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Experimental study on the mitigation via an ultra-fine water mist of methane/coal dust mixture explosions in the presence of obstacles

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ABSTRACT

In this paper, experimental investigations were performed for the mitigation via an ultra-fine water mist of methane/coal dust mixture explosions in the presence of obstacles to reveal the effects of the obstacles in this scenario. Two PCB piezo-electronic pressure transducers were used to acquire the pressure history, a Fastcam Ultima APX high-speed video camera was used to visualize both the process of the mixture explosion and its mitigation. The diameters of the coal dust, the types of obstacles and the volumes of ultra-fine water mist were varied in the tests. The parameters of the explosion overpressure and the range of critical volume flux of the ultra-fine water mist for explosion mitigation were determined. The results show that the mixture explosion and its mitigation are primarily influenced by the number, shape and set locations of the obstacles. When the volume flux of the water mist is larger than a certain amount, the mixture explosions and the effects of obstacles can be completely mitigated with the ultra-fine water mist.

1. Introduction

As one of the main energy sources for industry, coal contributes tremendously to the development of the economy. Coal mines are abundant in China, and approximately 60% of coal mines in China are rich in methane, which can cause gas explosions and gas–coal dust mixture explosions that result in disastrous consequences and casualty losses. Therefore, the study of the explosions of gas/coal dust mixtures and their mitigation is important for both scientific research and practical applications.

Research on gas–dust mixture explosions began in Europe and North America in 1675 after a gas explosion in the UK. The development of prevention and mitigation practices for dust explosions in industrial practice and testing of the ignition and explosive properties of dust were considered by Eckhoff (1996). Experimental studies were conducted by Krause and Kasch (2000) on the influence of the dust concentration and the flow velocity using a tube apparatus with three different diameters for laminar and turbulent flame propagation. Skjold, Arntzen, Hansen, Storvik, & Eckhoff (2006) introduced a new CFD-code (DESC) for the assessment of accidental hazards arising from dust explosions in complex geometries and compared the results with the literature data. A comprehensive numerical simulation model was applied by Eckhoff (2005) to promote the development of methods for prevention and mitigation of dust explosions in practice. In addition, an analysis of the data obtained from explosion experiments indicated that the observed behavior can be satisfactorily interpreted using this simple method, and the approach itself could be embodied in a predictive technique (Cleaver & Robinson, 1996). The application of the Multi-Energy Method and CFD modeling were demonstrated by Mercx, van den Berg, Hayhurst, Robertson, and Moran (2000) for an example problem involving calculation of the explosion blast load on a structure in an offshore platform complex located at a distance from the explosion.

Many obstacles exist in coal mines, including cross adits, pillars, bulk frames, and other structures, that may influence the explosion itself and affect the explosion prevention efficacy. Therefore, the effects of obstacles should be considered in gas or gas/coal dust mixture explosions. Ibrahim, Gubba, Masri, and Malalasekera (2009) performed calculations related to the explosion of deflagrating flames using a dynamic flame surface density model that included a small-scale vented chamber and turbulent reacting flows and the consideration of stagnant and stoichiometric propane/air mixtures. A validated Large Eddy Simulation (LES) model of unsteady premixed flame propagation was investigated to study the phenomenology underlying vented gas explosions in the presence of obstacles with different area blockage ratios and shapes (Sarli, Di Benedetto, & Russo, 2009). Tauseefa, Rashtchianb, and Abbasi (2011) employed CFD in the assessment of heavy gas dispersion in presence of obstacles. They found that the realizable

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k-ε model was the most apt and enabled the closest prediction of the actual findings in terms of spatial and temporal concentration profiles. In addition, experiments on the effects of flame interactions with different multiple obstacles within a top-venting explosion chamber with different L/D ratios were performed, and the propagation velocity of the local flame fronts around the obstacles was estimated (Park, Green, & Chen, 2004; Park, Lee, & Green, 2008).

Water, phosphate and carbonate powder area commonly used suppressant for explosion mitigation. Research on the topic mitigation of explosions with water mist has also gained interest in recent years. For example, a numerical simulation of the propagation of a premixed flame in a one-dimensional confined domain and its interaction with a water mist were analyzed by Parra, Castro, Mendez, Villafruela, and Miguel (2004) to mitigate the flame under different propagation regimes. Willauer, Ananth, Farley, and Williams (2009) investigated the effects of water mist on the overpressures produced by the chamber detonation of an equivalent amount of the high explosives (HE) TNT and Destex. Multiphase numerical simulations were applied by Schwer and Kailasanath (2007) to elucidate a subset of the issues associated with the use of water mist to mitigate explosive blasts generated by a TNT explosive in an unconfined space. Ananth, Ladouceur, and Willauer developed a computational multiphase model to study the dynamics of the interactions between water droplets and the radial expansion of a gas cloud in a spherical chamber. The effects of a fine water mist on the propagation of a deflagration in hydrogen-air mixtures was studied by Butz, French, and Plooster (2006) with two different spray droplet size distributions.

