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Numerical Simulation on Methane Coal Dust Composite Explosion in Restricted Space by Ultrafine Water Mist Suppression

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Abstract:

The purpose of this experimental investigation was to examine the effects of ultrafine water mist on explosions caused by methane and coal dust hybrids that occurred inside of a closed vessel. In this study, we built a small-scale semi-closed visualization experimental platform and ran simulations to study the effects of four factors on the explosion of methane coal mixtures: the amount of ultra-fine water mist sprayed, the volume fraction of methane, the position of the methane inlet, and the amount of time it took to premix. This allowed us to gain a deeper understanding of the repressive effect of this water mist on methane explosion. The findings demonstrate that ultrafine water mist is capable of suppressing methane explosions, with a notable inhibitory effect on 10% methane. This inhibitory effect becomes stronger with increasing amounts of sprayed ultrafine water mist. The effect of methane volume fraction on the maximum explosion overpressure ΔP_{max} is significant, and the amount of ultrafine water mist sprayed marks this effect to a certain extent. The application amount of ultrafine water mist affects the propagation time of the explosion flame, and the volume fraction of methane has a certain influence on this time.

Keywords: *Ultrafine water mist, Methane, Coal, Inhibition, Single factor, Orthogonal experiment, Flame propagation.*

Introduction

Gas explosions are common in the coal mining industry and can seriously injure workers and homeowners (Yuxin et al., 2023). With its low pollution levels and practical economics, ultrafine water mist is a powerful heat absorber and cooler. It can also successfully reduce thermal radiation. Consequently, it is very important to investigate the methane explosion-inhibiting effects of ultrafine water mist. There are four ways in which fine water mist can put out fires: endothermic cooling, oxygen replacement, attenuated thermal radiation, and dynamic disturbance (Liu, & Kim, 1999). These methods are based on the mist's properties, which include good dispersion, informal evaporation, high latent heat of evaporation, and high kinetic energy.

Heat Absorption Cooling

After the water mist droplets reach the flame area, they directly absorb heat from the flame. The evaporation of the water mist condenses the flame heat, resulting in a decrease in the thermal feedback obtained by the gas fuel from the flame. As a percentage, cooling efficiency measures how much heat is removed from combustion by the water mist droplets relative to the total heat that is released. When all droplets evaporate, they can absorb 90% of the heat. To ensure efficient evaporation of droplets within the flame zone, it is essential for the water mist to penetrate a minimum of one-third of the flame plume zone and maintain an adequate spray flux.

Oxygen Dilution

Under standard atmospheric pressure at 95 ℃, steam has the capacity to expand to 1900 times the volume of liquid water. This expansion results in the displacement of oxygen and combustible gas surrounding the flame by water vapor, causing the concentration of combustible gas to fall below the lower explosive limit. Due to the lack of oxygen and combustible gas, the flame extinguishes. This mechanism can be specifically divided into two parts: oxygen dilution and the dilution effect of combustible gas. Due to the ability of the generated water vapor to absorb heat, oxygen dilution usually works together with endothermic cooling. Liu and Liao (2011) studied the fire extinguishing mechanism of ultrafine water mist using a cup-shaped burner and found that the oxygen dilution effect is more pronounced above the flame, while the heat-absorbing cooling effect plays a more important role below the flame. In a confined space, the oxygen content is limited. In the absence of water mist, after 30 seconds of flame combustion, the oxygen content only decreases by 1%. Following the release of water mist for 30 seconds under identical initial conditions, there was a 3.8% decrease in oxygen content (Liu et al., 2023). In an open environment, if there is sufficient oxygen in the environment, the dilution effect on oxygen will be greatly weakened, and the cooling and heat absorption effect will be greater than the dilution effect of oxygen (Fan et al., 2023). Increasing the water mist flux can improve the oxygen dilution efficiency. Wang et al. (2018) measured the threshold of water vapor absorption for flame extinguishing. When the ambient temperatures are 100 ℃ and 300 ℃, the water vapor absorption needs to reach 36% and 44% or above to ensure that the oxygen absorption is below 13%.

