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Combustion behaviors and temperature characteristics in pulverized biomass dust explosions

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Flame propagation behaviors and temperature characteristics of four types of biomass with two different particle size distributions were studied experimentally. Results show that the flame front of a 50–70 μm biomass is nearly spherical and smooth, the flame zone is characterized by yellow or dark red spotted flames, and luminous flames are present behind it. The flame morphology of 100–200 μm biomass dust is irregular and discrete. The average flame propagation velocity and the amplitude of the velocity fluctuation are functions of the mass density of the biomass particles and depend on the particle size distributions. The flame-speed oscillation of biomass particles is caused by the velocity slip between the volatile gases and particles. Flame temperatures of 50–70 μm and 100–200 μm biomass dust reach the maximum value at 1000 g/m^3, and show a slight dependence on the particle size distribution. An analysis of the Knudsen number indicates that the combustion characteristics of biomass particles with particle size distributions within the range studied are characterized by a continuum regime. It is indicated that 100–200 μm poplar sawdust will be the “best” option as a biomass replacement feedstock for coal powered plants.

1. Introduction

Biomass is a type of organic matter, and includes various materials, such as wood and agricultural residues [1–3]. As an alternative to fossil fuels and a renewable energy source, biomass has received considerable attention owing to its low-cost supply, reduction in net carbon emissions, and geographically wide availability [4–6]. Different particle sizes are utilized with different equipment during the process of biomass utilization. In a power station, pellets are pulverized into small particles, which enable the biomass to be used in existing coal pulverized systems [7,8]. Accompanying the use of pulverized biomass, a dust explosion may occur. Furthermore, the risk of a dust explosion is significantly high during the production, transport, and storage of biomass fuel, owing to the existence of a high-concentration dust cloud [9]. Dust explosions always lead to serious casualties and financial losses [10]. Therefore, safe handling of pulverized biomass is crucial [11].

To assess the possibility and minimize the risk of a dust explosion, the basic explosion parameters of the biomass are required. Few experimental studies on pulverized biomass explosions have been carried out, and most have focused on the explosion characteristics (sensitivity and severity as explosion parameters) [12–16]. To mitigate and prevent an accidental biomass explosion, it is important to adequately understand the mechanisms of flame propagation through the biomass particle clouds [17]. In addition, an accurate measurement of the burning velocity and the temperature of the flame are essential to the development of the fundamental flame propagation mechanisms and combustion theories.

However, as the key information for an understanding of a dust explosion, the mechanisms of flame propagation through biomass dust clouds remain ambiguous. Flame propagation behaviors and flame temperature characteristics of biomass remain to be investigated. In this study, to investigate flame propagation behaviors and flame temperature characteristics, four kinds of widely used biomass were chosen for experiments using a high-speed camera system in an open-space apparatus. Furthermore, the mechanisms of flame propagation were analyzed.

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2. Experiments

2.1. Experiment apparatus

The experimental open space dust apparatus described in our previous study is shown schematically in Fig. 1 [18]. The apparatus was partially altered, and consists of cylindrical combustion tubes, an air-fuel dispersion system, a high-speed camera, an ignition system, a data acquisition system unit, a time controller, and a thermocouple.

The top tube is 60 mm high with a diameter of 95 mm. The moveable tube is 115 mm high with a diameter of 95 mm. The bottom tube, which is connected to a stainless-steel basement, is 125 mm high with a diameter of 80 mm. The thermocouple is composed of 13% Pt/Pt-Rh wires with a 25 μm diameter. The air-fuel dispersion system consists of a buffer pressure tank at a pressure of 0.45 MPa, a solenoid valve, and air pipelines. After injection of biomass fuel dust through the nozzle, two stoppers are triggered, and the moveable tube drops following a 150 ms delay to allow the head of the thermocouple to move toward the center of the dust cloud using an air driven cylinder. The ignition system consists of tungsten wire electrodes with a diameter of 0.4 mm and a 15-kV high-voltage transformer. The spark duration is 10 ms.

