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Flame-propagation behavior and a dynamic model for the thermal-radiation effects in coal-dust explosions

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A B S T R A C T

To reveal the flame-propagation behavior and the thermal-radiation effects during coal-dust explosions, two coal-dust clouds were tested in a semi-enclosed vertical combustion tube. A high-speed video camera and a thermal infrared imaging device were used to record the flame-propagation process and the thermal-radiation effects of the fireball at the combustion-tube outlet. The flame propagated more quickly and with a higher temperature in the more volatile coal-dust cloud. The coal-dust concentration also significantly affected the propagation behavior of the combustion zone. When the coal-dust concentration was increased, the flame-propagation velocity and the fireball temperature increased before decreasing overall. Based on the experimental results, a dynamic model of the thermal radiation was employed to describe the changes in the fireballs quantitatively and to estimate the thermal-radiation effects during coal-dust explosions.

1. Introduction

Dust explosions are phenomena in which a flame propagates through a dust cloud in air with increasingly subdivided combustible solids. These events are common risks in the coal, metallurgy, chemicals, wood, food processing, explosives and other industries (Abbasi & Abbasi, 2007; Eckhoff, 2009). As shown in Table 1 (Zhang, Jiang, & Zheng, 2005), dust explosions in China have caused severe casualties and damage. Many theoretical and experimental studies regarding dust-explosion phenomena have been performed to help prevent uncontrolled explosions in industry.

Most previous studies were devoted to measuring the minimum ignition energy, ignition temperature and explosible concentration, as well as the maximum explosion pressure, to assess the risk of dust explosions (Amyotte, Mintz, Pegg, & Sun, 1993; Bouillard, Vignes, Dufaud, Perrin, & Thomas, 2010; Cashdollar & Zlochower, 2007; Gao et al., 2013); other studies have focused on designing new explosion-protection equipment or methods (Holbrow, Hawksworth, & Tyldesley, 2000; van Wingerden, Arntzen, & Kosinski, 2001). Recently, several studies investigated the fundamental properties of flame propagation through suspended combustible particles (Dobashi & Senda, 2006; Proust, 2006). Various flame-propagation mechanisms have been proposed, particularly regarding the effects of the volatility on the flame-propagation behavior in various systems such as lycopodium (Han et al., 2000), coal (Xu, Li, Zhu, Wang, & Zhang, 2013) and alcohol (Gao, Dobashi, Mogi, Sun, & Shen, 2012).

Despite extensive research, few reports have been devoted to studying the relationship between the flame-propagation behavior and the thermal-radiation effects in coal-dust explosions. Therefore, two coal-dust clouds with different volatilities (#1 and #2) were employed to examine the flame-propagation behavior and the thermal-radiation effects of the fireballs (fireball temperatures and diameters were considered) at the combustion-tube outlet using a high-speed video camera and a thermal infrared imaging device. On the basis of the Martinsen dynamic model and the experimental results, the thermal dynamic properties of the fireball were calculated.

2. Experimental

2.1. Experimental apparatus

The experimental apparatus is shown schematically in Fig. 1. The entire system consists of a vertical combustion tube, a high-pressure

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Table 1
Frequency of dust-explosion accidents and injuries, including fatalities.

Type of dust	Frequency	Proportion (%)	Number of casualties	Death	Injury
Metal	44	21.53	155	35	120
Farm product	40	19.23	113	16	97
Organics chemicals	37	17.79	71	9	62
Compound	31	14.90	51	5	46
Inorganic compound	27	12.98	37	9	28
Fiber	17	8.17	70	5	65
Coal	12	5.77	45	7	38
Total	209	100	542	86	456

dispersion system, an ignition system, a high-speed video camera, a thermal infrared imaging device and a control system. The vertical cylindrical combustion tube is 600 mm high with a 68 mm inner diameter when the top is open. The coal particles were placed evenly in the tube base and were dispersed using a high-pressure powder-spray machine, forming uniform coal-dust clouds in the combustion tube.

The experimental conditions are as follows:

1) The dispersion pressure is 0.7 MPa.
2) The ignition system is positioned 100 mm above the bottom of the tube.
3) The electrode gap is 6 mm.
4) The igniter voltage is 8000 V.
5) The ignition energy is 5 J.
6) The frame rate of the high-speed video camera and the thermal infrared imaging device are 1000 frames/s and 100 frames/s, respectively.

