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Experimental and numerical study on flame propagation behaviors in coal dust explosions

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ABSTRACT

To reveal the flame propagation behaviors during coal dust explosions, a kind of coal dust cloud was studied through experiment and numerical simulation in semi-enclosed vertical combustion tubes with different lengths. A high speed video camera and a thermal infrared imaging device were used to record the flame propagation process. The result indicated that the supreme flame propagation velocity and the highest flame temperature both rose gradually with the tube length increasing. Meanwhile, FLUENT was applied to numerical simulation of flame propagation behaviors during the coal dust explosions. The simulation result showed the flame combustion and the temperature varying process was consistent with the experimental result. It also revealed the distribution of flow velocity in the flow field during the combustion process, which indicated that flow velocity higher than flame propagation velocity was an important reason for dust re-entrainment and consistent explosion.

1. Introduction

Attention on the dust explosion started from a report in 1795 which covered the explosion in a flour silo in Turin, Italy [1]. As for its great destructive power, the dust explosions have become an important research direction in the dust explosions in the recent years [2–4]. Although, many countries have made corresponding progress in the basic research of dust explosions [2,5], the tragedy caused by dust explosions has not been completely controlled yet. With the rapid development of powder technology, it has a great value in preventing and controlling major hazardous accidents in the process industries. Therefore, it is necessary to carry out further study on the characteristic parameter of dust explosions.

Some recent researches have focused on the flame propagation process which is one of the characteristic parameters during dust explosions [6–11]. Based on the theoretic study of premixed flame and using starch, sulfur and aluminum powder as test samples, Gao [7,11] researched on the flame propagation process of the organic dust with different concentration, such as hexadecanol, octadecanol and eicosanol, using a high speed video camera. Han [9] studied the flame structure and the flame propagation process of lycopodium in vertical tube. Proust [10] studied the effects of thermal radiation for the flame propagation process in terms of detonation, laminar and turbulent flame.

However, flame propagation mechanisms of dust clouds are not well-understood and the current research is an experimental study due to the dust explosion that is a complex combustion process of two-phase flow, causing great difficulties in the simulation process of dust explosion. Fortunately, with the development of the mechanical model, the numerical simulation technology based on computational fluid dynamics (CFD) has become the powerful tool during the researching process [12–15]. It is hopeful that this technology may become a design tool for safeguard measures, replacing the common empirical equations and charts gradually.

To promote understanding of flame propagation during dust explosions, a kind of coal dust cloud was applied to carry out systematic research on flame propagation through experiment and numerical simulation in semi-enclosed vertical combustion tubes of different lengths. Comparing with experiment, FLUENT was used for numerical simulation to provide a valuable simulation tool for dust explosion research and useful information for safety prevention design.

2. Experimental

2.1. Experimental apparatus

The experimental apparatus is shown schematically in Fig. 1, which is composed of vertical combustion tubes of different lengths including 300 mm, 600 mm and 900 mm, a high pressure dispersion system, an

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Table 1
Proximate and ultimate analyses of the coal.

Sample	Proximate analyses(%)				Ultimate analyses(%)			
	M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C	H	O	N
Coal	3.54	14.46	41.75	40.25	57.05	4.43	37.4	1.12

M_{ad}: moisture content; V_{ad}: volatile matters; A_{ad}: ash; FC_{ad}: fixed carbon.

ignition system, a high-speed video camera, a thermal infrared imaging device, and a control system. The vertical combustion tubes have a 68 mm inner diameter with the top open. The coal particles were placed evenly in the tube base and dispersed by a high dispersion pressure powder spray machine, whose pressure was 0.7 MPa. The uniform coal dust clouds with the concentration of 500 g/m^3 were formed in the combustion tube. The ignition system is positioned at 100 mm above the bottom of the combustion tube. The distance between the tips of the two electrodes is 6 mm. A high voltage transformer with an output of 8000 V was adopted to make an ignition spark with the ignition energy of 5 J. The frame-rate of the high-speed video camera and the thermal infrared imaging device are 1000 fps and 100 fps, respectively.

The weighed coal particles were placed evenly at 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 cloud and reduce the influence of residual turbulence on the flame propagation. After ignition, the flame temperature and the flame propagation process were recorded with a thermal infrared imaging device and a high speed video camera, respectively.

