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Experimental and numerical studies on the explosion severities of coal dust/air mixtures in a 20-L spherical vessel

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ABSTRACT

Severity parameters are critical for safety management and risk assessment of coal dust explosions. We evaluated explosion severity parameters using a 20-L spherical vessel and numerical simulation by the program FLUENT to reveal the explosion mechanism of coal dusts. The explosion pressure and the rate of explosion pressure increased with coal dust concentration and the ignition delay up to a concentration of 250 g/m^3 coal dust and an ignition delay of 60 ms for a maximum explosion pressure of 0.67 MPa and a rate of explosion pressure rise of 68.89 MPa/s. Comparison of the numerical and experimental explosion pressure profiles showed reasonable quantitative and qualitative agreement. Additionally, the numerical simulation was used to address the technical difficulties of understanding the mechanisms of dust explosion, it suggested that the airflow of the dust explosion played a more important role in the secondary explosion of dusts in a closed chamber than in a half-closed one.

1. Introduction

Superfine powder is widely used in civil, mining and food manufacturing applications. Owing to the high surface energy of superfine powder, the potential risk of dust explosions is increased when the powder diameter increases to micrometer size. Dust explosions present a continuing threat to the coal, food, chemical, metallurgy, and textile industries, leading to injuries, deaths, and property damage [1]. According to the CSB Investigation Report [2,3], 281 major combustible dust accidents occurred between 1980 and 2005, resulting in 119 people killed, 718 people injured, and significant damage to industrial facilities. Recently, in the period of 2001–2015, the coal industry had significant problems resulting from dust explosions [4,5]. Thus, improved understanding of coal dust explosions is important for the prevention and control of these industrial disasters and thus has important practical value for the protection of human life and property.

To understand the parameters that determine the severity of dust explosions, many recent studies have focused on the characteristics of dust explosions. For example, Medina [6,7] investigated the dust explosion parameters of coal samples including the deflagration index, maximum explosion pressure, and minimum explosible concentration using a 1 m^3 ISO explosion vessel test apparatus. They found that the dust explosion reactivity was increased for higher surface area coal due to the greater oxygen diffusion facilitated by the higher porosity of the char. Li [8–10] analyzed the explosion parameters of coal dust/air mixtures using a 20-L spherical explosion test apparatus and demonstrated that the presence of combustible gases significantly increased the maximum explosion pressure and rate of pressure rise and that the minimum explosible concentration of mixture decreased with increased combustible gases content. Their findings that combustible gases greatly increased the risk of coal dust explosion suggest that the storage safety of coal dusts would be effectively improved by reducing the oxygen concentration. Cashdollar [11,12] studied the explosibility of coal dusts of varying volatility and particle size, and evaluated the minimum explosible concentration and limiting oxygen concentrations of different dusts using a 20-L spherical explosion test apparatus. Xin [13–17] designed an in-situ diffuse reflection FTIR system to test the real-time chemical variations during coal reaction and concluded the presence of aliphatic groups on the coal varied with temperature. In our previous study [18–20], we also investigated explosion parameters including the maximum explosion pressure, the maximum rate of pressure rise, the flame propagation behavior, the thermal-radiation effects, and the deflagration index of coal dust/air mixtures, which indicated that airflow velocity is an important factor in dust re-entrainment and consistent explosion.

However, due to the scarcity of experimental data and the complexity in the selection of multiple safety-related parameters, analytical estimations remain insufficient and difficult. Additional data and the development of numerical tools are required to solve this difficulty.

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Table 1
Proximate and ultimate analysis of the coal.

Proximate analyses (%)				Ultimate analyses (%)			
M_{ad}	A_{ad}	V_{ad}	FC_{ad}	C	H	O	N
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.

Fortunately, with the recent development of improved computational resources, a three-dimensional numerical simulation technology based on computational fluid dynamics (CFD) was developed [21–26]. This technology may become a powerful tool for the design of safeguard measures and could gradually replace use of common empirical equations and charts. In this study, a coal dust/air mixture was used for systematic research of explosion severity behaviors by both experimental and numerical simulation using a 20-L spherical explosion test apparatus. The numerical simulation tool FLUENT was used to address the technical difficulties of understanding the mechanisms of dust explosion.

2. Experimental

2.1. Experimental materials

The proximate and ultimate analyses of the coal particles are summarized in Table 1. The coal particles were sifted in a 200 mesh vibrating sieve and were desiccated in a vacuum drying oven at 30 °C for 24 h before the experiments. The diameter distribution of coal particles given in Fig. 1 was characterized using a laser particle size analyzer and the morphology of the coal particles as shown in Fig. 2 was characterized using a scanning electronic microscopy (SEM). As shown in Fig. 1, the particle size distributions of most coal particles were (10 — 100) μm and the median diameter was 34 μm. As shown in Fig. 2, the coal particle size was non-uniform and was irregular in shape. The diameters of coal particles were all less than 100 μm, in agreement with the laser analysis result.