Thermal Radiation

Ultrafine water mist can reduce the thermal radiation of flames to the surrounding environment, thereby reducing the combustion rate. The efficacy of fine water mist in obstructing thermal radiation is linked to factors such as droplet size, water mist momentum, and the spectral range of the heat source. Gonome et al. (2020) suggested that the most effective particle size for achieving maximum radiation attenuation is in the range of 2-4 μm when the heat source temperature falls between 600-1200 K. Under the same conditions, water mist with particle sizes of $D_{V50} \leq 50\ \mu m$ and $200\ \mu m \leq D_{V50} \leq 300\ \mu m$ can attenuate thermal fallout by 60% and 40%, respectively (Ko, 2023). In the experiment of Cui et al. (2021), under the conditions of water mist flow rate of 1L / min, tap layout of 0.2 m, and average particle size of 50 um, the thermal radiation attenuation efficiency reached 90.69%. When the water mist flow rate is 0.5 L / min, the nozzle spacing is 0.4 m, and the average particle size is 2000 um, the thermal radiation attenuation rate is only 39.14%.

Dynamic Disturbance

Dynamic disturbance pertains to the occurrence in which the flame experiences attenuation or extinguishment due to momentum exchange between the water mist and the flame. A portion of the kinetic energy from the water mist is imparted to the flame, leading to interference with its stability. As droplets traverse the flame zone and water vapor emerges through heat absorption and evaporation within the flame region, alterations in the stable structure and heat transfer process of the flame occur. This results in a degree of deformation and wrinkling of the flame, ultimately fostering flame extinction (Han et al., 2019). However, if the particle size of the water mist is large or the momentum of the water mist is large, the disturbance to the flame will intensify, leading to turbulence and deteriorating the suppression effect of the water mist.

Ultrafine water mist is a subset of fine water mist that shares similarities with gases in addition to the aforementioned fine water mist features. Ultrafine water mist has not been defined in any way as of yet. Based on the particle size of the water mist, researchers determine if it is ultrafine or not. Particles in water mist are typically smaller than 200 um, yet there is some variation in how this size is classified as ultrafine (Lu, 2019). There are currently two primary methods for producing ultrafine water mist. One uses an atomizing nozzle to apply pressure to a water mist pipeline, which produces ultrafine mist. The ultrafine water mist that is produced, on the other hand, tends to have a high momentum and enhance explosions due to turbulence disturbances in the explosion field; an ultrasonic atomizer can produce a different kind of mist with small particles and low momentum (Han et al., 2020).

Supplementary Work

Zhang et al. (2022) discovered that various atomization techniques for ultrafine water mist can yield two contrasting outcomes: augmentation and inhibition. Finely dispersed water mist has the potential to disrupt the flame and facilitate an explosion, while simultaneously absorbing heat and reducing the explosion. Yu et al. (2016) believes that insufficient application of ultrafine water mist will enhance methane flareup, and charged fine water mist has a stronger inhibitory effect than ordinary fine water mist. Yu et al. (2022) found through experiments that the rate of gas explosion pressure increase and the propagation rate of combustion waves decrease with the increase of ultrafine water mist spraying amount, and obstacles will strengthen the explosion. According to Xu et al. (2017), the volume of the water mist and the concentration of methane are connected to the inhibitory effect of the mist on methane explosion. Li et al. (2019) found that additives can improve the fire extinction outcome of fine water mist. The primary component impacting the efficacy of fine water mist in putting out fires is its mass fraction, according to Yoshida et al. (2015). Ultrafine water mist can only stop methane explosions when there's sufficient of it, according to Yang et al. (2023), but carbon dioxide can stop it from making explosions stronger.

