第19卷第2期
2010年4月

火灾科学
FIRE SAFETY SCIENCE

Vol.19, No.2
Apr. 2010

文章编号：1004-5309(2010)-0051-09

Experimental study on suppression of methane explosion with ultra-fine water mist

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Abstract: Suppression of methane explosion has been investigated experimentally in this paper. Different concentrations of methane explosion and different volumes of ultra-fine water mist were considered. A GigaView High-speed camera was used to visualize the processes of methane explosion suppression with ultra-fine water mist, and the phenomenon in the process was analyzed. Four E12-1-K type fast response thermocouples were used to obtain the temperature history of methane explosion suppressed with ultra-fine water mist. The effects of methane concentrations and ultra-fine water mist volumes on explosion delay time are discussed. The results show that the suppressing efficiency of the methane explosion with ultra-fine water mist is related to both of the water mist volume and the methane concentration, and a critical volume value of ultra-fine water mist for suppressing methane explosion is primarily determined.

Keyword: Methane explosion; Explosion suppression; Explosion delay time; Ultra-fine water mist

0 Introduction

Although many coal mines are so mechanized nowadays, the accidents, mainly including methane explosions, still often happen with severe consequences. So grim is the situation of preventing methane explosion accidents and reducing the severity of accidents. However, the current status of eliminating the hazard is improving the ventilation of working area, by which the methane in coal mines is kept in safety concentration and the spark by friction is prevented from appearing due to the cold fresh air. Therefore, it is absolutely necessary to develop new approaches to prevent methane explosion or suppress the spread of flame and denotation wave even if the explosion occurs.

As is known to all, water has a tremendous cooling effect and can mitigate a fire hazard if used properly. Water mist as a newly sparked technology is used widely for suppressing fires in many areas due to many merits, such as high fire extinguishing effectiveness, less water consumption, no pollution to environment, safety to protected objects etc.[1~9]. The subject related to methane flame extinction and explosion mitigation with water spray or vapor had been studied in the past recent years for several intentions. Teresa Parra et al.[10] and Li et al.[11] performed numerical simulation on methane-air flame extinction and methane explosion suppression by vapor. Large-scale experiments on the effect of explosion suppression with water mist had been conducted by Kim et al.[12], Xie et al.[13] and Wlofe et al.[14]. Many small-scale experiments were also performed for different purposes, including investigating the influence of turbulence on the course of gas explosion mitigation[15,16], quantification of the basic chemical and physical processes of explosion mitigation by water mist[17], scaling for vented gas and dust explosions[18], and seeking the characteristics of methane flame propagation

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收稿日期：2010-03-05；修改日期：2010-03-18

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and methane-air flame emission spectrum under application of water mist[19,20].

However, due to droplet motion through the gas or gaseous viscous interaction with walls, when some part of their momentum is transferred to the ambient gas, it will be inevitable to give rise to turbulence in the gas phase. This could lead to an unexpected circumstance if the explosion were immoderately intensified by induced turbulence from water sprays. Only in a minority of experiments ultrasonic atomizer apparatus generated ultra-fine water mist, which had the diameter of 1-20 microns, low velocity and little possibility to induce turbulence. Therefore, in order to deepen the knowledge on explosion suppression mechanisms with ultra-fine water mist and prevent the effects of turbulence induced by water ejection on explosion suppression, a series of preliminary experiments were conducted.

1 Experimental apparatus

Fig. 1 shows the schematic diagram of the experiment apparatus for study on methane explosion suppression with ultra-fine water mist. The whole system includes six parts, which are ultrasonic atomizer, gas transportation system, ignition system, the tube for explosion propagation, data acquisition and processing system and a high-speed Photography System.

