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Mitigation of methane/air explosion in a closed vessel by ultrafine water fog

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ABSTRACT

The mitigation effect of ultrafine water fog on the methane/air explosions with methane concentrations of 6%, 9%, 11% and 13% were experimentally studied in an entire closed visual vessel. The ultrafine water fog was generated in the vessel directly by ultrasonic atomization method. A high speed camera was used to record the flame propagation processes. The explosion flame evolution processes were discussed. The experimental results indicate that the maximum explosion overpressure (ΔP_{max}), the pressure rising rate ($(dP/dt)_{max}$) and the flame propagation velocity decreased after adding water fog. The presentation of flame cellular structures after adding water fog and the stifling effect of water vapor caused the extinguishing of the flame in the burned zone and slowed down the flame propagation. The water fog could mitigate the methane explosion of low concentration (6%) absolutely. When applied at the high concentration conditions (9%, 11% and 13%), the water fog still presented a significant suppression effect. The maximum decreasements of ΔP_{max} under the three high concentration conditions with water fog were 21.1%, 26.7% and 22.9%, respectively, while the maximum decreasements of $(dP/dt)_{max}$ were 71.7%, 77.1% and 52.0%, respectively.

1. Introduction

The risk of gas explosion widely exists in the mining, transportation and utilization processes related to the flammable gases. In order to avoid gas explosion accidents, many experimental and theoretical studies on explosion mitigation methods were conducted (Huang et al., 2012; Yang et al., 2012; Zhang et al., 2012). Having significant extinguishment effects when applied in the fire hazards field (Jones and Nolan, 1995; Naito et al., 2011; Thomas, 2002; Yang et al., 2004), and as an economic and non-pollution resource, the water mist technology has attracted many attentions for the gas explosion mitigation.

Brenton et al. conducted small scale tests of the mitigation of methane/air explosions by water sprays in a tube (∅76 mm × 5 m) with an open-end. By varying the tube length of the initial accelerating section, the required conditions for explosion mitigation by water sprays were analyzed, and the effectiveness of water sprays in practical explosions was found to be linked with the initial explosion severity (Brenton et al., 1994; Thomas, 2000). The blast-induced water release and its effect on blast suppression in a wind tunnel were reported by Catlin and Ewan (Catlin, 2002; Ewan and Moatamedi, 2002), and the results indicated that droplet sizes were determined by shock wave velocity and a minimum velocity of between 150 and 170 m/s was required for the droplets to be small enough to cause suppression. Ye et al. investigated the passive and active explosion suppression in a field-scale pipe (Ye et al., 2005) and concluded that the suppression effects depended on the density and length of the water mist suspended in the pipe. Willauer et al. discussed the influence of water mist on the overpressures generated by the detonations of TNT in a confined space, and found that quasi-static overpressure reduced by 35% for the 50 lbs TNT after spraying water mist (Willauer et al., 2009).

Recently, ultrasonic technology is also used to generate ultrafine water mist in the mitigation of fire or explosion. Adiga et al. studied the effects of ultrafine water mist as a total flooding agent in a 28 m^3 compartment experimentally and numerically (Adiga et al., 2007) and the ultrafine water mist was found to be able to successfully extinguish all pool fires with ultrasonic technology. Even the findings was based on the fires, it was very instructive on the application of ultrafine water mist for the explosion mitigation. And later, Adiga et al. examined the blast-induced droplet breakup process to assess its implications on blast mitigation, and found that the energy extraction due to vaporization was much more significant than fragmentation in weakening the shock, but the droplet vaporization rate could increase 22-fold in the surface area of the ~23 μm child droplets (Adiga et al., 2009). Holborn et.al (Battersby et al., 2012; Holborn et al., 2012) also investigated

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the suppression effects of ultrasonic water fog on hydrogen–oxygen–nitrogen mixtures explosion in a cylindrical explosion chamber with vents, and the suppression effect was found to be greater when introduced nitrogen and water mist together than used either of them alone. Xu et al. even studied the mitigation of methane/coal dust mixtures explosion with ultrasonic water mist in a vented vessel (Xu et al., 2013), and found that when the volume flux of water mist was larger than a certain amount, the explosions could be completely mitigated.

Totally, the application of ultrasonic water fog is a promising technology in the gas explosion mitigation. Most studies about the explosion mitigation by ultrafine water mist currently were conducted in the vessels with open end or vented outlet and the visualization study on the influencing process of mist on explosion is much less. In addition, many gas explosion accidents happened in a confined or closed enclosure, the applying of ultrasonic water fog technology at such conditions requires much more detailed and direct researches. Therefore, the mitigation effects of different amount of ultrafine water fog on methane explosions in an entire closed vessel was analyzed by using high-speed photography. The results show that the ultrasonic water fog has a significant mitigation effect on methane/air explosion of four typical methane concentrations in the closed vessel.

