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The influence of the charge-to-mass ratio of the charged water mist on a methane explosion

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ABSTRACT

To study the influence of the charge-to-mass ratio of a charged water mist on a methane explosion, the induction charging method was used to induce charge on a normal water mist; a mesh target method was employed to test the charge-to-mass ratio of its droplets. The propagation images, propagation average velocities, and overpressures of a methane explosion suppressed by charged water mist were analysed. The influence of the charge-to-mass ratio of the suppressant water mist on a methane explosion was studied. Results show that the explosion temperature, propagation average velocity, and peak overpressure deceased more obviously with charged water mist than ordinary water mist. With increasing charge-to-mass ratio, the suppression effect of the charged water mist underwent a significant increase. Under experimental conditions, compared with ordinary water mist, when the charge-to-mass ratio was 0.445 mC/kg and the mist flux was 4 L, the minimum flame propagation average velocity was 3.456 m/s, with a drop of 2.37 m/s (40.68%), and the peak overpressure of the methane explosion was 10.892 kPa, with a drop of 10.798 kPa (49.78%). The suppression effect is considered from the changes of the physico-chemical properties of the water mist as affected by the applied charge-to-mass ratio.
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1. Introduction

Significant casualties and property losses are usually caused by methane explosions in coal mine and in operations which produce and use methane industrially. For example, an explosion occurring in a natural gas transportation pipeline tends to seriously threaten life, and cause potentially great loss of property, and may lead to pollution in large areas. To reduce the hazards associated with methane explosions, many experimental and theoretical studies on explosion suppression technology have been conducted (Modak et al., 2006; Korobeinichev et al., 2007; Ingram et al., 2012; Zhang et al., 2014). The suppression technology involving the use of water mist is non-polluting of high suppression efficiency, and is easy to implement: it has thus attracted more attention (Yoshida et al., 2013; Battersby et al., 2012; Willauer et al., 2009).

Experimental and numerical investigation of flame speed retardation by water mist was conducted by Yoshida et al. (2015). Their results indicate that water mist can reduce the rates of chemical reactions involving radicals which have positive sensitivity to flame speed, such as O, H, and OH, and enhance three-body chain terminating reactions involving H_2O, which have large negative sensitivities to flame speed due to the high chaperone efficiency of H_2O. Naito et al. (2011) studied the effect of fine water droplets on suppression of methane counter-flow diffusion flames. They found that the extinguishing time is determined by velocity gradient and fuel-ejection velocity. There exists a threshold below which droplets can be evaporated within the combustion zone, and the threshold depends on the velocity gradient. Liang and Zeng (2010) carried out a numerical study of this effect with water addition on a gas explosion: they found that the induced explosion time is prolonged, and that the mole fractions of reactant species and catastrophic gases decrease after water is added to the mixed gas. With increasing water fraction, both sensitivities of dominant reactions contributing to CO_2, CH_4, and the sensitivity coefficients of CO, CH_4, and NO mole fractions decrease. The suppression effect of water on gas explosions can be attributed to the significant decrease in OH, O, and H in the explosion process.

The inhibiting effect of water mist generally results from weakening heat transfer by heat absorption from the flame, absorption of thermal radiation from the combustion zone through

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the evaporation of droplets, and some chemical effects involving the destruction of free radicals. To improve the suppression effect of water mist, some researchers have introduced additives (Linteris et al., 2008; Koshiba et al., 2012). It is widely considered that the suppression effect of water mist with additives includes both the physical effects of absorbing heat and chemical effects from the participation in any combustion reaction.

Chelliah et al (2002; 2003) investigated the suppression effect of an ultrafine water mist with alkali metal compounds on methane/air pre-mixed and non-pre-mixed combustion. They found that the suppression effect on pre-mixed flames by droplets under 13 μm median diameter is insensitive to sodium hydroxide mass fraction in water, which is related to the residence time of droplets in the premixing zone of the flame. They also pointed out that alkali metallic additives play a role as a chemical inhibitor, and the suppression effect of sodium chloride is more effective than sodium hydroxide. Xu et al. (2013) focused on an experimental study of methane/coal dust explosions suppressed by ultra-fine water mist under obstacles, and found that ultra-fine water mist can effectively inhibit the mixture's explosion under a sufficient mist flux. Cao et al. (2015) conducted an experimental study of methane/air explosions suppressed by ultra-fine water mist with additives, the results show that the ultra-fine water mist with Nacl has a better suppression effect thereon.