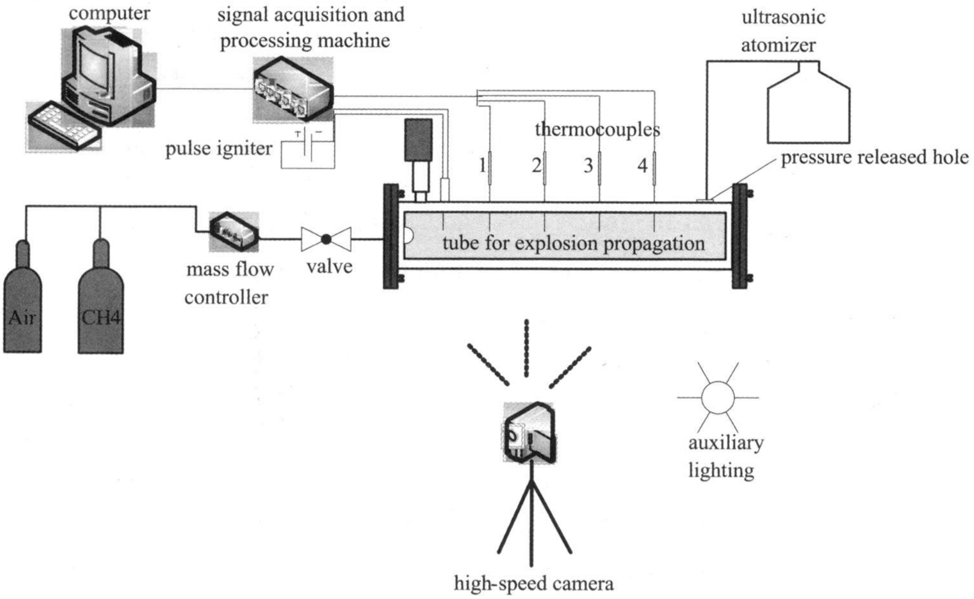

图 1 细水雾抑制甲烷爆炸实验装置

Fig. 1 Experimental apparatus of methane explosion suppression with water mist

1.1 Ultrasonic atomizer apparatus

Ultrasonic Atomizer mainly consists of high-frequency oscillating circuits and PZT (lead titinate-zirconate) piezoelectric ceramics transducers. High-frequency oscillation voltage causes resonance on the PZT wafers, which converts electrical energy to mechanical energy in the form of ultrasonic. Due to the particle vibration induced by ultrasonic oscillation, the liquid is compressed and stretched fiercely. When its tension is strong than cohesion, the formation of cavities in the liquid occurs. And the ultrasonic cavitation will cause the formation of shock waves which vibrate repeatedly with the same frequency as the wafers, and thereby generate the surface tension waves that make the liquid atomized. The atomized particles are sent outside through the inner fan in the apparatus. The temperature of the ultra-fine water mist is 19 ℃ and the diameter is about 1-20 μm. And the flow rate of the ultrasonic atomizer apparatus is 0.097ml/s.

1.2 Gas transportation system

According to the specific requirements of explosion experiment, we had chosen standard high-pressure gas cylinder, manometer, pressure regulators, D08-3B/ZM mass flow controller and pipelines, etc. This system has good sealing performance. And the required concentration was satisfied by controlling the flows of air and methane through mass flow controller.

1.3 Ignition system

This system uses the SMC-1R1 pulse igniter to discharge the spark for ignition. The range of the adjustable continuous voltage and output energy are 0-10KV and 0-900mJ, respectively. This apparatus has the characteristic of high precision. In the experiment the ignition energy is far larger than the minimum ignition energy of methane explosion.

1.4 The tube for explosion propagation

The tube has a length of 60cm and a square section of 10cm×10cm. Its walls consist of three pieces of 4mm thick transparent acryl glass and one piece of 6mm thick stainless steel plate and both ends are sealed by flanges and gaskets. Besides, four thermocouples, a pair of ignition electrodes and pressure released hole are distributed on the stainless steel plate. Also, their joints with the steel plate are sealed up completely. It is convenient for high-speed photography to capture the whole process of the methane explosion suppression with ultra-fine water mist through the tube.

1.5 Data acquisition and processing system

This system is composed of an ESC-CH01-03 signal acquisition and processing machine, E12-1-K type thermocouples with microsecond response time, ESC-TC02 fast response thermocouples input module and PCI-6250 data acquisition cards with the 1.25M sample rate, which can satisfy the requirement of microsecond data acquisition. The thermocouples are distributed at intervals of 10cm from the place 2cm away from the electrodes.

Table 1 Parameters of the E12-1-K type thermocouples

表1 E12-1-K型热电偶的特性参数

Measure Range	0~2300℃
Accuracy	0.75%F.S.
Response time	<20μs

1.6 High-speed Photography System

This system comprises a GigaView High-speed camera with high-speed data access memory, a laptop, a camera stand, lighting equipments, etc. And according to different frame sizes, the camera has different frame rates; the most one is 2000 fps. In the experiment we choose the frame rate of 1000 fps with the frame size of 1028×128 and exposure of 994 usec. In order to analyze and process the images further, they are transmitted to the computer in the form of digital signals.

