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Suppression of methane/air explosion by ultrafine water mist containing sodium chloride additive

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HIGHLIGHTS

- Effects of water and water/NaCl mists on explosion in closed vessel were compared.
- Developments of the structure and brightness of flame were captured and analyzed.
- The disappearance mechanism of tulip flame under water/NaCl mist was investigated.
- 6.5% and 13.5% methane explosions can be suppressed absolutely by water/NaCl mist.
- Adding NaCl can enhance the suppression due to physical and chemical inhibitions.

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ABSTRACT

The suppression effect of ultrafine mists on methane/air explosions with methane concentrations of 6.5%, 8%, 9.5%, 11%, and 13.5% were experimentally studied in a closed visual vessel. Ultrafine water/NaCl solution mist as well as pure water mist was adopted and the droplet sizes of mists were measured by phase doppler particle analyzer (PDPA). A high speed camera was used to record the flame evolution processes. In contrast to pure water mist, the flame propagation speed, the maximum explosion overpressure (ΔP_{max}), and the maximum pressure rising rate ($(dP/dt)_{max}$) decreased significantly, with the "tulip" flame disappearing and the flame getting brighter. The results show that the suppressing effect on methane explosion by ultrafine water/NaCl solution mist is influenced by the mist amount and methane concentration. With the increase of the mist amount, the pressure, and the flame speed both descended significantly. And when the mist amount reached 74.08 g/m^3 and 37.04 g/m^3, the flames of 6.5% and 13.5% methane explosions can be absolutely suppressed, respectively. All of results indicate that addition of NaCl can improve the suppression effect of ultrafine pure water mist on the methane explosions, and the suppression effect is considered due to the combination effect of physical and chemical inhibitions.

1. Introduction

Methane/air explosion often takes place in the coal mining, gas transportation, and other related fields, which has long attracted extensive interests. In the interest of preventing gas explosion accidents and reducing economic losses, scholars have conducted many experimental and theoretical studies on explosion suppression technology [1–5]. As a low-cost and non-pollution resource, the ultrafine water mist has attracted many attentions for flammable gas explosion suppression [6,7]. The suppression effect of the ultrafine water mist is generally considered to be a result of the weakening of heat propagation by reducing the flame temperature and absorbing the thermal radiation from burning zone to unburned zone through the evaporation of water droplets.

In order to further improve the suppression effect of ultrafine water mist, an effective method is to introduce additives. For the water mist with additives, it is widely believed that the suppression effect involves not only the physical effects of absorbing heat and blocking radiation, but also the chemical effects due to the participating of the additives in the combustion reaction. The significant enhancement in explosion suppression using water mist containing additives is due to the combination effect of the physical and chemical inhibitions [8]. Among the additives, alkalis metallic has attracted wide attentions of scholars and replaced halogenated hydrocarbon gradually with the growing of environmental protection consciousness and the effect of the Montreal Convention [9].

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The physical and chemical mechanisms of gas explosion suppression by ultrafine water mist containing alkali metal compounds have received significant attentions currently. Mitani et al., studied the flame suppression mechanism of alkali metal salts which were introduced into premixed flames in the form of mists of their water solutions, and pointed out that when the alkali metal compounds stayed in the flame reaction zone longer than a critical time, the flame would be suppressed obviously due to chemical suppression effect [10]. Chelliah and co-workers, researched the suppression effect of ultrafine water mist containing potassium hydroxide, sodium hydroxide, and sodium chloride on methane/air premixed and non-premixed combustion. The results indicated that the inhibition of premixed flames by droplets under 13 μm median diameter was insensitive to sodium hydroxide mass fraction in water, related to the shorter residence time of the droplets through the premixed flame structure, and that sodium chloride was more effective than sodium hydroxide on explosion suppression. Chelliah and co-workers, also pointed out that alkalis metallic additives play a role as a chemical inhibitor by comparing the suppression effects of sodium bicarbonate and inert silicon dioxide particles with the same size in premixed flame [11,12]. Lazzarini studied the interactions of fine droplets of water (median diameter of 20 μm) and water/NaOH solution with methane/air non-premixed flame by experiment. Results indicated that the water/NaOH solution (up to 17.5% by mass) can significantly enhance the suppression ability of water by complementing its thermal effects with chemical catalytic radical recombination effects of NaOH [13].