However, few studies exist in the literature related to the mitigation by water mist of a gas/coal dust mixture explosion with consideration of obstacles. Therefore, in this paper, an experimental study is carried out on mitigation with ultra-fine water mist of methane gas and methane gas/coal dust mixture explosions with consideration of the effects of different types of obstacles. Different coal dust concentrations, different obstacles, and different volumes of ultra-fine water mist are considered.

2. Experimental apparatus

A schematic diagram of the experimental apparatus for the methane/coal dust mixture explosions in the presence of obstacles and its mitigation by ultra-fine water mist is shown in Fig. 1. The entire system consists of an explosion vessel, a high-voltage pulse ignition system, a data acquisition system, a gas supply system, an ultrasonic atomizer and a high-speed video camera.

The explosion vessel is approximately 600 mm long with a square section of 100 mm × 100 mm, and both the ends of the vessel are sealed with flanges and gaskets. The two opposite sides of the vessel wall are constructed of stainless steel with a thickness of 6 mm and 4 mm, respectively. Several ignition electrodes, two PCB piezo-electronic pressure transducers and a pressure release hole are distributed on the stainless steel plate with a 6-mm thickness. The obstacles are fixed on the opposite stainless steel plate at intervals of 100 mm from allocation 190 mm from the igniter. The other two walls of the vessel consist of a transparent acryl glass convenient for optical observation. A hollow hemispherical dispersion nozzle is set at the bottom of the vessel to disperse the coal dust, which is previously piled at the bottom flange just under the dispersion nozzle. A D08-3 B/ZM mass flow controller is used to adjust the gas flow rate, and an SMC-1R1 high-voltage pulse igniter was used to induce the explosion. The ultra-fine water mist is generated by an ultrasonic atomizer, and the droplet diameter is approximately 1–20 μm. A Fastcam Ultima APX high-speed video camera was used to visualize the process of the explosion and its mitigation and was operated at 1000 fps with 1280 × 512 pixels of resolution.

As shown in Fig. 2, two types of obstacles are considered in the form of cylinders and square rings. The cylinder is approximately 84 mm high with diameter of 27 mm, and the external side length of the square ring is 84 mm with an internal side length of 70 mm. The obstacle is securely fixed with four screws on the 4-mm-thick stainless steel plate of the vessel. The blockage ratio of each obstacle is 0.3. Table 1 gives the case-specific information of the obstacles settings.

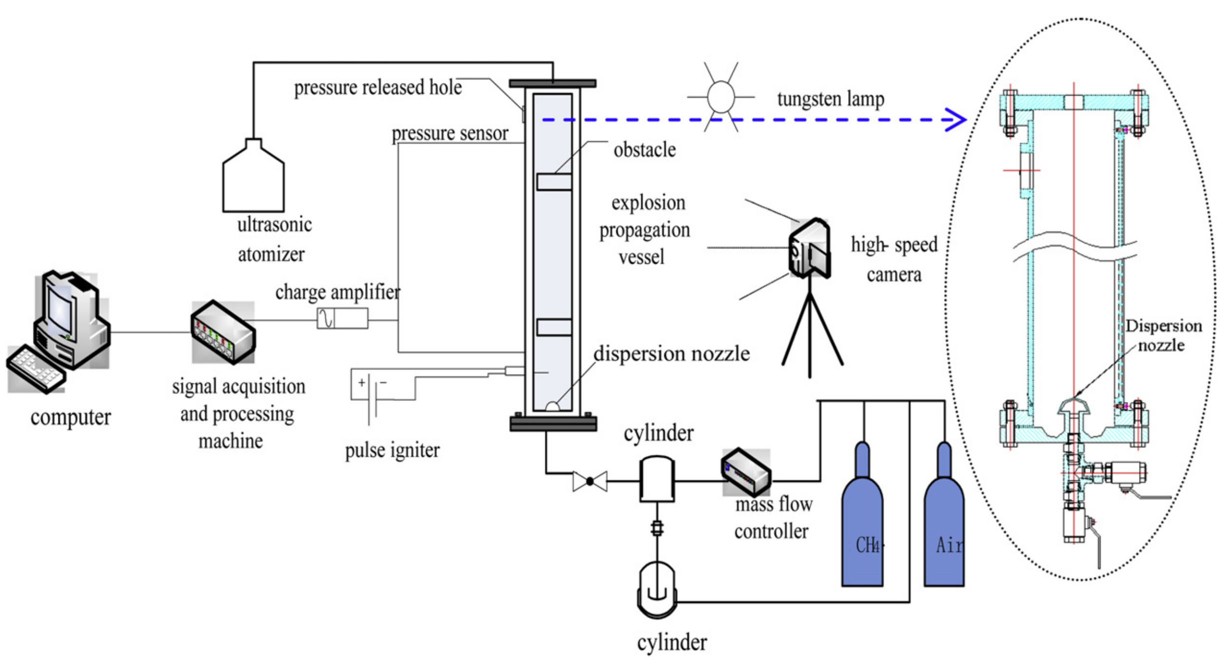

Fig. 1. Experimental apparatus for the methane/coal dust mixture explosion and its mitigation by ultra-fine water mist.