2 Experimental results and discussions

For the essence, the methane explosion is a kind of intense oxidation reaction and will happen in a certain range of concentration. The concentration range is 5.3%-15%. In this study, 5.3%, 6.8%, 8.4%, and 9.8% concentrations of methane explosion are considered. In order to prevent the residues of the ultra-fine water mist or methane in the tube from influencing the results of the experiment, the dry air was put through the tube before next experiment.

2.1 Explosion visualization

The methane explosion is a rapid and violent reaction. In order to visualize the reaction distinctly, a GigaView high-speed camera is used to take images of the process of methane explosion suppression with ultra-fine water mist. The typical pictures are shown in Fig.2, where the concentration of methane is 8.4% and the volumes of the ultra-fine water mist are 1.94mL, 2.92mL and 3.88 mL, respectively (The ultra-fine water mist is put into the tube for 20s, 30s and 40s. respectively).

The results show that when the volume of the ultra-fine water mist is 1.94mL, the average motion velocity of the water mist impelled by the shock wave in the distance from the electrodes to the second thermocouple, the third and the fourth one are about 2m/s, 10m/s and 2m/s, respectively. When the explosion occurs, the incipient velocity is zero but arises rapidly. After a while of acceleration, the velocity achieves the highest one. However, the velocity slows down rapidly because of the impediment of the other end of the tube. And all the ultra-fine water mist is pushed to the other end of the tube to pile up. After about 200ms, the pressure released hole is broken by the acting of the shock wave. Then the outside air is pushed into the tube and the ultra-fine water mist is dispersed back toward the electrodes.

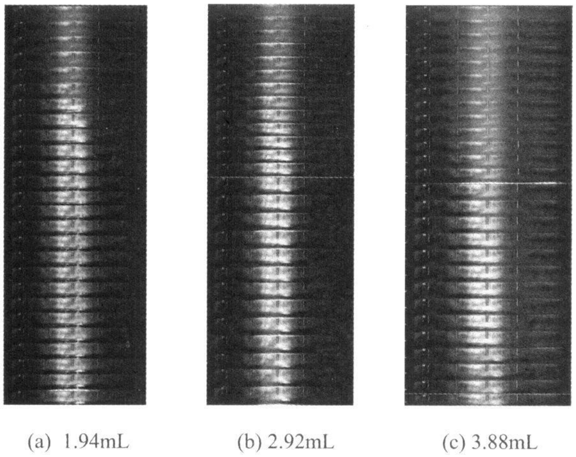
(a) 1.94mL (b) 2.92mL (c) 3.88mL

图 2 超细水雾抑制 8.4%浓度甲烷爆炸的图像(a) 间隔 10ms, (b) 间隔 20ms, (c) 间隔 20ms

Fig. 2 Images of 8.4% methane explosion suppressed with ultra-fine water mist;
(a) Interval of two slides is 10ms, (b) Interval of two slides is 20ms, (c) Interval of two slides is 20ms

When the volume of the ultra-fine water mist is 2.92mL, the shock wave cannot push all the ultra-fine water mist into the other end of the tube. After about 140ms, the water mist is separated into two parts: a smaller part and a larger part. The smaller one arrives at the second thermocouple with average velocity of about 0.6m/s, and stops at the place of the second thermocouple then goes back toward the electrodes due to the reflected shock wave; Until the pressure released hole is broken, the larger one is being pushed to the other end of the tube to pile up by the shock wave, arriving at the middle between the third and the fourth with average velocity of about 1.13m/s.

When the volume of the ultra-fine water mist is 3.88mL, the situation is similar to that of 2.92 mL. The only difference is that the power of the shock wave is weaker and the propagation velocity is slower.

2.2 Explosion temperature

In order to reduce the influences of turbulence generated by afflux of ultra-fine water mist on the experiment, both of the methane with required concentration and the ultra-fine water mist are put into the tube slowly. Then the data acquisition and processing system and the high-speed photography system begin to work. When water mist gets stabilization, the pulse igniter is triggered.

