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Experimental investigations on explosion behaviors of large-particle and formation rules of gas residues

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ABSTRACT

Using a standard 20 L spherical test vessel, the explosion characteristics of bituminous coal in the form of large particles were investigated. The goal of this research was to better understand the fundamental aspects of dust explosions and to obtain reference data for the investigation of accidental explosions. Following explosion testing, the residual gases were also analyzed by gas chromatography. The results show that large coal particles require more rigorous conditions, such as higher dust concentration and ignition energy, compared with smaller particles. Analyzing the explosion characteristics of mixtures of various particle diameters demonstrated that the addition of smaller particles dramatically increases the energy release rate and therefore increases the explosion risk of larger particles. Residue analysis showed that, with decreases in the particle size, there is an overall decline in the CO2 content together with a slight increase in CO. There were no obvious changes in the evolution of hydrocarbons with decreases in the particle size, although there were significant variations in the relative proportions of different hydrocarbons.

1. Introduction

Since the Eleventh Five-Year Plan, the number of miners and the proportion of primary energy consumption provided by coal have dropped on an annual basis. As an example, the Chinese share of energy generated by coal combustion fell from over 70% in 2009 to 63% in 2015 and the number of coal mines decreased from 24,800 in 2005–10,800 in 2015 (NBSC, 2016). However, although the relative amount of energy production based on coal has dropped, the absolute amount of coal consumed continues to grow, and coal is still the primary energy source in China. Additionally, the number of enterprises (annual yield > 10 million tons) increased from 30 in 2005 to 52 the year of 2015, nevertheless, the yield of these 52 coal enterprises accounted for 52% of total output (SACMS, 2016a). With the continuous enlargement and deepening of coal mines, gas and coal dust explosions and accidental fires tend to occur more easily owing to the complex underground conditions in such mines. There were serious underground coal mine explosions in March 2013 in Jilin Province (35 fatalities, 16 injuries, 11 disappearances), in November 2014 in Liaoning Province (28 fatalities, 50 injuries), in December 2015 in Heilongjiang Province (19 fatalities), in October in Chongqing City (33 fatalities) (SACMS, 2016b). Surveys of these accidents show that coal dust has also played a part in the majority of mining accidents that have resulted in heavy casualties. Therefore, further studies of laboratory dust explosions are still needed as a basis for the development of techniques and strategies for explosion prevention, dust control and dust explosion risk management (Ji et al., 2016; Han et al., 2016; Hu et al., 2016; Kurnia et al., 2015; Abuswer et al., 2014).

Recently, there has been significant worldwide research regarding the characteristics of coal dust explosions, which has been of benefit to the coal industry. Gummer and Lunn (2003) described tests in which clouds of dusts with a range of minimum ignition temperatures (MITs) were dispersed around smoldering dust agglomerations or flames at various temperatures. They found that smoldering nests with temperatures above approximately 700–800 °C were able to ignite sulfur clouds and flaming nests were able to ignite dust clouds up to an MIT of 600–675 °C. British scholars (Moen et al., 1982) conducted large-

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scale methane/air explosion tests in a vented 50 m^3 vessel (a tube 2.5 m in diameter and 10 m long, open at one end) with regularly spaced obstacles and found that pressure development resulted from turbulent flame propagation. Di Benedetto and Russo (2007) developed a numerical tool for the evaluation of the thermo-kinetic parameters of dust explosions, which calculate the deflagration index and the laminar burning velocity for dusts utilized in various process industries as function of dust concentration, and the obtained results were more practical compared with these models which simulate a single-particle explosion as occurring through different steps. Other literature reports (Dastidar et al., 2001; Kuai et al., 2011a,b; Mittal, 2013; Eckhoff, 2013; Dastidar et al., 1997; Traoré et al., 2009; Yuan et al., 2014; Liu et al., 2015) have explored the relationships between the ignition energy, particle size, coal dust concentration and the characteristic parameters of dust explosions. As well, there have been in-depth studies of the factors that inhibit coal dust explosions, such as the moisture content of the coal dust, the presence of ash, and the oxygen concentration.

The analysis of residues plays an extremely vital role in analyzing the causes of accidents and so the characteristics of such products have been increasingly researched in recent years. Using scanning electron microscopy (SEM) and image processing technology, the surface fractal characteristics of solid explosion products have been analyzed and compared (Li et al., 2012). Li and Lin identified three different kinds of pore distributions associated with pore shape factors ranging from 0.6 to 1.0. Based on SEM, Cashdollar (2000) found that burned particles are primarily composed of char residues that are often larger than the original particles, and some particles form obvious cenospheres. X-ray diffraction analysis of explosion products indicated the presence of micron-sized aluminum particles covered with greater amounts of Al_2O_3 than nano-sized aluminum particles (Li et al., 2011).

