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Effects of particle thermal characteristics on flame microstructures during dust explosions of three long-chain monobasic alcohols in a half-closed chamber

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ABSTRACT

To reveal clearly the effects of particle thermal characteristics on flame microstructures during organic dust explosions, three long-chain monobasic alcohols, solid at room temperature and similar in physical-chemical properties, were chosen to conduct experiments in a half-closed chamber. In the experiments, the dust materials were dispersed into the chamber by air to form dust clouds and the hybrids were ignited by an electrical spark. A high-speed optical schlieren system was used to record the flame propagation behaviors. A fine thermocouple and an ion current probe were respectively used to measure the flame temperature profile and the reaction behaviors of the combustion zone. Based on the experimental results, combustion behaviors and flame microstructures in dust clouds with different thermal characteristics were analyzed in detail. As a result, it was found that the dust flame surfaces were completely covered by cellular structures that significantly increased the flame frontal areas. Flame propagated more quickly and the number of the cellular cells increased as increasing the volatility of the particles. On the contrary, maximum temperature and the thickness of the preheated zone decreased as increasing the volatility of the particles. According to the ion current profile, the particles in the preheat zone were pyrolyzed to intermediate radicals and the radicals' fraction in the higher volatile dust flame was higher than that in the lower volatile dust flame.

1. Introduction

A dust explosion occurs when a fine dust in suspension in air is ignited, causing a very rapid burning and then the expanding of gaseous products with a subsequent pressure rise of explosive force that will damage plant, property and people (Eckhoff, 2003). To take appropriate measures against such dust explosion accidents, it is necessary to sufficiently understand the characteristics of flame propagation through combustible particle clouds, such as the flame propagation mechanisms and microstructures. Although some recent research were performed to reveal the flame propagation process during dust explosions (Anezaki & Dobashi, 2007; Ballal, 1983; Dobashi & Senda, 2002; Dobashi & Senda, 2006; Dobashi, Sun, Ju, & Hirano, 2001; Proust, 2006; Proust & Veyssiere, 1988; Wang, Pu, & Jia, 2006; Yin, Sun, Ding, Guo, & He, 2009), most of them focused on the flame configurations and macroscopic parameters, such as the flame propagation velocity, the maximum explosion pressure etc. Unfortunately, to date the basic knowledge on the characteristics of flame propagation through combustible particle clouds is not enough because of several major problems facing flame propagation research in dust explosions.

One major problem is that the flame propagation process is always unsteady, and there are some interactions among the particles. The flame propagation process is affected by the physical and chemical properties of the fuel, the average size, shape, distribution of the particles, the initial pressure, the oxygen concentration and the initial turbulence intensity. In all of these factors, the physical and chemical properties of the particles, especially the thermal characteristics, are essential. In our previous study (Gao, Dobashi, Mogi, Sun, & Shen, 2012), the flame propagation behaviors, the velocities and the temperature profiles of the combustion zone, the effects of the concentrations on flame propagation and the heat

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transfer modes were analyzed in detail in the flame propagation process during dust explosions of three long-chain monobasic alcohols. However, in order to clarify the effects of particle thermal characteristics on flame propagation mechanisms, it is also necessary to determine the dust flame microstructures, especially the characteristics of the preheat zone, which is critical for the particle combustion type, either homogeneous combustion or heterogeneous combustion, which is shown in Fig. 1.

The aim of present study is to examine the effects of particle thermal characteristics on flame microstructures in a half-closed chamber using the same three long-chain monobasic alcohols. The dusts were dispersed into a vertical rectangular chamber by air and ignited by an electrical spark. A high-speed optical schlieren system was used to record the flame propagation behaviors. A fine thermocouple and an ion current probe were used to measure the flame temperature profile and the reaction behaviors of the combustion zone, respectively. Furthermore, the detailed flame microstructures in dust clouds with different thermal characteristics were analyzed.

2. Experimental

2.1. Experimental apparatus

Most of the sensitivity and severity parameters of the dusts were measured in the dust explosion chambers specified by the internationally accepted ASTM standards, such as the Hartmann tube, and the 20 L spherical explosion test chamber. These apparatuses were suitable for measuring the minimum ignition energy, minimum explosible concentration, maximum explosion pressure and deflagration index (Gao et al., 2013), but were inconvenient for examining the flame microstructures and propagation mechanisms.