2.2. Experiment material

Four types of biomass provided by Dalian Jiayuan New Energy Technology Development Co., Ltd. of China were chosen for the experiments. Biomass pellets were broken into smaller particles and sieved into two particle size distributions of 50–70 μm and 100–200 μm. A scanning electron microscope (SEM) was used to observe the surface morphology of the biomass particles. The biomass particles shown in Fig. 2 have an irregular morphology. The poplar sawdust particles of 100–200 μm and the pine sawdust particles of 100–200 μm are fibrous in shape, and the other types of particles have an irregular block shape.

3. Results and discussion

3.1. Pyrolysis characteristics

To obtain the pyrolysis characteristics of the biomass particles, a thermal gravity analysis (TGA) and differential scanning calorimetry (DSC) were conducted with a heating rate of 10 K/min under an air atmosphere. The initial mass of the samples was within the range of 3–6 mg. Fig. 3 shows the weight loss of eight samples. The TGA curves can be divided into three stages corresponding to (1) water evaporation ($T < 150$ °C), (2) oxidative degradation of the biomass ($150 < T < 500$ °C), and (3) oxidation of the charred residue ($T > 500$ °C) [19].

The features of the combustion stages are qualitatively similar for the four types of biomass resulting from their similar constituent fractions. The temperatures at the beginning of the degradation processes are significantly different between the different samples. However, the 100–200 μm biomass particles have a long degradation process in comparison with the 50–70 μm biomass particles. The peak values of the differential thermogravimetric (DTG) curve for the various samples show a definite difference, and the maximum value of the DTG curve for the 100–200 μm biomass particles is larger than that of the 50–70 μm biomass particles. The DSC curves show several distinct regions related to the pyrolysis reactions from 40 °C to 500 °C. A slight endothermic peak without an obvious heat flow appears within the temperature range of 40–150 °C, and the enthalpy change depends on the moisture content. With a temperature increase from 150 °C to 500 °C, there are two remarkable peaks characterized by an intense pyrolysis reaction with abundant heat inflows.

3.2. Flame propagation behaviors and flame microstructures

The combustion properties of biomass are quite different from those of fossil fuels such as coal. Biomass has the characteristics of highly volatile materials, low carbon content, low heating value, and high moisture content. However, the high moisture content makes biomass difficult to ignite, and leads to problems of flame stability of a pure biomass fuel. The biomass combustion process is dominated by the volatile combustion. Therefore, once ignited, the overall burning rate of biomass dust is significantly higher, which is attributed to the rapid release of volatiles and the high porosity of the char particles [5,20]. In conclusion, devolatilization or thermal pyrolysis plays a significant role in the biomass combustion process.

A series of dust explosion experiments using four kinds of biomass of 50–70 μm and 100–200 μm in size with a mass density

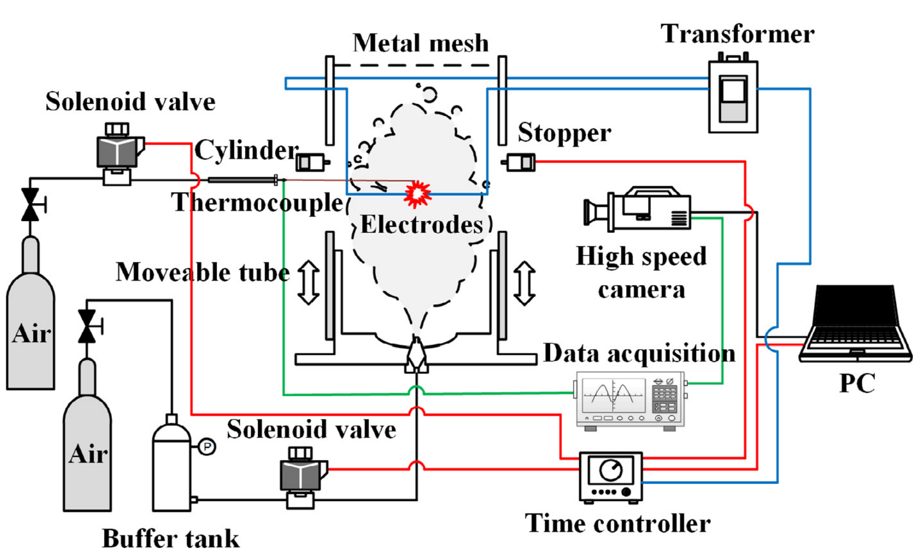

Fig. 1. Experiment apparatus.