8.4% concentration of methane explosion without ultra-fine water mist reacts very violently and accompanies a tremendous roar and yellow jet flame occurring at the pressure released hole. For the rest situation, the explosion sound is weaker and no flame occurring at the pressure released hole.

Fig.3 presents the temperature history of the 8.4% methane explosion suppression under different conditions of ultra-fine water mist. When no ultra-fine water mist is put into the tube, the explosion temperatures arises rapidly and the results measured with the furthest thermocouple (32cm away from the electrodes) are still higher than 800℃.

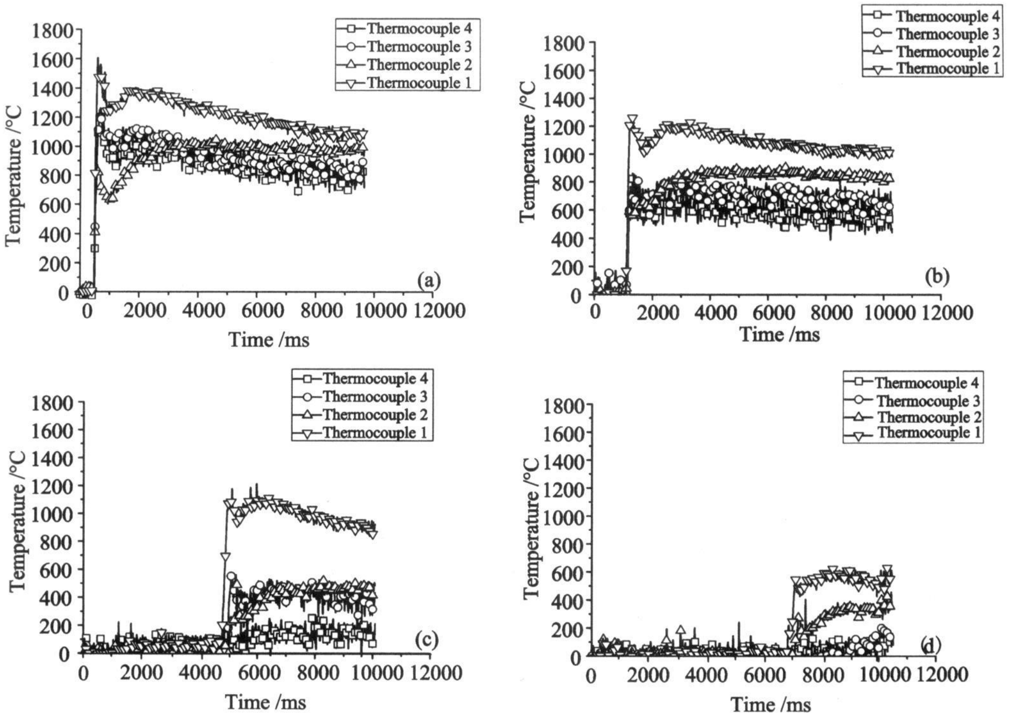

图 3 超细水雾抑制 8.4%浓度甲烷爆炸的温度曲线:

(a) 无细水雾 (b) 1.94mL 超细水雾 (c) 2.92mL 超细水雾 (d) 3.88mL 超细水雾

Fig. 3 Temperature history of 8.4% methane explosion suppressed with ultra-fine water mist:

(a) no ultra-fine water mist, (b) with 1.94mL ultra-fine water mist,

(c) with 2.92mL ultra-fine water mist, (d) with 3.88mL ultra-fine water mist

When the volume of the ultra-fine water mist is 1.94mL, the explosion temperatures also arise rapidly, but the temperatures measured with the nearest (2cm away from the electrodes) and the furthest thermocouples are only about 400 ℃ and 200 ℃, respectively.

When the volume of the ultra-fine water mist is 2.92mL, the explosion is further suppressed. Although the explosion temperature drop of the nearest thermocouple from the electrodes is not obvious, the temperatures at the locations 12cm and 22cm away from the electrodes fall by 400 ℃ or so, and the important one is that the temperature raising rate decreases and the flame just stops when it does not arrive at the fourth thermocouple 32cm from the electrodes.

When the volume of the ultra-fine water mist is 3.88mL, the explosion temperature of the nearest thermocouple drops obviously by 600 ℃, and the temperatures of the rest also further fall. The temperature raising rate decreases clearly. The flame just stops when it does not arrive at the third thermocouple (22cm from the electrodes).

