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Experimental research on methane/air explosion inhibition using ultrafine water mist containing additive

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The inhibition effects of ultrafine mists of 5%, 8%, and 15% water/NaCl solutions on 6.5%, 8%, 9.5%, 11%, and 13.5% methane explosions were experimentally studied in a closed vessel which was equipped with two tempered glasses in the front and back sides respectively. Ultrafine water/NaCl solution mist was generated in the vessel directly by ultrasonic atomization method, and mist size was measured by a phase doppler particle analyzer. Explosion flame evolution processes under different spraying conditions were recorded by a high-speed camera. The relationship between pressure rising and flame propagation was analyzed. Results indicate that explosions could be suppressed by ultrafine water/NaCl solution mists. Moreover, the inhibition effects, which were characterized by reductions in the flame propagation speed, the maximum explosion overpressure (ΔP_{max}), and the maximum pressure rising rate ($(dP/dt)_{max}$), could be improved by increasing the water/NaCl solution concentration and mist amount. The pressure underwent two accelerating rises and was influenced obviously by solution concentration. The absolute inhibition of methane explosion was influenced by the water/NaCl solution and methane concentrations. The mist amount required for absolute inhibition of the explosion decreased after addition of more NaCl to the spraying solution. The enhancement in inhibition of methane explosion was due to the combination of improved physical and chemical effects.

1. Introduction

Gas explosion has been a serious threat to the processes involving flammable gases such as coal mining, and always led to very serious damage to persons and property. Therefore, explosion inhibition will keep abstracting interests of relevant researchers (Koshiba et al., 2012). Because of environmental reasons, attentions have being focused on seeking the alternative agents to halogenated hydrocarbon. And the water mist, particularly the ultrafine water mist (i.e., droplet size below 50 μm), featuring relatively low cost, wide availability, and low environment pollution, is considered as a potential candidate (Yoshida et al., 2013; Jones and Nolan, 1995).

Scholars have conducted numerous experimental and theoretical studies to comprehend the mechanism of explosion inhibition by ultrafine water mist (Fuss et al., 2002; Thomas et al., 1990; Ye et al., 2005; Yu et al., 2009). And the cooling of the flame front, the dilution and disturbing of the mixture gas, as well as the interruption of the chain reaction were considered as the mainly effects. Introduction of additives is extensively concerned as a practical method to strengthen the inhibition effect by improving the physical and chemical effects of ultrafine water mists on explosion inhibition. Zheng conducted suppression experiments of methane/air counter flow flame by water/NaCl mist and found that water/NaCl solution was more effective than pure water in promoting flame extinction. Extinction promotion may be related to increases in external radiative heat loss, increased heat absorption due to droplet vaporization, and reductions in global heat release from chemical reactions (Zheng et al., 1997). Adding an alkali metal additive to water for hydrogen explosion inhibition, Ingram demonstrated that the additive acts as a chemical inhibitor and that this inhibitory effect may be considered to occur because of homogeneous gas phase mechanisms and additive radicals that participate in the inhibition process (Ingram et al., 2012). Lazzarin performed experiments to investigate the interaction of finer water droplets and alkali metal solutions with a steady laminar methane/air flame and demonstrated that this concept of combining thermal and chemical effects could lead to obvious increases in inhibition ability (Lazzarini et al., 2000).

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Based on the previous research works, the investigations of the effects of water/additive solution and spraying concentrations, especially the relationship between absolute inhibition of explosions and water/additive solution concentration is helpful for further understanding the inhibition mechanisms. Moreover, the addition of additives can affect the flame propagation processes, such as the flame propagation speed, the flame temperature and color (Chen et al., 2009; Liu and Liao, 2010). Therefore, in our experiments, the explosion vessel was equipped with two tempered glasses to analyze the flame propagation processes.

In the open literature, different kinds of droplet generation methods were also investigated. Lazzarini analyzed the atomization characteristics of a fluid jet atomization system and an ultrasonic fluid surface breakup system (Lazzarini et al., 2000). Zhang adopted ultrafine water mist produced by a pressure spray method to suppress methane explosion. The opposite inhibition result was obtained after spraying, and explosion intensity was enhanced with increasing droplet diameter (Zhang et al., 2014a). However, the ultrafine mist generated by ultrasonic atomization in Zhang's experiment yielded satisfactory explosion inhibition result, and the effect was enhanced by increasing the spray amount (Zhang et al., 2014b).

Jones and co-workers proposed that the aerodynamic effects produced by the moving liquid drops resulted in the turbulization of the premixed gas and the flame front, which would increase the surface area and thickness of the flame, and the flame propagation would accelerate finally (Jones and Thomas, 1993). Marian also pointed out that water droplets could cause great changes in the flame structure with increasing droplet diameter. An irregular flame front structure would accelerate the propagation speed, and the enhancement effects intensified with increasing water amount (Gieras, 2008). van Wingerden adopted a pressure spraying method to suppress explosions and pointed out that the turbulent effect attributed to spraying was the main reason for accelerations in flame propagation speed (van Wingerden and Wilkins, 1995). Cheng pointed out that the inhibition effect depends on volume flux, spraying position and mist momentum, and emphasized that insufficient volume flux would strengthen the combustion reaction and cause detonation (Chen et al., 2009). A detailed explanation of explosion intensity enhancement was also discussed by relevant scholars (Abdel-Gayed et al., 1984; Bradley et al., 2001; Thomas, 2000).

