequential combustion of volatiles and char. The luminous intensity of the small particle illustrates a monotonously decreasing trend, suggesting again a simultaneous devolatilization/volatile and char combustion.

1. Introduction

Although renewable energy has been attracting much attention in recent years due to environmental concerns, conventional fuels such as pulverized coal will remain a major worldwide energy resource for years to come due to their wide availability and competitively low cost, particularly with the development of new combustion technologies such as co-firing coal and biomass and oxy-coal combustion [1]. While the effects of chemical composition and other fuel properties of coal on combustion have been widely studied, the physical characteristics of a pulverized solid fuel, such as particle size, and shape have also been found to have a significant impact on the ignition and combustion behaviors of fuel particles, and consequently the flame stability, combustion efficiency and pollutant emissions [2]. The combustion process of solid fuel particles comprises typically three stages, i.e., heating, volatiliza tion/devolatilization, and char oxidization [3]. Depending upon not only the fuel properties, but also the heating rate, particle size, combustion environments (temperature and stoichiometry, etc.) and the volatile matter evolution, the homogeneous ignition and heterogeneous ignition of fuel particles may occur sequentially or simultaneously [4]. This makes it more difficult to characterize the combustion behaviors of fuel particles. Therefore, the measurement and characterization of individual fuel particles are required to explore the insight into the combustion mechanism of fuel particles, and consequently advance the knowledge to optimize combustion processes and validate computational modeling results.

There is a range of experimental and modeling work that has been carried out to investigate the combustion behaviors of coal and biomass fuel particles of different ranks and sizes under different combustion conditions in drop tube furnaces (DTFs), using non-visualized and visualized technical approaches [5–11]. For instance, Wang et al. [12] investigated the combustion behaviors and ash characteristics of coal and biomass particles through analyzing

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the particles sampled from different heights of the DTF, using X-ray fluorescence spectroscopy and a particle size analyzer. Costa et al. [13] evaluated the gas temperature, particle burnout and particle fragmentation of raw and torrified pine shells and olive stones in a DTF using various instruments (e.g. a low pressure three-stage cascade impactor, a particle size analyzer and a scanning electron microscope). Pereira et al. [14] studied the kinetics of poplar short rotation coppice in a DTF through thermogravimetric analysis. The above investigations are based on non-visualized technical approaches. With the advent of high-speed digital imaging and image processing techniques, the visualization and characteristics of burning particles have become feasible. Simões et al. [11] investigated the ignition mode and delay time of biomass fuels through the analysis of particle images from a high-speed camera. The impact of gas temperature and oxygen concentration on the ignition mode and ignition delay time was assessed. Shaddix and Molina [15] analyzed the ignition and devolatilization characteristics of both high-volatile bituminous and subbituminous coal particles through single-particle imaging in both N_2 and CO_2 diluent gasses. Kim et al. [16] investigated the ignition behaviors of coal particles under high heating-rate conditions using a flat flame burner and particle images. Levendis et al. [4,17] and Riaza et al. [1] employed three-color pyrometry and high-speed high-resolution cinematography to study the combustion behaviors of single coal particles in both air and simulated oxy-fuel environments. Köser et al. [18] also studied the combustion characteristics of individual coal particles in an oxygen-enriched environment using high-speed OH-PLIF (Planar Laser-induced Fluorescence).

Although certain progress on the characterization of burning particles using visualized approaches has been made, few studies have been undertaken on the quantitative profiling of single fuel particles. Podczeck [19] proposed a shape factor, which used the deviations of the 2-D (two-dimensional) particle outlines from the images of a circle, triangle and square, for the particle analysis. Gao et al. [20] conducted the on-line measurement of particle size and shape and their distributions through image processing, where the images of particles were acquired from a color CCD camera coupled with multi-wavelength laser sources. Carter et al. [21] and Qian et al. [22] combined digital imaging and electrostatic sensors to obtain the size distribution and volumetric concentration of particles in pneumatic conveying pipes. It is clear that, while the combustion behaviors of fuel particles influence the overall performance of a combustion process, limited studies have been carried out to investigate the combustion behaviors of burning particles through the measurement of physical characteristics such as size, shape, surface roughness, rotational frequency and luminosity.