Previous researchers have conducted extensive experimental studies on the overthrow of methane explosions by ultrafine water mist but have yet to analyze the degree of influence of various factors on methane explosions. In view of this, we will comprehensively consider four factors:

- The amount of ultra-fine water mist sprayed;
- Methane volume fraction;
- Methane injection position, and premixing time;
- Analyze their impact on methane explosion, in order to provide guidance for the suppression of methane explosion by ultra-fine water mist.

Here is how the rest of the paper is structured. Section 2 provides a detailed description of the experimental framework including test equipment, and test methods. Section 3 delivers results and analysis about numerical simulation on methane coal dust composite explosion in restricted space by ultrafine water mist suppression in detail. Section 4 presents our concluding conclusions and some valedictory remarks.

Experimental Framework

Test Equipment

The current research focuses on ultrafine water mist preventing single combustible chemical explosions. Due to the excellent fire extinguishing characteristics of ultrafine water mist, many scholars worldwide have conducted research on the effectiveness of ultrafine water mist in explosion suppression, and have achieved good research results in simple gas explosion suppression. Roosendans et al. (2017) investigated the inhibitory impact of water mist with a particle size of 500 μm on hydrogen explosions within pipelines. The findings revealed that water mist can significantly diminish the explosion pressure and extinguish the explosion flame. The study emphasized that the inhibitory effect is associated with the particle size of the water mist. Thomas et al. (1991) calculated the outcome of water mist on flareup in shock tube, and found that spray under different conditions can lead to two effects of explosion suppression and enhancement.

Furthermore, the somewhat ideal theoretical framework was absent from the mist inhibition mechanism of hybrid explosions, and post-explosion changes in temperature and surface microstructure were similarly omitted. The experimental device mainly consists of six parts: methane conveying system, high-speed camera system, ultra-fine water mist system, pressure acquisition and processing system, vacuum pumping system, and explosion pipeline. Its overall structure is shown in Figure 1. The ultrafine water mist inhibition mechanism was more complicated, and gas and dust hybrid explosions were more intense than single-substance explosions. The particle size distribution of ultrafine water mist is shown in Figure 2.