The analysis of the flame propagation processes is also helpful for further researching the physical and chemical inhibition mechanisms. Chen et al., conducted suppression experiments of 9.5% methane explosion using ultrafine water mist containing alkalis metallic compounds and analyzed how the addition of sodium bicarbonate, sodium chloride, and potassium chloride affected the flame propagation speed. The suppression effects of three kinds of additives were investigated, and the results showed that the effectiveness of ultrafine water mist with additives were better than that of ultrafine pure water mist [14]. Liu et al., studied the suppression effects of ultrafine water mist including metal chlorides on methane/air explosions. The chemical suppression mechanism was discussed by analyzing the variation of flame temperature and color. And the result indicated that the ultrafine water mist containing alkali metal has good suppression effect on gas explosion due to the combination effect of physical and chemical inhibitions [15]. However, they only reported suppression effect of additives under certain explosion condition without investigating different methane concentrations inner the explosive range, in addition, the flame propagation processes were not captured and analyzed.

Totally, the application of alkali metal compounds in ultrafine water mist is an enhancing technology in the gas explosion suppression. However, the visualization study about the influencing process of ultrafine water mist containing alkali metal on gas explosion in closed vessel is much less. In order to understand the suppression mechanisms, it is necessary to gain amount of detailed and direct data about the evolution of the flame front and the flame propagation character. Suppression experiments under ultrafine pure water mist and water/NaCl (5% by mass fraction) solution mist (abbreviated as "5% NaCl mist" in the following statements) on methane/air explosion were conducted in this study, and the visualized flame propagation process, the maximum explosion overpressure (ΔP_{max}), and the maximum pressure rising rate ($(dP/dt)_{max}$) were analyzed under different spraying concentrations (namely the ratio of mist amount to vessel volume). This extends our previous work of ultrafine pure water mist is to seek suppressents and conditions with the better inhibiting effects and inhibiting condition, and to realize absolutely inhibition of methane/air explosion and so as to prevent the methane/air explosion accidents [7].

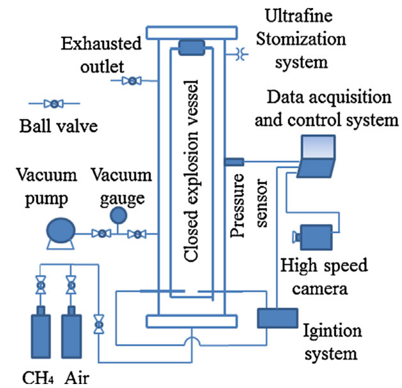

Fig. 1. Schematic of experimental system.

2. Experimental apparatus and procedures

The experiments were performed basing on the equipment described in our earlier works [7]. The experimental apparatus was partial altered and consists of an explosion vessel, a gas supply system, a mist generation system, an ignition system, and a process control and data acquisition system, as shown in Fig. 1. The volume of the explosion vessel is 23.2 L and the design pressure is 1.5 MPa. Two tempered glasses were installed in the front and back sides of the explosion vessel for the visualization of the flame evolution process. The ultrasonic atomization system was located at the top of the explosion vessel and with the mist amount increasing, the ultrafine water mist spread into the whole vessel through the outlet uniformly set on the sidewall of the atomization device. Before the outlet, there laid a stainless steel mesh guarding against the large diameter droplet splashing into the vessel and causing large disturbance to the flame front. In order to avoid the interference of impurities, distilled water was adopted to prepare NaCl solution. The quality loss of the liquid by the escaping of mist was measured using precision balance. The test results indicate that the atomization rate was stable and almost not affected by the addition of NaCl (5% mass fraction). A pair of ignition electrodes with a gap of 5 mm was set 8 cm apart from the bottom of the vessel to activate the explosion. The high-frequency data acquisition card (PCI8348AJ), with high speed parallel analog inputs and programmable digital outputs, was adopted in the process control and data acquisition system to start the ignition and pressure acquisition in proper sequence. A 50 kHz piezoresistive pressure sensor (MDHF20) with a dynamic responding time of 1 ms was installed in the middle of the explosion vessel to acquire the pressure history. A high speed camera (FASTCAM SA4) was used to record the flame propagation process. The frame rate and saving format(videos or photos)of the shooting process were controlled by program.

Before preparing methane/air mixture, the explosion vessel was vacuumed to −0.095 MPa and confirmed well-sealed. Then the gas mixture of a certain methane concentration (6.5%, 8%, 9.5%, 11%, and 13.5%) was prepared in the explosion vessel based on Dalton's law of partial pressures and stood for 20 min. The absolute pressure of the well-premixed mixture before ignition was 0.1 MPa. The explosion suppression experiments were conducted under five ultrafine water mist concentrations (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) and each certain mist amount was accomplished according to the scheduled time and atomization rate in the vessel. After igniting, the flame propagated from bottom to top in the vessel, and the flame evolution process was recorded by the high speed camera with a frame rate of 1000 fps. At the end