When the volume of the ultra-fine water mist put into the experimental tube is 4.38mL, the situation is similar to that of 3.88mL. The only difference is that the explosion temperature is lower and temperature raising rate is smaller than that circumstance.

When the volume of the ultra-fine water mist put into the experimental tube is 4.86mL, the explosion is completely suppressed.

2.3 Explosion delay time

In order to investigate the efficiency of methane explosion suppression with ultra-fine water mist and reflect the difficulty in causing the explosion, a custom parameter named explosion delay time, which refers to the period from the time as the electrodes sparks to the time when the explosion occurs, is considered in this work. The experimental results indicate that the explosion delay time is prolonged evidently with the application of ultra-fine water mist. In addition, the explosion delay time significantly gets longer with the increase of the volume of ultra-fine water mist. For instance, the explosion delay time of the case with 2.92mL ultra-fine water mist is two magnitudes longer than that with 1.94mL (as shown in Fig. 4).

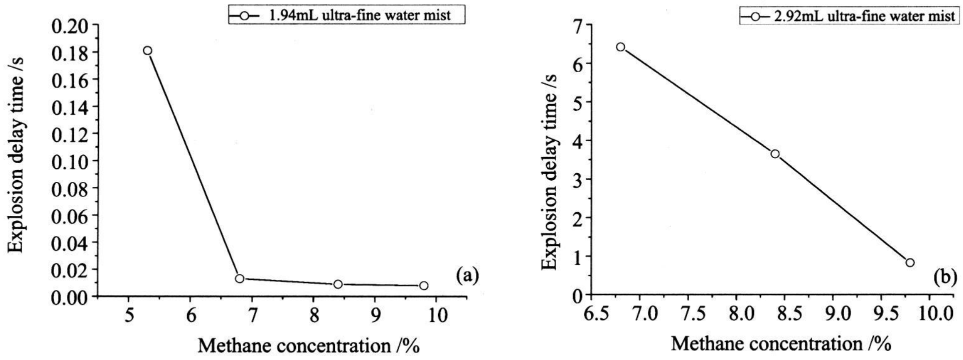

图 4 不同浓度的甲烷的爆炸延迟时间

Fig. 4 Explosion delay time of methane with different concentrations

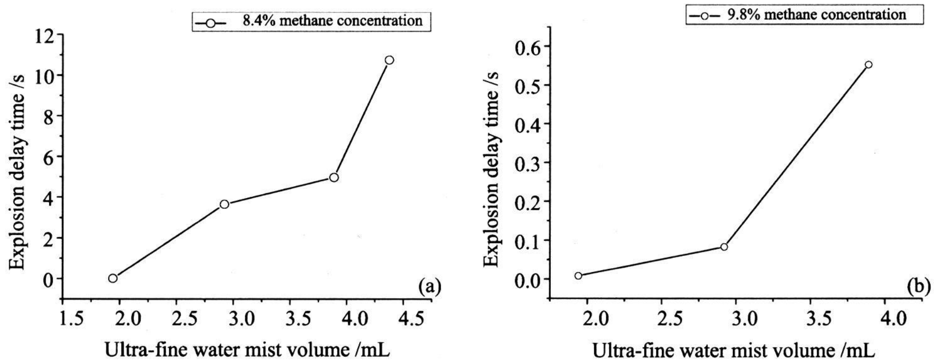

图 5 不同体积的超细水雾抑制甲烷爆炸的爆炸延迟时间

Fig. 5 Explosion delay times of methane suppressed by ultra-fine water mist with different volumes

Given a specific concentration of methane (for example 8.4% and 9.8%), the explosion delay time gets longer with increasing volume of ultra-fine water mist, and the rate of explosion delay time increasing is very rapid(as shown in Fig. 5). This indicates that it is very efficient for the ultra-fine water mist to suppress the methane explosion.

