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Experimental investigation of methane/coal dust explosion under influence of obstacles and ultrafine water mist[☆]

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A B S T R A C T

Experimental investigations were performed on mitigating methane/coal dust-mixture explosion in the presence of obstacles using ultra-fine water mists to reveal the effects of the obstacles and water mist. The explosion pressure and temperature history were obtained through PCB piezo-electronic pressure transducers and fast-response thermocouples, respectively. A Fastcam Ultima APX high-speed video camera was used to visualize both the explosion process and its mitigation. The LaVision laser diagnostic system was employed to measure the blast flow field considering the obstacles and ultrafine water mist, wherein the coal dust particles were considered the tracer particles. The results show that the explosion is primarily influenced by the number, shape, and installed locations of the obstacles; the reinforcement effect of the square ring is stronger than that of the column ring. The maximum explosion pressure, explosion temperature, and increase rate of pressure decrease by employing the ultrafine water mist, though the obstacles affect the suppression efficiency. In the explosion flow field, the dust particles distribute evenly in the explosion tube when the ultrafine water mist is not employed. The vortex of the flow field is unclear, whereas the vortex of the flow field becomes apparent in the presence of the ultrafine water mist. The results of this study can be helpful in guiding the design of water-mist systems for mitigating the risk of accidents in mines or other related areas and provide valuable data for model development.

1. Introduction

As one of the major energy sources fueling various industries, coal contributes tremendously to the economy of China. More than 90% of the coal mines in China are being exploited at the risk of gas explosions, resulting in irreversible environmental pollution and human casualties. Hence, studies on gas explosion and its mitigation have scientific and practical significances in preventing and reducing methane-gas explosions (Xu et al., 2004).

Many obstacles exist in coal mines, including pillars, bulk frames, and other structures, which may directly cause an explosion or reduce the effectiveness of explosion-prevention measures. Hence, obstacles play an important role in propagating explosions. In previous studies, obstacles were considered in the analyses because of their significant effect on explosions. A validated large-eddy simulation model of an unsteady premixed flame propagation was used to study the phenomenon underlying vented gas explosions in the presence of obstacles. Methane-air mixtures of various compositions and obstacles with different area-blockage ratios and shapes were investigated (Di et al., 2009). The effects of flame interactions on different types of multiple obstacles within the chambers of different L/D ratios were experimentally analyzed, wherein five chambers were employed to examine the flame interaction with multiple bars in each chamber (Park et al., 2008). The abilities of predicting the explosion-venting mechanism using existing models such as the NFPA, Molkov, and Yao equations, were analyzed with respect to experimental data of peak pressures obtained in various chambers with internal obstacles (Park et al., 2008). The interaction of the cloud (debris) with a solid beam located at some distance from the explosion was investigated under the influences of different parameters such as the pressure of the explosion, particle size, number of particles, and obstacle location (Kosinska, 2010).

Water mist is a commonly used suppressant for fire suppression

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because of its high efficiency, environmental friendliness and other advantages, but the studies on explosion mitigation via water mist have been conducted in recent years. For instance, the suppression of blast waves using water mist, chemical and physical processes of explosion suppression using ultrafine water mist, and suppression of TNT explosion using ultrafine water mist were studied (Schwer and Kailasanath, 2003; Thomas, 2000; Willauer et al., 2009). Recently, experimental investigations on methane explosion and methods of reducing the methane-coal dust-mixture explosion using ultrafine water mist were conducted to study the characteristics of mixture explosion and its suppression (Gu et al., 2010; Qin et al., 2012; Xu et al., 2012, 2013).

Particle image velocimetry (PIV) is an important and non-intrusive method for quantitative and instantaneous measurement of laboratory flows. Sancho et al. (2016) analyzed the effects of different flow structures obtained at different Reynolds numbers on the irreversible fast acid–base neutralization measured using PIV and PLIF technique, for which they conducted a numerical simulation using a finite volume code. The recirculation bubbles in the vortex breakdown regions and numerical velocity profiles are in good agreement with the measurements and previous studies. Ferguson et al. (2015) performed scale-model experiments on a forward-facing bent duct to generate two-dimensional (2D) PIV velocity fields at four longitudinal planes across the width of the device. They demonstrated that there are significant three-dimensional aspects to the flow within and around the device, which must be considered when designing underwater structures. Ebara et al. (2014) investigated the flow field in a sphere-packed pipe using a two-dimensional PIV method by matching the refractive indices of a channel material with that of the working fluid. The three-dimensional flow structure was verified by integrating the obtained data. Sengupta et al. (2015) used the PIV technique to study the turbulent mixing behavior of two opposing flows inside a 1/18 scaled-down model of a square chimney structure of a pool-type research reactor. Serra and Semiao (2013) presented a set of experimental data obtained using the 3D PIV technique and a set of profile thermocouples. The results showed that the high momentum of the inlet flow and the large recirculation zone formed downstream of the buoyant plume above the heat source promoted a homogeneous temperature field. Ayati et al. (2015) simultaneously combined the two-phase PIV technique and wave-field measurements to investigate the flow dynamics of both the phases, e.g., velocity profiles, turbulence profiles, distribution of turbulent structures, and wave statistics.