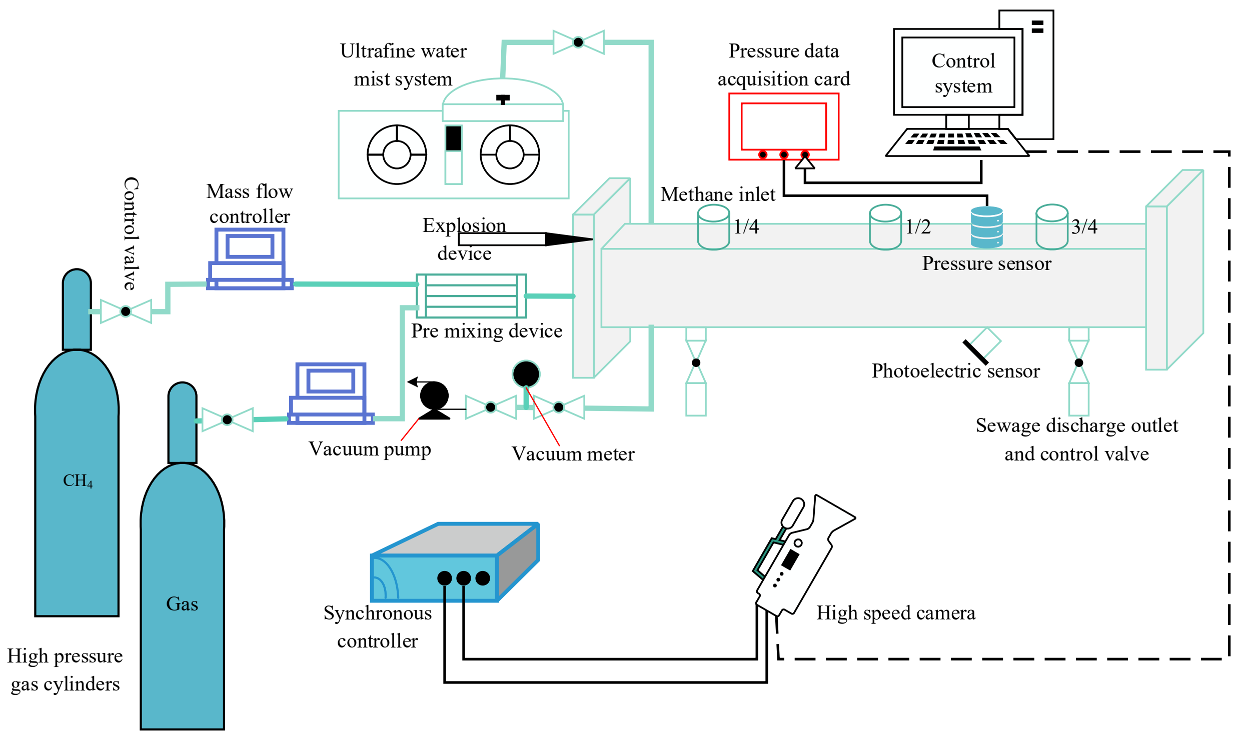

Figure 1. Overall Structure of the Testing Device, Including High Pressure Gas Cylinders, Mass Flow Controller, Pre Mixing Device, Ignition Position, Pressure Sensor, Pressure Data Acquisition Card, Ultrafine Water Mist System, Synchronous Controller, High Speed Camera, Sewage Discharge Outlet and Control Valve, Explosion Pipeline, Control Valve, Photoelectric Sensor, Vacuum Gauge, Vacuum Pump, and Methane Intel with (1/4), (1/2), and (3/4)

Test Methods

In order to further study the inhibitory effect of ultrafine water mist on methane explosion, the experiments were divided into single factor experiments and multi factor orthogonal experiments. The single factor experiments were divided into pure methane explosion experiments (methane volume fractions in methane air mixture were 7%, 8.5%, 10%, 11%, and 13%), and 0.7 mL ultrafine water mist inhibition methane explosion experiments (methane volume fractions were 7%, 8.5%, 10%, 11%, and 13%), 10% methane explosion test under different spraying rates (spraying rates of 0.35, 0.7, 1.05, 1.4, and 1.75 mL). The multi factor experiment consists of four factors and five levels of orthogonal design: ultra-fine water mist spraying amount (0, 0.35, 0.7, 1.05, and 1.4 mL), pre mixing time (30, 60, 90, 120, and 150 s), methane volume fraction (7%, 8.5%, 10%, 11%, and 13%), and methane inlet position (ignition end, 1/4 pipe length from ignition end, 1/2 pipe length from ignition end, 3/4 pipe length from ignition end, and 1 pipe length from ignition end).

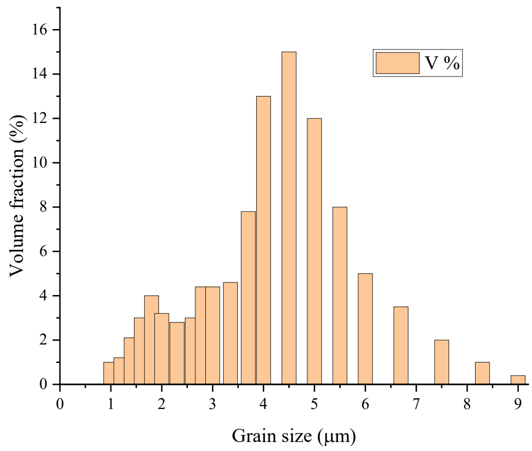

Figure 2. Particle Size Distribution of Ultrafine Water Mist

Results and Analysis

Single Factor Test Results

A total of 5 volume fraction pure methane explosion tests were conducted, with volume fractions of 7%, 8.5%, 10%, 11%, and 13%. Figure 3 shows the pressure variation curves of pure methane explosions with 5 different volume fractions.