In this study, an experimental system similar to the traditional Hartmann tube was designed to reveal the microstructures of the propagating flames in dust explosions. The experimental apparatus is schematically shown in Fig. 2 and was composed of a small-scale combustion chamber, a gas supplying unit, an ignition system, a thermocouple, an ion current probe, a data recorder, a high-speed video camera, an optical schlieren system and a time controller system. The small-scale combustion chamber was 500 mm in height with a square cross-section of 80 mm × 80 mm. The top end was opened and the bottom end was closed. To conveniently observe the flame propagation process, two sides of the chamber wall were constructed using a glass material, and two sides were constructed using stainless steel. A gas nozzle, a dispersing cone, and a sample plate were mounted at the bottom of the chamber.

The ignition system consisted of a high voltage transformer and a pair of tungsten wire electrodes with a 0.4 mm diameter positioned 50 mm above the bottom of the chamber. The distance between the tips of the two electrodes was approximately 5 mm. A high voltage transformer with an output of 30 kV was used to generate the ignition spark. The ignition duration was 0.01 s and the nominal ignition energy was 30 J. The optical schlieren system mainly included an iodine lamp, a knife edge, two focusing lenses and two concave mirrors with the same focal length of 2.0 m.

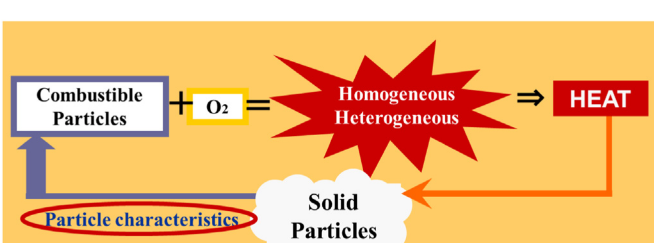

Fig. 1. Particle combustion type.

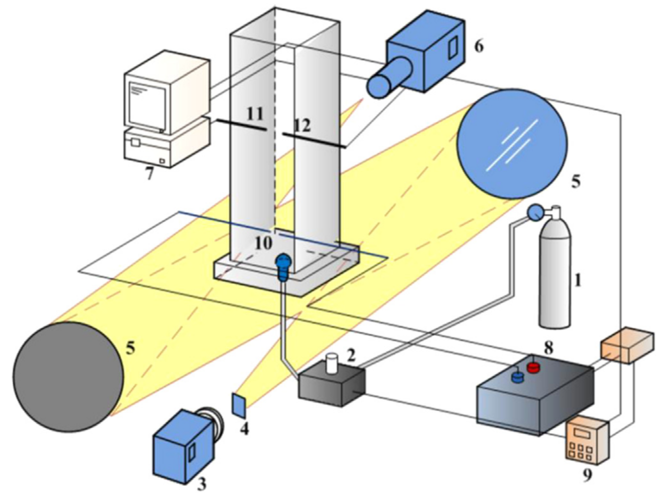

Fig. 2. Experimental apparatus. 1 Air tank 2 Electromagnetic valve 3 High speed camera 4 Knife edge 5 Concave mirror 6 Iodine lamp 7 Data recorder 8 High voltage transformer 9 Time controller 10 Ignition electrodes 11 Thermocouple 12 Ion current probe.

To explore the propagation characteristics and microstructures of the dust flames, a thermocouple and an ion current probe were positioned at the same height (35 cm above the bottom of the chamber), which is shown in Fig. 3.

The thermocouple was comprised of 25 μm-diameter Pt–Pt/Rh13% wires. The ion current probe consisted of a pair of electrodes, an electrical source and an electrical resistance. The electrodes were comprised of 100 μm-diameter Pt wires with anti-oxygenic property and good conductivity. The structures of the thermocouple and ion current probe are shown in Fig. 4.

In the experiments, the startup times of the high-speed video camera, the data recorder, the high voltage igniter, and the on-off time of the electromagnetic valve were controlled using an Omron synchronization controller. The detailed experimental conditions were as follows: ignition voltage, 30 kV; discharge period, 0.01 s; framing rate of high-speed video camera, 4000 frames/s; injection time, 0.5 s; pressure in the tank, 0.4 MPa.

2.2. Experimental materials

Three long-chain monobasic alcohols, solid at room temperature and similar in physical-chemical properties, were chosen for

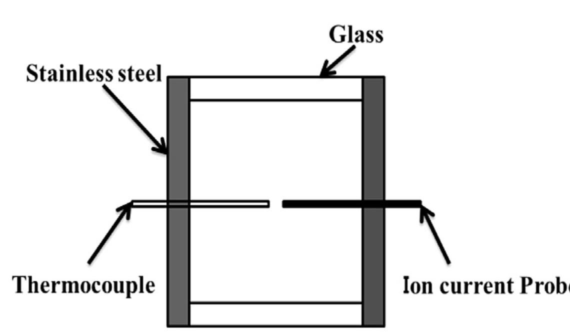

Fig. 3. Schematic of the measurement system (a) Thermocouple (b) Ion current probe.