In the aforementioned literature, the suppression characteristics of water mist on methane explosions were studied: they showed good inhibitory effects. However, in practical applications, water mist is often affected by wind, and the stability of the mist field is poor, which reduces its efficiency in explosion suppression. Furthermore, the inhibition of methane explosions by ordinary water mist is mainly endothermic, with little chemical action occurring. Charging effects can change the physico-chemical properties of a water mist and thus endow the mist field with a higher dispersivity and greater stability. The charge is carried on the surface of each droplet which can affect the methane combustion process (Marcum and Ganguly, 2005). Based on this, the current research carried out an experimental study of methane explosion suppression by charged water mist. Firstly, the charge-to-mass ratios of charged water mist were measured, then the characteristics of flame propagation images, flame propagation average velocities, and overpressures of a methane explosion affected by charged water mist under different charge-to-mass ratios were analysed, to determine the influence of charge-to-mass ratio of charged water mist thereon. Meanwhile, the suppression mechanism by which charge-to-mass ratio affected methane explosions was analysed from the perspective of the physico-chemical properties of charged droplets. This study promoted the application of charged water mist, and enhanced the suppression efficiency thereof on explosions, and in fire-fighting.

2. Experimental apparatus and methods

2.1. Charge-to-mass ratio measurement

The charge-to-mass ratios of charged water mist were measured using the mesh target method. The experimental device mainly comprised a microampere meter, measuring cylinder, metal cone collection bucket, water mist nozzle, ring electrode, and high-voltage power supply, as shown in Fig. 1. Among them, the water mist nozzle was provided with a metal ferrule, through a grounded conductor. The ring electrode was connected to the positive electrode of the high-voltage power supply output, so that the water mist was given a negative charge. An HV-503P4 digital display DC high-voltage power was used, with an output voltage range of 0–50 kV, and a rated current of 4 mA.

By electrostatic induction, the droplets jetted from the water mist nozzle were taken by their opposing charge to the ring electrode passing through the area between it and the nozzle ferrule. When charged droplets reached the wire mesh and metal cone collecting barrel, the charges on the droplets were transferred through the microampere meter and flowed to ground. According to the amount of water mist collected per unit time, and the current recorded, the charge-to-mass ratio can be calculated as:

$$A_{\mathrm{q}} = \int_0^t I\mathrm{d}t \Big/ \int_0^t m\mathrm{d}t = It/Q_{\mathrm{g}}t = I/Q_{\mathrm{g}} \tag{1}$$

Where A_q-charge-to-mass ratio of water mist, C/kg; I-stability current of microampere meter, A; Q_g-mass flow of water mist, kg/s. During the experiments, we changed the electrode interval between the nozzle ferrule and ring electrode, ensured that the charged droplets were satisfactory, and then carried out the experiments to assess the inhibition of a methane explosion with various charge-to-mass ratios of water mist.

2.2. Experimental device and method of inhibiting methane explosions

The experimental system comprised a charged water mist generator, an experimental pipeline, ignition device, data acquisition device, and a gas distribution device. The charged water mist generator was affixed to the top of pipeline A. The mean particle diameter of droplets in the pure water mist was 15 um, and their rate of production was 1.5 L/min. The experimental pipeline was made of two identical sections of transparent organic glass pipe with a length of 500 mm, a thickness of 20 mm, and a cross-section measuring 100 × 100 mm. The pipeline was divided into two parts (A and B). Both of them had a volume of 5 L. The right-hand end of pipeline B was sealed with a steel plate, and the left-hand end of pipeline A was sealed with an explosion venting membrane. During explosion development, this membrane will break and the explosion can be vented towards the atmosphere. There was a diaphragm with a thickness of 0.3 mm between pipeline A and B, to separate the charged water mist from the premixed gases. The ignition device included an ignition controller, ignition electrode, and a regulated power supply. The ignition electrode was installed at the right-hand end of pipeline B. The working voltage from the regulated power supply was 6 V (DC). The data acquisition device consisted of a photoelectric sensor, a pressure sensor, a data acquisition card, and a high-speed camera system. The pressure sensor (MD-HF) was installed in a central position beneath a 30 mm thickness of steel plate on the right-hand side of pipeline B; it had a measurement range of −0.1 to 0.1 MPa, a response time of 0.2 ms, and a precision grade of 0.25. Overpressure data can be accurate to three decimals in the later data processing. The photoelectric sensor (RL-1), which was situated to the right of the ignition electrode, was affixed to the right-hand side of pipeline B, 100 mm from the right pipe wall. A data acquisition card (USB-1208FS) was applied to collect both photoelectric, and pressure, signals, at a sampling frequency of 15 kHz. A high-speed camera system (Davis 7.2, Nikon) was used to record the methane explosion at a rate of 2000 frames/s. The gas distribution device comprised a methane bottle (methane volume fraction of 99.99%), air compressor, and mass flow meter. We configured the premixed gases (methane/air) to achieve a methane volume fraction of 9.5% based on Dalton's law of partial pressures. The experimental apparatus is shown in Fig. 2.

During the experiments, according to the effective volume of pipe B and the premixed gas concentration, we respectively set the mass flow meter flow velocities of methane and air, put premixed

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