This paper presents experimental investigations into the combustion behaviors of individual coal particles with the aim of providing a quantitative description of particle dynamics during combustion through high-speed imaging and digital image processing. The videos of two sets of individual coal particles were recorded using a high-speed camera during the combustion process in a visual drop tube furnace (V-DTF). Algorithms are developed to acquire and process the particle images in terms of physical quantities, including size, shape, surface roughness, rotation and luminosity. These quantities are then used to describe the characteristics of the burning particles during their residence time in the furnace.

2. Materials and methods

2.1. V-DTF and high-speed camera

DTFs have been widely used for combustion research as they can provide critical data for the in-depth understanding of ignition and combustion behaviors of fuel particles in power plant boilers [23]. The tiny size, short residence time of the particles and the variations of the size and shape make it very difficult to visualize and characterize the burning particles. With the aid of high-speed imaging, it is possible to visualize burning particles in a DTF. Fig. 1 is the overview of the experimental setup in this study. The V-DTF used in this study is an electrically heated drop tube furnace equipped with a 1400 mm long quartz tube with an inner diameter of 50 mm, capable of maintaining gas temperatures up to 1050 °C within the 1000 mm-long heated zone [24,25]. The quartz work tube is insulated by a spun ceramic fiber blanket to minimize the heat loss during experimentation. The fuel particles are injected into the quartz tube from the water-cooled feed probe mounted at the top of the quartz tube. The particles are heated, ignited and combusted in the furnace with the residual ash being vacuumed away or collected with the collection probe mounted at the bottom end of the quartz tube. There is a long and narrow viewing window at the front side of the furnace which allows a camera system to access and view the combustion process of the fuel particles inside the quartz tube.

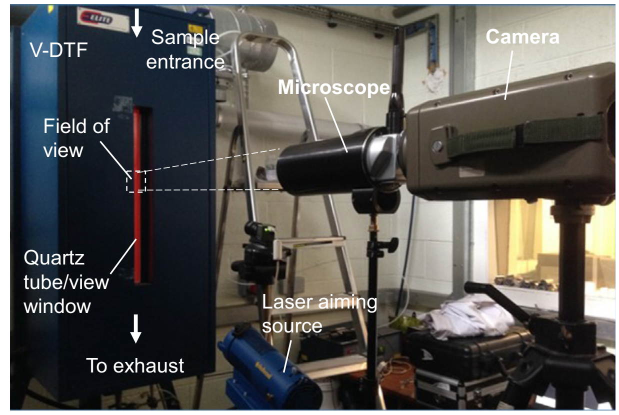

Fig. 1. Overview of the experimental setup.

A high-speed camera (Phantom v12.1), capable of recording a video at a frame rate up to 1,000,000 fps (frames per second), acquires videos of burning coal particles. A long-distance microscope (Questar QM-1, which has a 56–152 cm working distance, a 30–1 variability in the field of view and a resolution better than 3 μm at 56 cm) is coupled with the camera to ensure that coal particles can be captured during their residence time in the furnace. The resulting field of view is around 8 mm × 8 mm.

2.2. Coal properties and test conditions

Two sets of coal sample with different particle sizes (Particles A and B) were prepared from the same batch of Colombian bituminous coal (El Cerrejon, which was sourced directly from a UK power plant). Each sample was separately dried, sieved with particle size ranging from 150 to 212 μm for Particle A, and 106 to 150 μm for Particle B. The proximate and ultimate analyses of the samples are summarized in Table 1. In the test, a small amount (in milligrams) of the sieved coal particles were dropped manually through the feed probe into the quartz tube which was pre-heated to 800 °C and supplied with air at a rate of 5 L/min. The high-speed camera tracked and took the videos of the particles at a frame rate of 6200 fps during their residence time in the quartz tube.

2.3. Contour detection and extraction

Once the videos were recorded, individual images of a particle were read frame by frame in a computer. Image progressing algo-