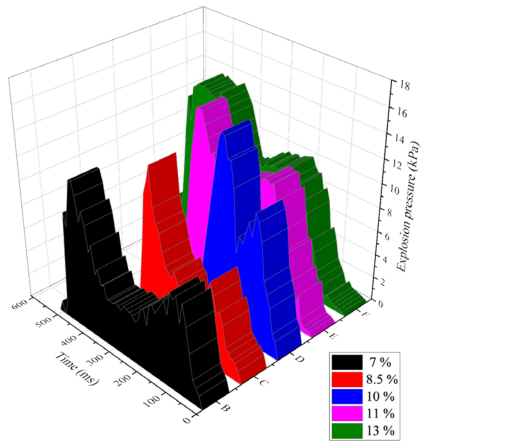

Figure 3. Changes in Explosion Pressure of Methane with Different Volume Fractions

The ultrafine water mist inhibition mechanism was more complicated, and gas and dust hybrid explosions were more intense than single-substance explosions. The process of methane explosion pressure change can be divided into three periods, namely the first peak period, the second peak period, and the rapid decline period. During the first peak period, the pressure of methane explosion increases rapidly. When the pressure inside the pipeline rushes towards the pressure relief port on the right side of the pipeline, some of the pressure is released to the outside world, and the force of methane explosion decreases. During the second peak period, the reaction rate accelerates and the methane explosion pressure increases at a faster rate. During this period, the maximum explosion overpressure ΔP_{max} appears, with five volume fractions of methane explosion ΔP_{max} being 12.17, 13.34, 15.36, 14.1, and 13.21 kPa, respectively. The time required to reach ΔP_{max} is 417, 298, 223, 381, and 502ms, respectively. During the period of rapid decline, the reaction ends, and the pressure is released through the pressure relief port, resulting in a linear decrease in pressure.

The flame spread times t for 5 different volume fractions of methane explosions are 425, 307, 234, 389, and 505 ms, respectively. The flame propagation distances for different volume fractions of methane explosions are shown in Figure 4. From the graph, it can be seen that the flame spread rate of the 10% methane explosion is the highest. Different volume fractions of methane explosion flames first accelerate forward propagation, and then due to the result of the reverse shock wave, the flame propagation rate decreases and approaches a straight line. During the flame spread procedure, the flame initially becomes spherical. When the flame links the pipe wall and is constrained by the pipe wall, the flame shape changes to a finger shape. As the flames continued to spread forward, the tulip flame appeared. The tulip flame is the result of the interaction between countercurrent and eddy currents (Ponizy, Claverie, & Veyssière, (2014; Wu et al., 2023; Zheng et al., 2023).

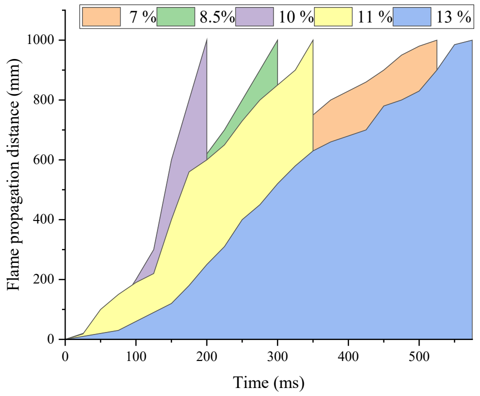

Figure 4. Flame Propagation Distance of Methane Explosion with Different Volume Fractions

Ultrafine Water Mist Suppresses

The ΔP_{max} of 7%, 8.5%, 10 %, 11%, and 13% volume fractions of methane under 0.7 mL ultrafine water mist spray were 11.34, 11.98, 13.35, 12.93, and 12.12 kPa, respectively. Compared with pure methane explosion, ΔP_{max} decreased by 7.82%, 10.19%, 13.09%, 8.29%, and 8.25%, respectively. The time to reach ΔP_{max} was 688, 618, 536, 657, and 782 ms, respectively. Compared to the explosion of pure methane air mixture, it was delayed by 271, 320, 313, 276, and 280 ms, respectively. The suppression effect of 0.7 mL ultra-fine water mist on the flareup pressure of 10% methane is better than other volume fractions of methane.