TG and DTG curves of the coal particles are depicted in Fig. 3. As shown in Fig. 3, the coal particles start to lose weight at a very low temperature of approximately 30 °C. When the temperature increased to (100 — 300) °C, the TG curve became flat and the weight loss decreased slowly. The weight loss rate of the sample increased significantly upon heating at 300 °C. The DTG curve exhibited two steps, corresponding to the low-temperature combustion stage and the high-temperature combustion stage. A weak peak appeared at temperatures below 150 °C, which is mainly caused by the loss of moisture and volatile matters in the coal particles during the low-temperature combustion stage. As the temperature increased, the weight loss rate of coal particles decreased, mainly due to complete volatilization of the moisture in the coal dust, decreasing the release of light volatile matter. When the temperature of the sample was in the range of 100–300 °C, the weight loss rate was low. When the temperature went beyond 300 °C, the weight loss rate increased gradually, and the maximum weight loss rate occurred at approximately 400 °C, due to the burning of some nonvolatile organic matter in the coal particles, which released a lot of heat and caused fixed carbon burning. The combustion process was terminated when the sample mass no longer changed. The mass fraction for residuals or the ash in the coal particles was about 15% of the total weight, which is consistent with the industrial analysis presented in Table 1.

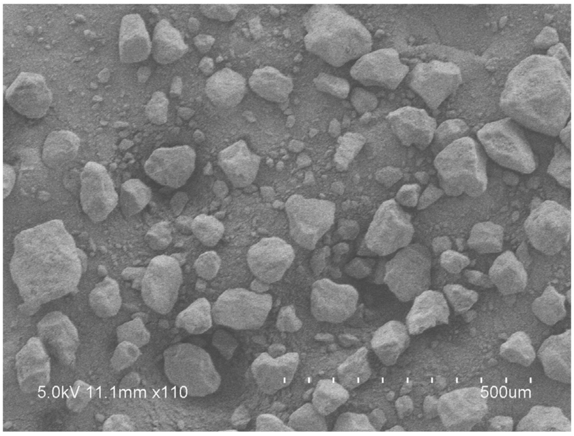

Fig. 2. Scanning electron microscopy of the coal particles.

2.2. Experimental apparatus

The experimental apparatus was comprised of a 20-L spherical explosion chamber, a dispersion system, an ignition system, and a control and data acquisition system that is shown schematically in Fig. 4. A pyrotechnical igniter of 10 kJ energy was prepared according to the standard ASTM E1226 [27] and was located in the center of the explosion chamber. The chamber was vacuumed to −0.06 MPa (gauge pressure). A two-phase valve was mounted under the bottom of the vessel, and driven by compressed gas. A dust chamber of 0.6-L was connected to the two-phase valve and pressurized to 2 MPa. After opening the two-phase valve, the coal particles were dispersed into the explosion chamber to form dust/air mixtures by compressed gas through the dispersion nozzle. When the pressure in the explosion chamber increased to 0 MPa (a standard atmospheric pressure), the pyrotechnical igniter was detonated to ignite the dust/air mixtures. A high-speed camera captured the process of coal dust explosion through a sight glass mounted in the front

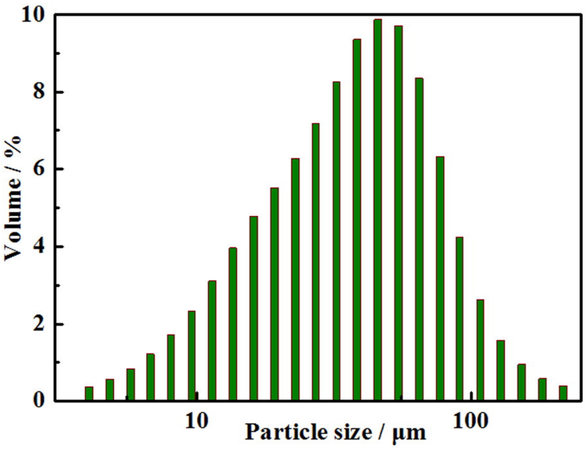

Fig. 1. Diameter distribution of the coal particles.

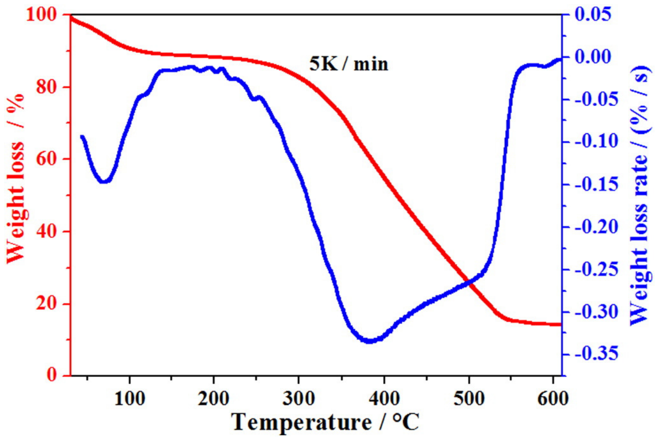

Fig. 3. TG and DTG curves of the coal particles.