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Motion of single pulverized coal particles in a hot gas flow field

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ABSTRACT

This experimental investigation was aimed to understand the dynamic interaction of a fine particle in a hot gas flow field, where the particle experienced the typical coal combustion. Size classified pulverized coal and char particles were introduced into a hot environment by means of a cross jet injection of a cold carrier gas in a nearly instantaneous manner. High speed visualization of the single particles showed the expected progress of combustion, as well as their motion. Understanding particle motion is believed to be an essential step in interpreting the appearance of the coal particle and its associated flame. The observed phenomena showed statistical variation because the particles were not uniform in shape and size and because the penetration and mixing of the jet were associated with uncertainties in fluid motion. An experimental approach was proposed to define the statistically averaged trajectory of each particle in space. The major parameters were identified as particle size, fuel type, and the hydrodynamic and thermal characteristics of the flow environment. Particle velocities during the entrainment process were derived and interpreted, revealing the effect of the particle size and the jet momentum. The observed motion of the coal particles in the oxidizing environment was discussed by comparing their results with those of the char particles. As expected, the coal motion was influenced by the mass change of the coal particle during the sequential progress of combustion. The particles also exhibited evidence of rotational motion in addition to the translational motion.

1. Introduction

The fundamental understanding of coal behavior is supported by combustion experiments performed on single coal particles. Typically, a spherical solid mass in an infinite gas medium is considered to undergo the processes of particle heat-up, devolatilization and combustion, i.e., diffusion of oxygen and reactions of combustible fuel components. The temperature profile of the gas and the particle, as well as oxygen availability, is commonly identified as major parameters. In pulverized coal combustion, which is one of the major forms of coal utilization, coal particles are transported by a carrier gas into a hot gas stream, and the combustion environment is commonly interpreted to be sufficiently dilute to support single particle combustion. In this configuration, the temperature distribution and the gas environment are strongly influenced by the particle to gas mixing; thus, it is essential to understand this area of combustion.

The computational modeling of pulverized coal combustion incorporates the aforementioned descriptions of the coal particle behavior in the gas flow [1,2], and it has been developed to a point that the combustion and heat transfer of the coal flame in the furnace are believed to be appropriately modeled. Experimental investigations have also shown progress and direct observation of single pulverized coal particles moving in the gas stream enabled a visual inspection of the particle behavior. Both in the computational modeling and the experimental investigation, combustion is a combination of multiple effects from solid particle behavior in the gas medium. Thus, it is important to understand how a coal particle interacts with the hot gas environment, i.e., motion or mixing of the particle in its environment.

Considering the particle motion and the particle-to-gas interaction, one of the typical assumptions is to treat the particle geometry as an ideal sphere with a homogeneous distribution of maceral composition. In reality, however, particles in general are naturally non-spherical and arbitrary in shape and composition. Each particle can be described as any one of many irregular shapes (e.g., chip, plate, and rock), which are probably formed during the pulverizing process. Figure 1 shows the scanning electron microscope images of the coal and char used in this study. It has been indicated that the particle shape and rotation play an important role in characterizing the heat and mass transfer between the gas flow and the particle, as well as the physical forces acting on it [2,3]. Physical characteristics associated with the lack of sphericity can lead to complex particle motion and non-uniform heat release,

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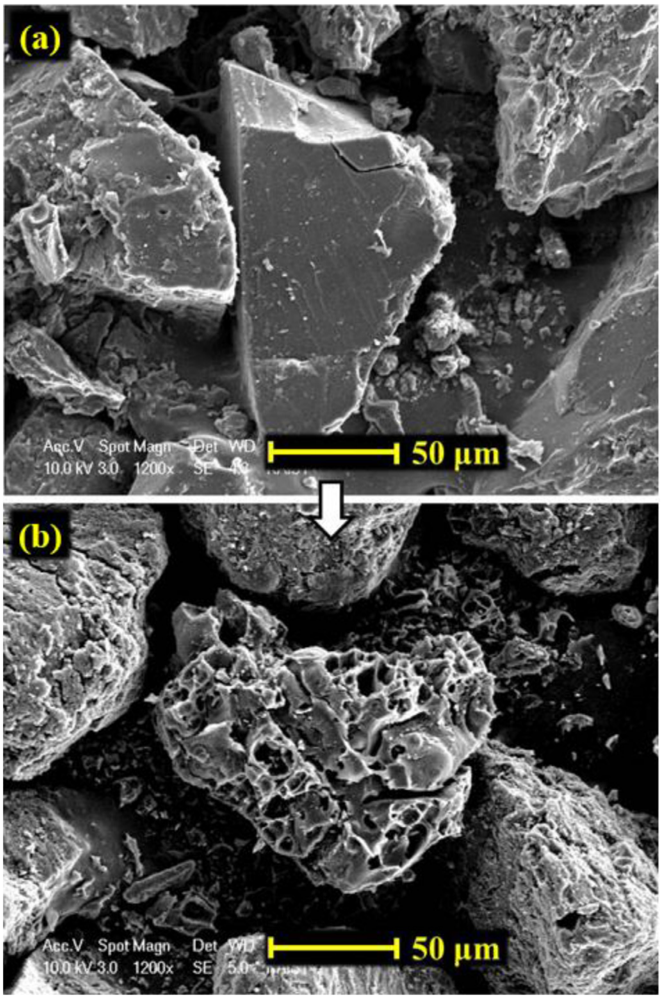

