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Experimental analysis on post-explosion residues for evaluating coal dust explosion severity and flame propagation behaviors

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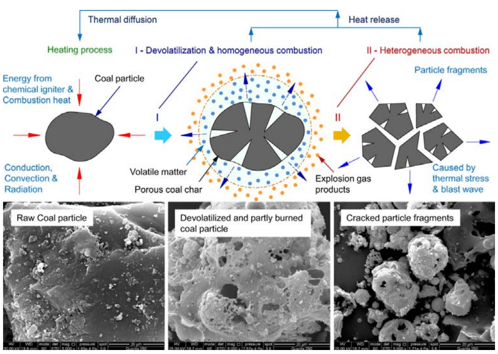
GRAPHICAL ABSTRACT



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ABSTRACT

Coal dust explosion is a major threat to coal mine and other coal processing or utilizing industries. A deep investigation and accurate knowledge of coal dust explosion mechanism are still essential for the development of safety techniques for coal dust explosion prevention. In present work, the explosion severity of coal dust/air mixture, flame propagating properties, the characteristics of gas and solid residues had been studied. And, the correlations between the residues characteristics and explosion severity had been analyzed systematically. Results show that there is a linear relationship between explosion flame propagation speed (V_F) and dust concentration (C_{dust}). With the increasing of vitrinite reflectance ($R_{o,max}$), explosion pressure (P_m), explosion pressure rise rate $(dP/dt)_m$, explosion index (K_{st}) and flame propagation speed (V_F) are all presenting a first increasing and then decreasing trends. During coal dust explosion, much more solid fragments are produced by the thermal stress and blast shock impacts. Compared with raw coal dust, particle size dispersities of all residues are increased obviously. Chemical functional groups in the coal dust particles, such as aromatic C—H, aromatic C$=$C, aliphatic C—H bonds, and oxygen-containing functional groups, etc. are all involved in coal dust explosion process. Furthermore, aliphatic C—H and oxygen-containing matters may be the key factors influencing on the reactivity of dust explosion. For coal dust explosion under poor dust concentration conditions, the main gas components in the mixtures are CO_2 product, residual oxygen and nitrogen gas in balance. The other combustible component (CO, CH_4, C_2H_2, C_2H_4, C_2H_6 and C_3H_8) is almost undetectable. However, under dust-rich conditions, the combustible components would be increased sharply. The firstly detected combustible gases

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(CO, CH_4, C_2H_2, C_2H_4, C_2H_6 and C_3H_8) can be used as the characteristic gases to determine the maximum explosion intensity of coal dust explosion.

1. Introduction

Coal is one of important energy supply of the worldwide, especially to that of China. However, in the coal mine and other coal processing or utilizing industries, there are always some safety problems, such as coal dust explosion accidents, need to be solved urgently. According to the statistics, in China, 87.32% of the 532 national key mines are facing the risk of coal dust explosion [1]. Therefore, a deep investigation and accurate knowledge of coal dust explosion mechanism and the causes of disaster are still essential for the safety development of techniques and strategies for coal dust explosion prevention.

For a long time, researches on coal dust explosion were mainly focused on the sources and triggers of dust explosions, explosion characteristics parameters, flame propagating properties and suppression factors associated with dust explosions [2]. Basically, explosion parameters such as overpressure, pressure rise rate and explosion index are very important for the assessment of explosion severity. Using large-scale horizontal tube, Liu et al. [3] studied coal dust/air mixture explosions properties and the maximum overpressure, the thickness of the flame and flame structure had been analyzed systematically. Cao et al. [4,5] investigated the combustion sensitivity parameters such as explosion overpressure and the explosion pressure rise rate by 20L spherical explosion apparatus. Javier et al. [6] determined the explosivity of Colombia coal by chemical analysis based on the volatile ratio. And also, the fire and explosive properties of methane-coal dust hybrid fuels were also investigated by Ajrash et al. [7] using a cylindrically shaped explosion chamber. Their results showed that both the ignition energy and the diluted combustible fuel dust have significant impacts on the over pressure rise (OPR). Furthermore, Li et al. [8] had also pointed that present of combustible gas would greatly improve the explosion severity of coal dust. Besides coal dust/air explosion properties, the ignition and explosion of different rank coals in simulating oxyfuel combustion gas conditions had also been focused by some researchers [9]. Generally, there is a close relationship between the explosion flame propagations and the scope of disaster spread. Therefore, the explosion severity parameters and flame propagation speed of pulverized biomass [10], μm-size conveyor rubber dusts [11], premixed liquefied petroleum gas (LPG) [12] and agricultural waste materials [13] had also been investigated by experiments. Basically, previous researches had shown that coal rank, dust concentration, particle size and igniter had significant effects on the explosion severity. Furthermore, the participation properties of large particles [14], particle size distributions, specific surface areas (SSA) had also great effects on coal dust explosions and the explosion suppression effectiveness [15]. By experiments, Li et al. [16] had reported that the evaluation of coal dust explosion hazard should be considered in terms of not only dust concentration, but also particle size and size dispersity.