2.2. Experimental materials

The source of coal particles is from Huolinhe Coal Mine. The proximate and ultimate analyses of the coal particles are summarized in Table 1. The morphology of the coal particles was characterized by field emission scanning electronic microscopy (FESEM, JEOL JSM-6700F) and the diameter distribution of coal particles was characterized by laser particle size analyzer (Mastersizer 2000).

As shown in Fig. 2, according to laser particle size analysis, the particle size distributions of most coal particles are (10 ~ 100) μm and the median diameter is 34 μm. FESEM result shows that the coal particle size is non-uniform and the shape is irregular. The diameters of coal particles are all less than 100 μm,which are well consistent with the laser analysis result.

3. Numerical simulation

3.1. Governing equations

CFD is applied to numerical simulation of the coal dust explosions. It is supposed that the coal particles are spherical particles. Based on chemical reaction kinetics and fluid mechanics, the governing equations are established through mass conservation, energy conservation, momentum conservation, and chemical reaction balance [16]. The main equations are as follows:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \tag{1}$$

Energy conservation equation:

$$\frac{\partial \rho h}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_j h-\frac{\mu_e}{\sigma_h}\frac{\partial h}{\partial x_j}\right)=\frac{dP}{dt}+S_h \tag{2}$$

Momentum conservation equation:

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i u_j-\mu_e\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial \rho}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu_e\frac{\partial u_j}{\partial x_j}\right)-\frac{2}{3}\frac{\partial}{\partial x_j}\left[\delta_{ij}\left(\rho k+\mu_e\frac{\partial u_k}{\partial x_k}\right)\right]. \tag{3}$$

Chemical reaction balance equation:

$$\frac{\partial\left(\rho Y_{fu}\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j Y_{fu}-\frac{\mu_e}{\sigma_{fu}}\frac{\partial Y_{fu}}{\partial x_j}\right)=R_{fu} \tag{4}$$

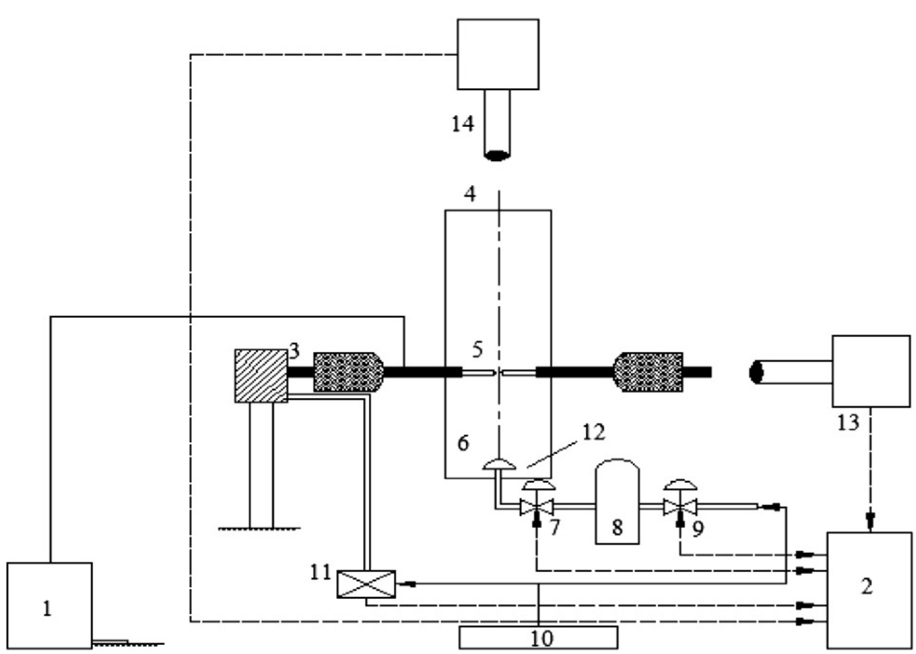

Fig. 1. Experimental apparatus. 1 electric spark generator; 2 programmable logic controller; 3 pneumatic piston; 4 combustion tube; 5 ignition electrodes; 6 nozzle; 7 powder injection valve; 8 gas tank; 9 air inlet valve; 10 high pressure air; 11 piston-actuated valve; 12 powder tank; 13 high speed camera;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