Fig. 1. SEM images of (a) raw bituminous coal particles and (b) char particles.

causing force and heat gradients on the particle surface that are different from those of a spherical particle. Efforts of modeling associated with the non-sphericity of solid fuel particles have been made by considering the effects of rotating motion [4–6] and non-uniform heat gradients [7,8].

Recently, Lee and Choi presented a case of the experimental observation of pulverized coal particles entrained into hot gas flow [9], where a cold particle was heated to a combustion temperature within a few milliseconds at heating rates of 10^5–10^6 K/s. The observed particle behavior was obviously an integrated result of the particle motion, as well as the mass reaction of the coal. The interpretation of the observed coal combustion required additional information on the particle motion in the gas flow field. The current report focuses on describing the motion of single pulverized coal particles in a hot gas flow. Experimental identification of particle motion with respect to the gas stream is intended to improve the understanding of coal particle behavior in combustion.

2. Experimental approach

2.1. Motion of coal and char particles in a high temperature environment

The experimental procedure was designed to observe the single fuel particles in a hot gas flow while controlling the flow and reaction conditions and the particle properties. A cross-jet configuration was chosen to introduce a cold fuel particle into the hot gas environment in a nearly instantaneous manner. High speed observation in a laboratory-scale entrained flow reactor at high magnification was proposed, and the combustion behavior was previously reported [9]. By comparing the coal and char samples, this paper focuses on the particle motion and describes the interaction of a single particle with the gas flow during a varying degree of mass reaction.

Observation of coal particle motion in the early stages of combustion inevitably faces many complexities because the particles vary in shape and size and they undergo entrainment into the gas flow, and the fuel particles also experience mass reactions of devolatilization, envelope flame, and char combustion. The inhomogeneous gas flow is also turbulent to a certain extent. Therefore, an experimental approach is necessary for determining the particle behavior based on statistical averaging. The experiments consisted of two parts: the first part on the flow characteristics and the second one on the combustion phenomena. The base case, in which a particle motion mainly depended on the flow parameters, was planned by minimizing the effects of combustion. This goal could be achieved when the fuel particles were highly non-reactive. Thus, char derived from the coal was selected for this purpose, and the first set of the experiments was performed at an oxygen concentration close to that of air. Coal combustion experiments were then executed while holding the flow parameters constant.

2.2. Fuel characterization

The coal specimen was Bituminous F, which was tested in Ref. [9]. The coal at the air dried state had the following proximate analysis: moisture 2.38/volatile matter 35.32/fixed carbon 49.62/ash 12.68 and ultimate analysis of C 70.38/H 4.65/O 7.91/N 1.48/S 0.52. The char was prepared in the laboratory by heating the coal particles at approximately 900 °C to a point they had almost no volatile matter. These samples were sieved in three size groups: −170 and +200 mesh, −100 and +120 mesh, and −70 and +80 mesh, representing the nominal size ranges of 75–90, 125–150, and 180–200 µm, respectively. For the most part, particles of noticeably irregular shapes and size were discarded, aiming for better repeatability and consistency of the data. Mass-mean particle diameters were measured to be 85.7 µm for the 75–90 group, 139.2 µm for the 125–150 group, and 191.4 µm for the 180–200 group. In the following, the size groups are represented as d_{75-90}, $d_{125-150}$, and $d_{180-200}$. Considering that the density of the particles would significantly affect their entrainment into the main flow, the apparent density of the coal samples was measured as 0.73 g/cm^3, and the density of the char sample was approximately 65%–68% of the density of the original coal.

2.3. Cross-jet apparatus

The cross-jet injection method is used widely, particularly in fuel injection systems, such as gas turbine combustors and industrial burners, due to its enhanced mixing characteristics [10]. The current experimental configuration was designed to achieve an almost instantaneous introduction of cold fuel particles into a high temperature environment, and the cold jet, which contained a highly dilute amount of particles, was allowed to mix with the hot gas flow, as illustrated in Fig. 2 [9]. In the flow configuration, single coal particles experienced intense heat and mass transfer in the hot gas stream, showing the sequential combustion processes along the trajectory.

The flow rate of the main stream gas in the flow reactor was selected as 22.5 standard liters per minute (slpm) to avoid a flashback. The base experiment was performed at an oxygen volume fraction of 25%, and the coal combustion experiments also covered