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Enhancement effects of methane/air explosion caused by water spraying in a sealed vessel

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ABSTRACT

Experiments about the influence of ultrafine water mist on the methane/air explosion were carried out in a fully sealed visual vessel with methane concentrations of 8%, 9.5%, 11% and 12.5%. Water mists were generated by two nozzles and the droplets' Sauter Mean Diameters (SMD) were 28.2 μm and 43.3 μm respectively which were measured by Phase Doppler Particle Anemometer (PDPA). A high speed camera was used to record the flame propagation processes. The results show that the maximum explosion overpressure, pressure rising rate and flame propagation velocity of methane explosions in various concentrations increased significantly after spraying. Furthermore, the brightness of explosion flame got much higher after spraying. Besides, the mist with a larger diameter had a stronger turbulent effect and could lead to a more violent explosion reaction.

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1. Introduction

Gas explosion prevention and mitigation attract wide attentions because of frequent explosion hazards in the process industry. As a clean and economic measure, the ultrafine water mist has been proved to be an effective suppression agent in the extinction of building fire, ship fire and electrical fire (Naito, Uendo, Saso, Kotani, & Yoshida, 2011; Yang, Parker, Ladouceur, & Kee, 2004). So, many researchers have focused on how to apply this technology in the explosion mitigation recently (Liang & Zeng, 2010; Willauer, Ananth, Farley, & Williams, 2009; Xu, Li, Zhu, Wang, & Zhang, 2013; You, Yu, Zheng, & An, 2011). The mitigation effects of ultrafine water mist were believed to be attributed to droplets' breakup, evaporation, heat absorption and inhibition of chemical reaction etc.

The liquid droplets' breakup process has been widely investigated theoretically (Adiga, Willauer, Ananth, & Williams, 2009; Pilch & Erdman, 1987) and experimentally (Joseph, Belanger, & Beavers, 1999; Watanabe et al., 2010). Adiga et al. propose that ultrafine water mist below 23 μm would easily extract energy from the shock by vaporization (Adiga et al., 2009). Van Wingerden et al. conclude that the most effective explosion-mitigating water-spray systems are those generating either very small droplets (less than 10 μm) or large droplets (larger than 200 μm), and droplets of approximately 10 μm or smaller will evaporate in the flame directly, while the larger droplets must breakup into smaller droplets to have a mitigation effect (van Wingerden, Wilkins, Bakken, & Pedersen, 1995).

However, apart from the mitigation, enhancement effects of water mist on gas explosion are also reported in the literature. Other experimental explosion results indicate that the turbulence generated by spraying or during the flame/wall interactions would increase the explosion effects and accelerate the flame propagation (Gieras, 2008; van Wingerden and Wilkins, 1995). Thomas suggests that as sprays are introduced into large volumes, increase in turbulent combustion velocities and associated overpressures is inevitable (Thomas, 2000). Traoré et al. also find that the maximum rise of pressure rate increases with the water added in the explosion experiments and they propose that water probably takes part in the explosion reactions and generates hydrogen (Traoré, Dufaud, Perrin, Chazelet, & Thomas, 2009).

Most of the works described above were conducted in the vessels with open ends or with venting membranes. Through their analysis, it is shown that ultrafine water mist influence on explosion has dual character which means both mitigation and enhancement effects may occur. As Catlin et al. suggest, under high confinement conditions flame accelerations were not high enough to cause droplet breakup, whereas under open conditions, they were sufficiently high to cause breakup (Catlin, Gregory, Johnson, & Walker, 1993). Considering the explosion characteristics of higher

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pressure and slower shockwave in the entire sealed vessel, whether water mist play a role of mitigation or enhancement remains not clear. This question calls for more direct experimental researches.

Therefore, a series of experiments were conducted in an entire sealed visual vessel. By direct photography method, the complete flame propagation processes were obtained and presented by videos. The explosion overpressure, pressure rising rate and flame propagation velocity of methane/air explosion under various spraying conditions were analyzed to investigate the effects of ultrafine water mist on gas explosion.

2. Experimental apparatus

The experimental system consists of a sealed explosion vessel, a gas preparation system, an ignition system, water spraying system, a high speed camera, a data acquisition and control system et al., as shown in Fig. 1. The sealed explosion vessel is a vertical rectangle tube with an inner size of 150 mm × 150 mm at cross-section and 910 mm high. Two tempering glasses with the same size of 100 mm × 682 mm locate in the front and back sides of the tube respectively in order to make the flame propagation process visible. A ball valve to vent exhausted air is set on the top of the vessel. The flange gasket sealing structure could keep the explosion vessel sealed well. The volume is 23.2 L and the explosion vessel's design pressure is 1.5 MPa.