Figure 5 shows the explosion pressure change of 10% methane without spray and 0.7 mL ultrafine water spray.

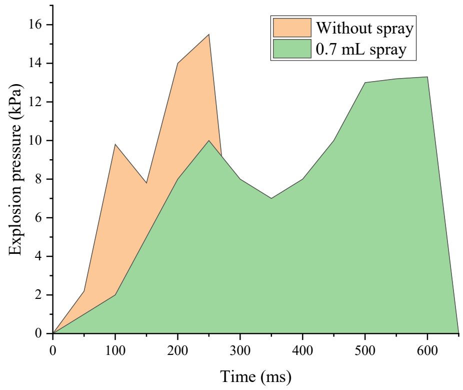

Figure 5. Explosion Pressure Change of 10% Methane without Spray and 0.7 mL Spray Rate

From the graph, it can be seen that 0.7 mL of ultrafine water mist not only effectively reduces the ΔP_{max} of methane explosion by 10%, but also effectively reduces the rate of pressure rise. Under the condition of spraying 0.7 mL ultrafine water mist, the "tulip" flame also appeared, as in the condition of no spray, but because the intensity of reverse flow and vortex became weaker under the action of ultra-fine water mist, the flame became a "finger" flame after the "tulip" flame.

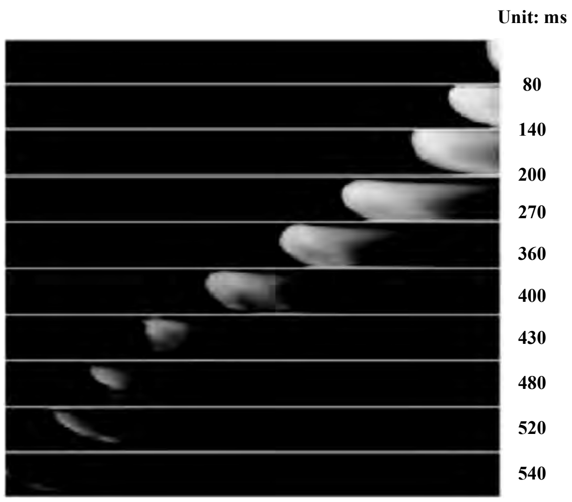

Figure 6. Flame Propagation of 10% Methane at a Spray Rate of 0.7 mL

In Figure 6, the flame propagation process of 10% volume fraction methane is illustrated under two conditions: one with no ultrafine water mist and the other with the spraying of 0.7 mL of ultrafine water mist. Under the achievement of ultrafine water mist, the brightness of the methane explosion flame is significantly improved, and similar situations are also observed in other volume fractions of methane. In addition, the flame spread time t also changed. The flame spread time t of methane with 7%, 8.5%, 10%, 11% and 13% volume fractions under the condition of ultrafine water spray application amount of 0.7 mL was 693, 625, 542, 662 and 782 ms, respectively. Compared with the condition without spray, the flame propagation time t was delayed by 268, 318, 308, 273 and 277 ms, respectively. The ultrafine water spray effectively delayed the flame propagation.

In Figure 7, the flame propagation distance of a 10% methane explosion is depicted under two conditions: without spraying and with the spraying of 0.7 mL of ultrafine water mist. Under the condition of 0.7 mL ultrafine water mist, the flame propagation of 10% methane explosion lags behind that of no ultrafine water mist. 0.7 mL ultrafine water mist can effectively defeat the flame spread of methane explosion.