2. Experimental apparatus

Experiments were performed in a closed rectangle explosion vessel as shown in Fig. 1. The experimental system includes a closed explosion vessel, ultrasonic water fog generation system, ignition system, high speed camera, data acquisition and control system et al. The inner size of the closed explosion vessel is 150 mm × 150 mm at cross-section and 910 mm high. In order to make the flame propagation process visible, two tempering glasses with the same size of 19 mm × 100 mm × 682 mm are installed in the front and back sides of the explosion vessel respectively. Two pairs of rectangle flanges on the two ends of the vessel could keep the vessel sealed well. The volume and design pressure of the explosion vessel are 23.2 L and 1.5 MPa, respectively.

Two ignition electrodes with a gap of 5 mm are located at 8 cm above the bottom of the vessel to ignite the mixture. The mist generation system includes an ultrasonic fogger unit, a water cup, and a transformer (220–24 V), etc., as is shown in Fig. 2. The ultrasonic fogger unit is situated below the water surface at a depth of 3–5 cm. In operation, the high frequency vibration of the piezoelectric element in the fogger unit generated violent cavitation and capillary waves at the water surface. This leaded to the formation of ultrafine water fog above the water surface. With the increasing amount of water fog, the fog diffused from the cup into the whole vessel. The atomization rate of the mist generation system is 1.875 mL/min which was measured by precision electronic balance. The stainless steel mesh can prevent the large diameter water droplets from splashing into the vessel and causing turbulization in the vessel.

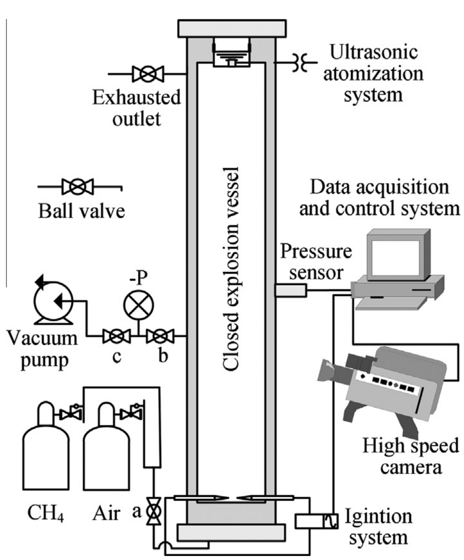

Fig. 1. Schematic of experimental system.

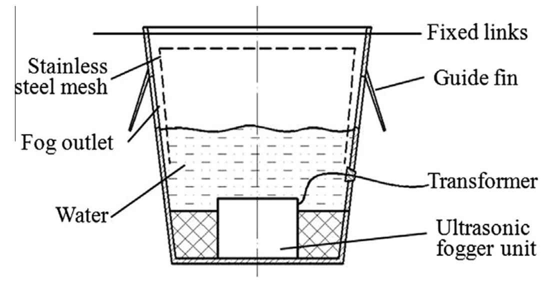

Fig. 2. Schematic of ultrasonic atomization system.

The fast camera used in the experiments is FASTCAM SA4 made by Photron. With a maximum resolution of 1024 × 1024 pixel, the maximum frame rate could reach to 3600 fps. The photographing and photos saving are controlled by 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 explosion process. A 50 kHz high-frequency data acquisition card (PCI8348AJ) is used to realize spraying, sparking and pressure acquisition in proper sequence.

After the experimental system connected according to Fig. 1 and the fast camera adjusted, the explosion vessel was vacuumed to −0.095 MPa. According to Dalton's law of partial pressure, a certain concentration of methane/air mixture was prepared in the explosion vessel directly and stood for 15–20 min. The absolute pressure of the well-premixed mixture before ignition was 0.1 MPa. To ensure the accuracy of the results, each explosion experiment was repeated 4–5 times under the same conditions.

3. Results and discussions

3.1. Visualization of the methane explosion process

Shown in Fig. 3 are the flame propagation pictures in the early stage of 11% methane explosion. Several milliseconds after electrodes discharging, the methane/air mixture was ignited (t = 5 ms). Then a spherical flame appeared, centered on the ignition point. With the increase of diameter, the flame touched the inside wall at 30 ms, then began to acceleratingly move upwards. The decreasing of flame front curvature can also be seen from Fig. 3. With the proceeding of flame propagation, the flame front shape began to change from spherical to ellipsoidal (t = 40–55 ms).

Fig. 4 indicates the corresponding relationship between the explosion pressure and the flame pictures of 11% methane explosion. As is seen in Fig. 4, the explosion overpressure did not rise immediately when the gas mixture got ignited. After the flame propagated for a certain distance close to the middle height of the explosion vessel (t = 95 ms), the explosion overpressure started to rise dramatically. At the same time, the curvature of flame front decreased further and the plane flame structure appeared (t = 135 ms).

After that, with the flame moving upwards, the flame front began to form a cone pointed to the burned zone, which is named