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Experimental study on ignition behavior of pulverized coal particle clouds in a turbulent jet

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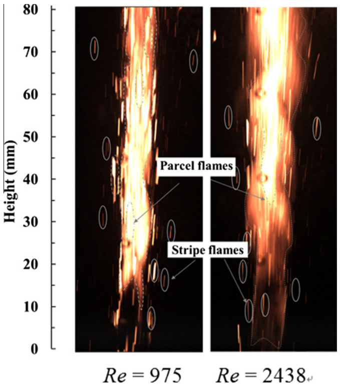
GRAPHICAL ABSTRACT



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ABSTRACT

Ignition behaviors of pulverized coal particle clouds in a jet with different turbulent intensity, O_2 concentration and coal concentration were experimentally studied using an entrained flow reactor. Mie scattering technique and high-speed cameras were employed to record the particle motions and flame behavior. Results revealed that a cloud flame consisted of a number of parcel flames and stripe flames, which were located in the center and around boundary of the cloud flame, and resulted by the burning of the evolved volatile matter or the clusters of fine fuel particles, and the burning of the single particles respectively. As Reynolds number of the primary flow increased, the cloud flame changed from narrow and structured to wide and turbulent. At the same time, the particle dispersion became more intensive, leading to a lower flame incandescence. The increase of O_2 concentration in the primary or secondary flow promoted ignition of cloud flames. For laminar cloud flame, ignition distance was more sensitive the O_2 concentration in the primary flow, and a minimum value was found at certain coal concentration, but for turbulent cloud flame, ignition distance was shorter, and no obvious non-monotonic trend was found over the tested coal concentration range.

1. Introduction

In application, coal is often ground into pulverized particles and then mixed with combustion air and injected into the furnace as a coal/air turbulent jet. Understanding the ignition of coal particles

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in a turbulent jet is significant for clean and efficient utilization of coal.

So far, a number of studies have been conducted on the ignition of single coal particles. The studies revealed the evolution and structure of flame around the coal particles [1,2], ignition mechanism [3,4] and devolatilization and volatile combustion [5–7] under various experimental conditions during the ignition process. Relatively, the studies on the ignition of pulverized coal cloud in turbulent flows are much fewer. Existing studies found in the turbulent flow, coal particles strongly interact with each other and the surrounding gas flow, while turbulent eddies greatly affect the particle motion, heat and mass transfer and chemical reaction processes surrounding the coal particles [8–10]. Thus, the research results on ignition behavior of a single particle may be not directly applicable to pulverized coal particles in a turbulent jet significantly [11–15].

In a turbulence jet, the flame of pulverized coal cloud is of a special jet flame appearance, sometimes named pulverized coal cloud flame, strongly depended on the fluid dynamics, particle heating and chemical reaction in the two-phase flow. Even when no combustion happens, Budilarto [16] found that fluid aerodynamics affects the particle motion. Fine particles disperse preferentially to the outer boundary of the jet flow, enhancing the axial mean velocity of the coarse particles near the jet center. For the oxy-coal flames in an entrained flow reactor under various conditions, as found by Shaddix and his coworkers [11,17], longer ignition delay and flame instabilities are introduced by the presence of CO_2 and decrease of O_2 content in the coal particle stream. Also, ignition time delay decreases with O_2 concentration in the carrying gas flow, especially under low temperature conditions [11]. However, their experiments were conducted for a very low flow rate of feed gas and in laminar flow region only. For the coaxial jet coal flames, Taniguchi et al. [5] found that the ignition of coal pulverized cloud can be divided into preheating, ignition and continuous flame regions and only fine particles are pyrolyzed before ignition. Also, reaction of the coal particles are confined to the interface between the coaxial jets, and fine particles tend to preferentially disperse outwards or be burnt earlier than larger particles. Zhang et al. [8,9] experimentally found that for coal particle loaded turbulent flows, both the composition of the primary jet and the effective temperature of the mixture of the secondary jet and recirculation flue gas control the heat up of particles. Using an empirical model, they also found that the partial O_2 pressure in the turbulent coal–air flow has a quantifiable, first-order effect on flame stability and it determines the initial O_2 concentration on the particle surface.