Ignition is achieved by high-voltage point discharge. Two ignition electrodes with a gap of 5 mm are located at 8 cm above the bottom of the vessel. The water spraying system comprises a water storage vessel with a design pressure of 5.0 MPa and a volume of 2.5 L, a magnetic valve and a fine atomizing nozzle. The needed ultrafine water mist is generated by the nozzle fixed on the upper flange at the top of the explosion vessel under a spraying pressure of 0.6 MPa. The water temperature is about 20 °C.

The amount of water mist sprayed into the explosion vessel can be controlled via the opening time of the magnetic valve. Two kinds of atomizing nozzles with spraying angles of 60° and 20° were used. The diameter distributions measured by PDPA are shown in Fig. 2 (a) and (b) and the droplet Sauter Mean Diameters (SMD) are 28.2 μm and 43.3 μm respectively.

The fast camera used in this paper is FASTCAM SA4 made by Photron. The maximum resolution of the camera is 1024 × 1024 pixel and the maximum frame rate is 3600 fps. The photographing and photos saving are controlled by the program. A high frequency piezoresistive pressure sensor with a dynamic responding time of 1 ms is set on the middle of the explosion vessel to obtain the pressure history of the methane explosion process. A 50 kHz high-frequency data acquisition card (PCI8348AJ) is used to realize spraying, sparking and pressure acquisition in proper sequence.

The premixed methane/air mixture of certain concentration was inflated into the explosion vessel after connecting the experimental system. The absolute pressure in the explosion vessel was 0.1 MPa before ignition. The fast camera was activated and the mixture was ignited 15 min later. To ensure the accuracy of the experimental results, each explosion experiment was repeated 4–5 times under the same conditions.

3. Results and discussions

3.1. Visualization analysis of methane explosions with ultrafine water mist

Two pressure–time curves of 11% methane explosion with and without water mist are shown in Fig. 3. The atomizing nozzle with a droplet size of 28.2 μm SMD was used. Comparing with the case of no mist, the maximum explosion overpressure increased from 0.492 MPa to 0.546 MPa and the peak value appeared earlier after spraying water mist, which means that the addition of mist increased the maximum explosion overpressure and pressure rising rate.

Fig. 4 presents the comparison of flame propagation processes of 11% methane explosion with and without water mist during the early stage of explosion. It is clear that flame front propagated as a

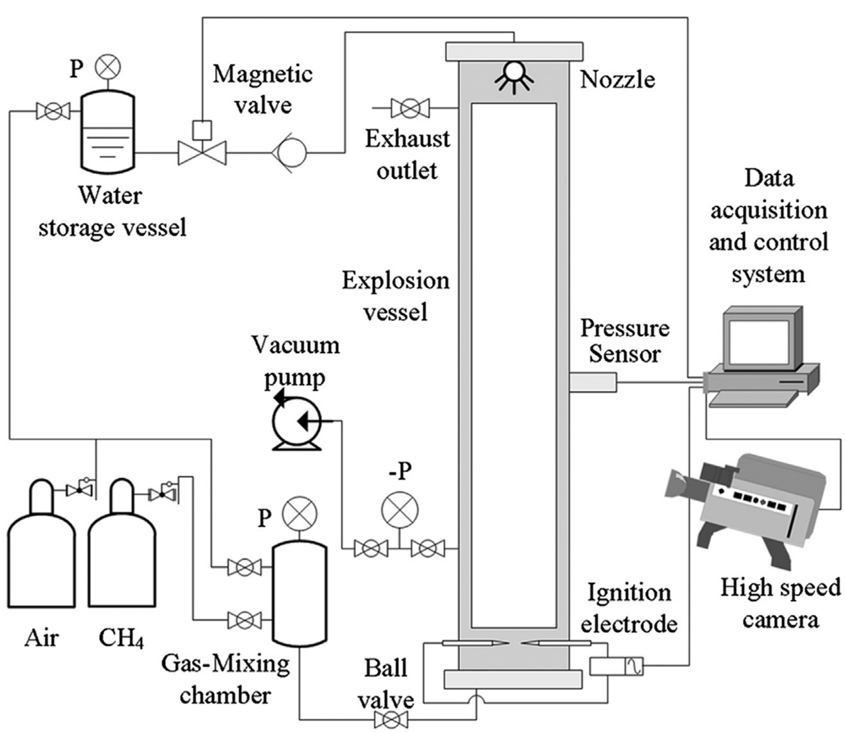

Fig. 1. Schematic of methane–air explosion experiment system with ultra fine water mist.

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