For coal dust explosion, flame propagation is another important aspect to reveal the explosion severity and reaction mechanism. Chen et al. [17] analyzed the combustion behaviors and flame structure of methane/coal dust hybrid propagating flame by high-speed video camera and photodiode. Their results presented that the flame emits strong yellow light and the luminous zone length increases during propagation. Using semi-enclosed vertical combustion tubes and high speed video camera, Cao's results [18] showed that the supreme flame propagation velocity and the highest flame temperature would rise gradually with the tube length increasing and the flow velocity is higher than flame propagation velocity, that was an important reason for dust re-entrainment and consistent explosion. To reveal the effects of particle characteristics, including particle thermal characteristics and size distributions, on flame propagation mechanisms during dust explosions, Gao et al. [19] studied the flame structures using an approach combining high-speed photography and a band-pass filter. Two obviously different flame propagation mechanisms were observed in their experiments: kinetics-controlled regime and devolatilization controlled regime. And, results of Bai and Liu et al. [20] also showed that there were three concentric zones for the explosion flame structure (from outside were the red zone, the yellow illuminating zone and the bright white illuminating zone respectively) and the thickness and the propagation speed of the flame increased gradually.

Coal is a natural porous energy material. The physicochemical property of coal varies greatly. During coal dust combustion or explosion, coal particles would be rapidly heated and undergo a series of complicated physical and chemical changes, including pyrolysis, evaporation, condensation, fusion, breakage and eventually forming solid residues. Therefore, the structure analysis on coal and coal char will have a great significance for understanding their activities. With an image processing method to the coal dust explosion residues, our previous research [8] had shown that pore shape factors of residual particles were distributed among the range of 0.2–1.0, but for the shape factor among the range of 0.6–1.0, pore distributions were significant difference. Using 20L explosion vessel, the microstructure, morphology and proximate result of original coal and the solid post-explosion residues had been analyzed by Liu et al. [21,22]. Analysis of solid residues also showed that volatile and fixed carbon contents would greatly reduce and ash contents would increase significantly. However, the moisture content changes slightly. And also, by energy-dispersive spectrometry, scanning electron microscopy, and automatic surface area and pore analyzer, Hong et al. [23] compared the explosibility and microstructures of residues of first and secondary explosions. Therefore, it can be speculated that the structure of the explosive products contains a wealth of important information that reflects the explosion process and reaction characteristics.

However, because of the complex nature of a coal dust explosion, post-explosion surveys are still very difficult. Generally, analysis on the causes of coal dust explosion disasters in China is primarily based on expert inspection and onsite evidence collection, which would be impractical, inaccurate and lack credibility to some degrees. Despite this, it is pleasing that the detection technology on the explosion residual samples had been successfully used to analyze the causes of the disaster or to determine the type of explosive material in some explosion accidents [24,25] And also, Cashdollar et al. [26] had reported that during coal dust explosion, coke is almost always found whenever coal particles are dispersed into a flame, and therefore the presence of coke is a good indicator of explosion flame spread. Therefore, analysis on post-explosion residual samples may be important for the reveal of reaction mechanisms.

To date, there is still a lack of systematic research on the relationship between the coal dust explosive residue characteristics and its explosion severity. Investigation on this topic may have important significance to reveal the mechanism of coal dust explosion. In the present research work, the explosion severity, flame propagating properties and the characteristics of gas and solid residues had been studied. And, the correlations between the residues characteristics with explosion severity had been analyzed systematically.