Despite the importance of the turbulence impact on ignition of coal particles, and the difference between ignition of coal particle cloud and single coal particle were recognized, ignition behaviors of coal clouds in a turbulent jet, including particle motion in reacting turbulent flow and detailed structure of the turbulent coal cloud flames, have not been fully assessed. In this paper, experimental studies were conducted by introducing a turbulent primary jet into a laminar co-flow with an easily-controlled, lab-scale burner and measurement with multiple optical methods, and the effects of O_2 concentration and coal particle concentration with different turbulent intensities were especially assessed.

2. Experimental setup

2.1. Experimental system

The experiments were carried out in a Hencken type entrained-flow reactor shown in Fig. 1, similar to the one used by Shaddix group at Sandia National Laboratory [18,19]. The base of the burner was a square honeycomb ceramic plate with cross-section area of 55 mm × 55 mm, through which 500 fine round steel tubes were inserted. These tubes were connected with fuel gas (CH_4) and oxidant (mixture of O_2 and N_2) streams alternatively, such that a group of small diffusion flames could be established near the burner exit to generate hot flue gas. The temperature and composition of the flue gas could be adjusted by setting the mass flow rates of CH_4, O_2 and air streams. The burner was enclosed by a furnace made of thermal-insulated refractory, with the inner dimension of 67 mm (depth) × 67 mm (width) × 920 mm (height). One side of the furnace was installed with a quartz window to allow optical measurements. The top of the furnace was opened to the atmosphere.

Pulverized coal particles were sent into the furnace by the primary flow through a stainless-steel tube with $\varnothing$2.6 mm inner diameter (d_0), protruding ~5 mm out of the base surface. All gas flow rates were controlled by the sonic nozzle type flowmeters, which were pre-calibrated using a high-accuracy wet gas meter. The whole burner system was placed under a ventilation hood.

Fig. 2 shows the temperature profile along the axial centerline for a typical experimental case, measured with a $\varnothing$0.2 mm B-type thermocouple with radiative loss correction. It can be seen the axial temperature distribution was rather uniform in the furnace, with an average value of ~1473 K. In this situation, a coal particle with size of 80 μm could experience a heating rate of 10^4–10^5 K/s. The average residual O_2 concentration of the secondary flow was estimated to be ~14.6%. Thus, the combustion environment in present study well mimicked the furnace of a coal-fired boiler.

2.2. Coal samples and test conditions

One bituminous coal (SC coal) from Sichuan province and a lignite coal (HLE coal) from Hai'laer, Inner Mongolia of China were employed, and their proximate and ultimate analyses are listed in Table 1. The coal samples were sieved to 0–100 μm, and the volume weighted mean diameter is 44.5 μm. Fig. 3 shows the size distribution of SC coal measured by a laser particle size analyzer (Malvern Instruments Ltd.).

2.3. Settings of the primary and secondary flows

The primary flow was a mixture of coal particles and air. To examine the effect of turbulence intensity on the characteristics of the coal particle cloud flames, experiments were carried out at two different primary flow velocities u_0's of 6 m/s and 15 m/s, with Reynolds' number ($Re = u_0 d_0/v$, where u_0 was the mean velocity at the jet exit, d_0 was the jet diameter and v was the kinetic viscosity of primary flow at 298 K) at the tube exit of 975 and 2438 respectively. Steady coal feeding was provided by a scraper type coal feeder (Sankyo Pio-tech CO., Ltd) and the feeding rate varied from 0.3 to 4 g/min. The maximum of primary flow rate was 4.38 L/min (@273.15 K, 101325 Pa) and the ratio of the secondary flow rate to the primary flow rate was around 16.7:1.

The effect of O_2 concentration in the primary flow on ignition of coal cloud was investigated for both SC coal and HLE coal at $Re = 975$ and 2438 respectively. The mole fraction of O_2 in the primary flow varied over 0–40%, while the coal concentration was maintained at 0.52 kg/N m^3 for SC coal and 0.8 kg/N m^3 for HLE coal.

The influence of O_2 concentration in the secondary flow on ignition distance were investigated by keeping the same primary flow conditions, with 21% O_2 and 0.52 kg/N m^3 coal feeding rate. The mean furnace temperature and total flow rate of the flow were also kept unchanged.