A review of the literature concerning coal dust explosions found that most studies focused on investigating the factors that affect the explosion characteristics of fine coal dust (25–150 μm), while research into the parameters and residues associated with explosions of larger (250–850 μm) and mixed particle sizes has been very limited. In the present work, a 20 L spherical vessel was used to systematically assess the explosion characteristics of large particles (250–850 μm) and the evolution of gaseous products. The effects of the average particle size of mixed coal samples on the explosion characteristics were also considered and discussed. The results may improve our ability to understand, predict and suppress coal mine gas and dust explosions hazards.

2. Materials and methods

2.1. Experimental facilities

The full-scale explosion tests in this study were conducted in a standard 20 L stainless steel spherical vessel, consisting of three main parts: the main spherical body, the control system and the data acquisition system. The body of the test apparatus was the key part of the testing system and consisted of a double walled stainless steel sphere with a water-cooled jacket and a gas distribution system. The control system was used to control the air intake as well as to trigger sampling, valve opening and ignition. The intermediate operations, such as the air intake, dust introduction, sample collection and ignition were all performed on the millisecond scale. The data acquisition system recorded pressure variations during the explosion, over the range of 0–1.7 MPa. Two explosion severity parameters (maximum explosion pressure, P_{maxmax}, and maximum rate of pressure rise, $(dP/dt)_{max}$) were determined using this apparatus in accordance with the principles of the ISO 6184-1 Standard. 1(ISO (1985)). P_{max} is typically related to the thermodynamics of the explosion reaction and is a measure of the amount of heat liberated during combustion, whereas $(dp/dt)_{max}$ is associated with the rate at which the reaction heat is liberated (Dahoe et al., 1996). Experimental system diagram of explosion test device are presented in Fig. 1.

The gaseous products of the explosion, including O_2, N_2, CO, CO_2, CH_4, C_2H_2, C_2H_6, C_2H_4 and C_3H_8, were analyzed using a GC-9790 gas chromatograph (GC). The temperature control of this instrument was accurate to ±0.1 °C and the heating gradient was accurate to ±1%. The detectable heating rate range was from 0.1 to 30 °C/min, and the hydrocarbon detection limit was 0.1×10^{-6}. The GC analysis of gaseous products was performed quantitatively using external standard method. The flowchart of Gas Chromatography Analysis is presented in Fig. 2.

2.2. Experimental methods

In accordance with the established experiment plan, a specific amount of coal dust was weighed out using an analytical balance and dust clouds in the vessel were ignited by a pyrotechnic igniter that imparted a known quantity of energy. Three replicate trials were performed at each set of experimental conditions and the data presented in this work represent the means of the resulting values. Following each coal dust explosion, we connected a latex hose to the exhaust port of the test vessel and opened the vent valve, after which the gaseous products were extracted with a sampler. To reduce the effects of residual air in the sampling hose, the gaseous explosion products extracted in two previous were discharged into the air, after which the test aliquot was obtained by sampling the products from the explosion vessel. All the gas samples were stored in aluminum foil bags for analysis.

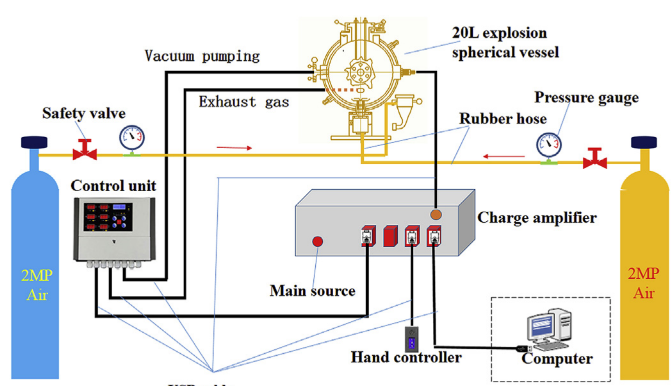

Fig. 1. Experimental system diagram of explosion test device.

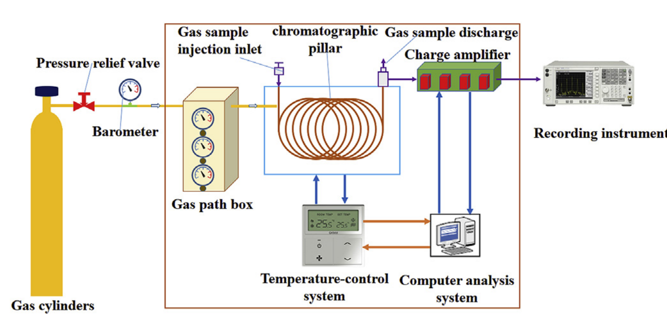

Fig. 2. The flowchart of Gas Chromatography Analysis.