As mentioned previously, many studies have been conducted on gas ignition, gas explosion, and even the effects of obstacles on gas explosions. However, only few studies exist on the flow-field visualization of gas-explosion mitigation using water mist affected by obstacles using the PIV technique. Hence, in this study, experiments are conducted on methane-coal dust explosion and its mitigation using ultrafine water mist considering different types of obstacles. The explosion pressure and temperature are obtained and are analyzed. The results can be helpful in guiding the design of water-mist systems for mitigating the risk of accidents in mines or other related areas and providing valuable data for model development.

2. Experimental apparatus

Fig. 1 shows the schematic of the experimental apparatus of the methane/coal dust hybrid explosion and its mitigation using the ultrafine water mist. The entire system comprises the following parts: a) explosion vessel, b) high-voltage pulse ignition system, c) gas-supply system, d) ultrasonic atomizer e) LaVision PIV measurement system, and f) data acquisition and analysis system.

The explosion vessel is approximately 600 mm long with a square section of dimensions 100 mm × 100 mm. Both the ends of the vessel are sealed using flanges and gaskets. The two opposite sides of the vessel are made of stainless steel with thicknesses of 6 mm and 4 mm. The other two sides of the vessel are made of transparent acryl glass convenient for optical observation. A couple of ignition electrodes, two E12-1-K C-U type fast-response thermocouples with microsecond response time, and two PCB piezotronic pressure transducers are placed on the stainless-steel plate with a thickness of 6 mm; moreover, a hole is drilled to release the pressure. The obstacles are placed on the opposite stainless-steel plate at intervals of 100 mm from a distance of 190 mm from the igniter. A hollow hemispherical dispersion nozzle is installed at the bottom of the vessel to disperse the coal dust. A D08-3B/ZM mass flow controller is used to adjust the gas flow rate, and an SMC-1R1 high-voltage pulse igniter is used to induce the explosion. The ultrafine water mist is generated using an ultrasonic atomizer. The droplet diameter is approximately 1–20 μm. A Fastcam Ultima APX high-speed video camera is used to visualize the explosion process, which is operated at 1000 fps with a resolution of 1280 × 512 pixels. The LaVision PIV system is employed to measure the blast

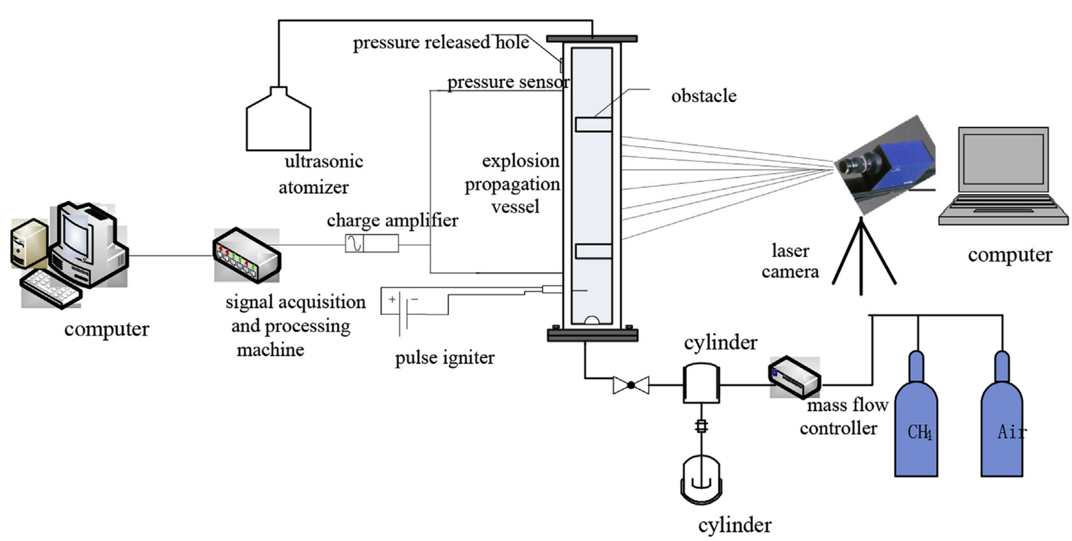

Fig. 1. Experimental apparatus of hybrid explosion and its mitigation using water mist.