Analysis

The experiment was conducted using four factors: ultrafine water mist spraying amount, premixing time, methane volume fraction, and methane inlet position. Each factor had five levels, and methane ΔP_{max} and flame propagation time t were measured under each operating condition. The range analysis results of methane explosion ΔP_{max} and flame propagation time t are listed in Table 1. From the table, it can be seen that the order of ΔP_{max} response to methane explosion from high to low is: methane volume fraction, ultrafine water mist spraying amount, methane inlet position, and pre mixing time. The degree of influence on the propagation time t of methane explosion flame, from large to small, is as follows: ultrafine water mist spraying amount, methane volume fraction, methane inlet position, and premixing time.

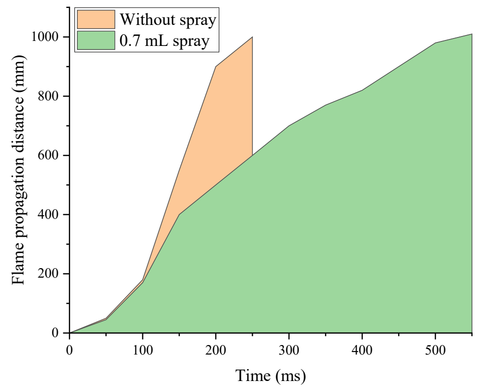

Figure 7. Flame Propagation Distance of 10% methane under anhydrous mist and 0.7 mL ultrafine water mist conditions

Table 1. Extreme Values of Experiment Range Analysis

Experimental factors	Ultrafine water mist spraying volume (mL)	Pre mixing time (s)	Methane volume fraction (%)	Methane inlet position
ΔP_{max} (kPa)	2.95	0.125	3.20	0.51
Flame propagation time t (ms)	463	42.8	288.9	72.7

From the table, it can be seen that the volume fraction of methane has a significant influence on the ΔP_{max} of methane explosion. The amount of ultrafine water mist sprayed has a certain impact on the ΔP_{max} of methane explosion, while the position of methane introduction and pre mixing time have little consequence on the ΔP_{max} of methane explosion. From the table, it can be seen that the amount of ultrafine water mist sprayed has a significant impact on the propagation time t of methane explosion flames. The volume fraction of methane has a certain influence on the propagation time t of methane explosion flames. The position of methane introduction and premixing time have little effect on the propagation time t of methane explosion flames. The position and premixing time of methane introduction have little effect on methane explosion, mainly due to the strong diffusion of methane in air. Generally, methane can quickly and uniformly mix with air.

Conclusion

This article investigates the features of methane coal dust composite explosions and the suppression mechanism of ultrafine water mist on composite explosions in a visualized explosion through experimental means. Utilize pressure sensors to collect pressure responses during the explosion process, and use high-speed cameras to record the dynamic evolution of flames. We studied the impact of coal dust particle size, and water mist concentration on the pressure behavior and flame propagation behavior of methane coal dust composite explosions, with a focus on analyzing the flame propagation characteristics under the influence of coal dust particle size, coal dust concentration, and water mist concentration. Conduct single factor and multi factor experiments, analyze the experimental data, and draw the following conclusions:

1) Ultrafine water mist can effectively suppress methane explosions, especially 10% methane, and the inhibitory effect increases with the increase of ultrafine water mist spraying amount.

2) The order of the influence of four factors on methane explosion ΔP_{max} from large to small is: methane volume fraction, ultrafine water mist spraying amount, methane inlet position, and pre mix time. Among them, methane volume fraction has a significant impact on ΔP_{max}, ultrafine water mist spraying amount has a certain impact on ΔP_{max}, and the influence of methane inlet position and pre mix time on ΔP_{max} is very small.

3) The order of the influence of four factors on the propagation time of methane explosion flame from large to small is: ultrafine water mist spraying amount, methane volume fraction, methane inlet position, and premixing time. Among them, the amount of ultrafine water mist spraying has a significant impact on the flame propagation time, methane volume fraction has a certain impact on the flame propagation time, and the influence of methane inlet position and premixing time on the flame propagation time is very small.

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