Overall, if the spray technology is incapable of delivering sufficient water with finer droplet sizes and minimal disturbance to the flame front and unburned bulk flow field, explosions more violent than those without spraying may occur. Thus, in our experiments, ultrasonic atomization method was selected to generate ultrafine water/NaCl mists to avoid disturbing the flame front and bulk flow field.

Totally, addition of alkali metal compounds to water mists has been proven to enhancing explosion inhibition effects. Nevertheless, detailed studies focusing on the influence of water/additive solution concentration on flame structure and explosion intensity are necessary to comprehend the relevant inhibition mechanism better. In addition, detailed and accurate experimental data of flame propagation characteristics and explosive parameters under different spraying concentrations must be obtained. These parameters include flame propagation speed, explosion pressure, and absolute inhibition condition of the explosion. The mists of 5%, 8%, and 15% mass fraction water/NaCl solutions (abbreviated "5%, 8%, and 15% NaCl mists" in the following sections) with different spray concentrations (i.e., the ratio of water mist amount to vessel volume) were adopted to suppress methane/air explosions. This extends our previous work on explosion inhibition and aims to determine conditions that result in better inhibition effects and achieve absolute inhibition of methane/air explosion (Cao et al., 2015).

2. Experimental apparatus

Explosion inhibition experiments were conducted on the apparatus described in our previous works (Cao et al., 2015). The apparatus was partially altered, consisting of a closed rectangular vessel (910 mm × 150 mm × 150 mm), a gas supply system, a mist generation system, an ignition system, and a procedure control and data acquisition system, as shown in Fig. 1. The volume of the explosion vessel is 23.2 l, and the thickness of the wall is 14 mm. Two tempered glasses were installed respectively in the front and back sides of the explosion vessel to achieve the flame propagation process visible. Methane and air were supplied by a gas cylinder and dispersed uniformly in the whole vessel.

The mist generation system includes an ultrasonic fogger unit, a water cup (80 mm × 80 mm × 150 mm), and a transformer (Zhang et al., 2014b). The system was located at the top of the vessel, and the mist diffused from the side outlet of the atomization cup into the whole vessel. The quality loss of the solution by the escape of the mist was measured using a precision balance. Results indicated that the atomization rate was not affected by NaCl solution concentrations, which ranged from 5% to 15% by mass fraction. The premixed gas was ignited by the high voltage discharge method at 80 mm above the bottom of the vessel, and a high-speed camera with a frame rate of 1000 fps was used during experiments to capture the explosion flame. A 50 kHz piezoresistive pressure sensor with a dynamic responding time of 1 ms was installed in the middle of the vessel side to acquire the pressure value. The measurement accuracy and range were 0.5% FS and 2 MPa respectively. A high-frequency data acquisition card (PCI-8348AJ) was adopted to realize the ignition and pressure acquisition successively (Cao et al., 2015).

Based on Dalton's law of partial pressure, the premixed gas of a certain concentration (6.5%, 8%, 9.5%, 11%, and 13.5%) was prepared in the explosion vessel. To ensure good mixing of methane and air, the gases were introduced to the vessel through several entrances uniformly distributed in a pipe along the axial direction and laid aside for 30 min. Mists of 5%, 8%, and 15% NaCl at five spraying concentrations (i.e., 18.52 g/m^3, 37.04 g/m^3, 55.56 g/m^3, 74.08 g/m^3, and 92.60 g/m^3) were adopted to suppress methane/air explosions. Each certain spraying concentration was accomplished according to

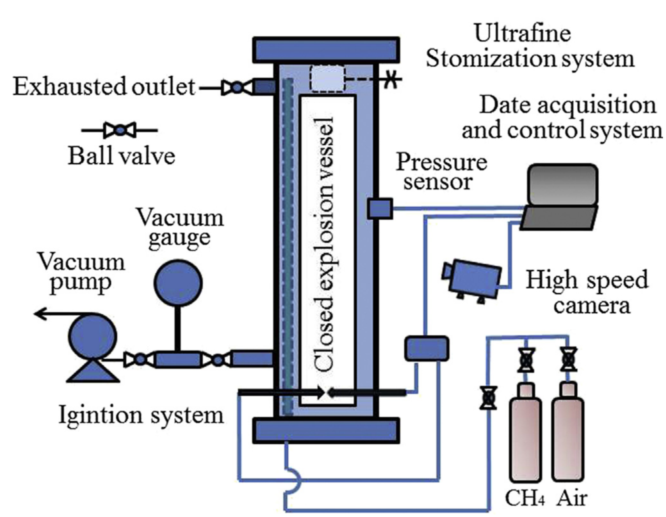

Fig. 1. Schematic of experimental system.