The weighed coal dust was placed evenly on the bottom of the vertical combustion tube and dispersed into the tube under high pressure to form a uniform coal-dust cloud. The suspended particles were ignited by an electric spark after reaching a height of 300 mm to guarantee a consistent concentration of coal-dust clouds and reduce the influence of residual turbulence on the flame propagation. After ignition, the flame-propagation process was recorded using a high-speed video camera, and the temperatures and diameters of the fireball located at the combustion-tube outlet were recorded with a thermal infrared imaging device.

Table 2
Industrial analysis of the coal-dust samples.

No.	Mad (%)	Aad (%)	Vad (%)	FCad (%)
Coal dust #1	3.54	14.46	41.75	40.25
Coal dust #2	3.93	19.72	35.40	40.95

2.2. Experimental materials

The industrial analysis of the two types of coal dust, which were supplied by the National Quality Supervision and Inspection Center for Industrial Explosive Materials, is summarized in Table 2. To ensure that the particle sizes were in the same range and to reduce the effect of the particle-size distributions on the flame-propagation process, the coal-dust samples were crushed and sifted in a 200-mesh vibrating sieve to obtain median diameters of 32 μm and 34 μm for the two types of coal dust.

The nitrogen adsorption–desorption isotherms and the pore distributions in the two types of coal dust are presented in Fig. 2. The profiles have representative "type-IV" hysteresis loops at $P/P_0 = 0.45–1.0$, indicating that the samples are mesoporous. The specific surface areas of coal dusts #1 and #2 are 4.6 m^2/g and 2.6 m^2/g, respectively. The pore-size distributions displayed in the figure were calculated using the Barret–Joyner–Halenda (BJH) model with the desorption branch. A sharp peak for the two coal-dust samples was centered at 3.3 nm.

3. Experimental results and discussion

3.1. Flame-propagation behavior

The flame propagation of the two coal-dust clouds in and above the combustion tube is depicted in Fig. 3, which shows data that was recorded by the high-speed video camera. The concentration of the coal-dust clouds was 500 g/m^3. A time series of the flame-front position was analyzed using the recorded images. It is presumed

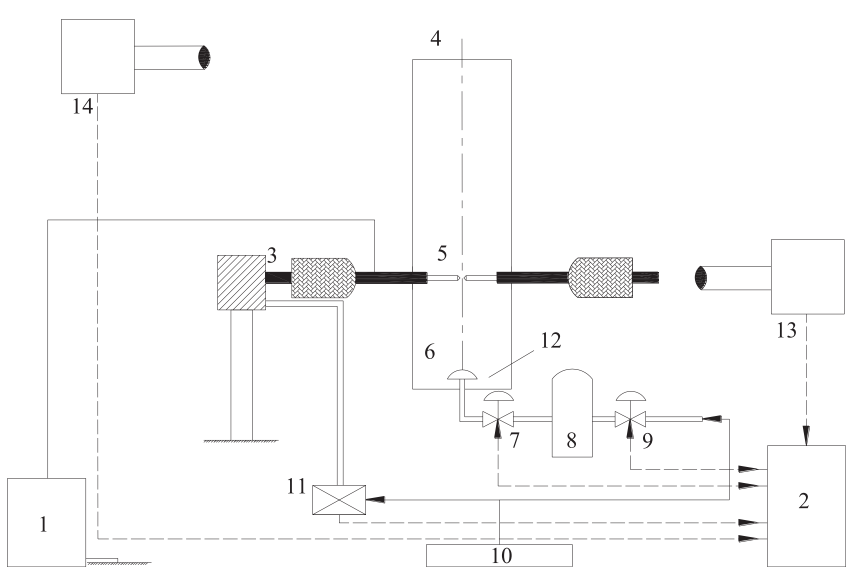

Fig. 1. Experimental apparatus: 1) electric-spark generator; 2) programmable logic controller; 3) pneumatic piston; 4) combustion tube; 5) ignition electrodes; 6) nozzle; 7) powder-injection valve; 8) gas tank; 9) air-inlet valve; 10) pressurized air; 11) piston-actuated valve; 12) powder tank; 13) high-speed camera; and 14) infrared imager.