In a word, when the volume of ultra-fine water mist is smaller than 2.92mL, the electrodes are not surrounded by the water mist. Although the ignition delay time will be prolonged due to the ultra-fine water mist diffusion, but the time is comparative short and still has ms scale. However, when the volume of ultra-fine water mist is larger than 2.92mL, the electrodes are completely surrounded by the water mist. It is hard for the electrodes to initiate the methane explosion, the explosion delay time is very long and get to s scale because the electrodes need to spark all the time to generate the turbulence of the water mist, which involves methane and air to the neighbor of electrodes for explosion. This means the methane concentration in the neighbor of the electrodes is far lower than the lower explosive limit. Therefore reducing the concentration of methane is one of the mechanisms of methane explosion suppression with ultra-fine water mist.

2.4 Critical volume of ultra-fine water mist for suppressing methane explosion

During the period of the experiment, it is found that ultra-fine water mist for suppressing methane explosion always has a critical volume, beyond which methane will not explode no matter how high energy the electrodes release. From the lower explosive limits to stoichiometric concentration, the critical volume augments with increasing of methane concentration (as shown in Fig. 6).

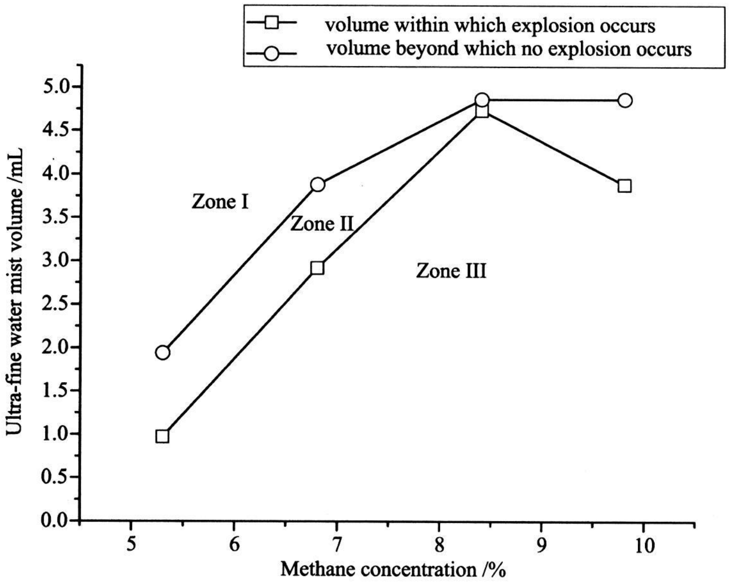

图 6　超细水雾抑制甲烷爆炸临界体积曲线

Fig. 6　Critical volume curves of ultra-fine water mist for suppressing methane explosion

The zone I is defined as non-explosion zone, and the zone III is defined as explosion zone, while the zone II occurs due to the limitation of the quantity of experimental cases, and is regarded as unknown zone, where whether the explosion will happen is not sure. So the next step needs to be done is to increase the experimental cases in order to get a perfect critical volume curves of ultra-fine water mist for suppressing methane explosion.

3　Conclusions

Experiments of 5.3%, 6.8%, 8.4%, and 9.8% concentrations of methane explosion suppression with different volumes of ultra-fine water mist are carried out. The results show that:

(1) The explosion temperature and the temperature raising rate get lower with the increase of the volume of ultra-fine water mist, which means that it is efficient for ultra-fine water mist to suppress the methane explosion and absorption of heat is one of mechanisms of methane explosion suppression with ultra-fine water mist.

(2) The explosion delay time shortens with the increase of methane concentration from the lower explosive limits to stoichiometric concentration, while it gets longer with the increase of the volume of ultra-fine water mist, and the rate of explosion delay time increasing is very rapid.

(3) The turbulence phenomenon in the neighbor of the electrodes indicates that reducing the concentration of methane is one of the mechanisms of methane explosion suppression with ultra-fine water mist. In addition, it is found that the suppression of methane explosion with ultra-fine water mist has a critical volume, beyond which methane will not explode no matter how high energy the electrodes release. From the lower explosive limits to stoichiometric concentration, the critical volume augments with increasing methane concentration.

Acknowledgments

The authors appreciate the support of the Natural Science Foundation of China (NSFC) (Grant No. 50774072) and the Program for New Century Excellent Talents in University (No. NECT-07-0794).

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超细水雾抑制甲烷爆炸的实验研究

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摘要:用自行设计的三面透明的细水雾抑制甲烷爆炸的实验装置,研究了不同体积超细水雾对不同浓度甲烷爆炸的抑制现象。运用GigaView高速摄影观察了超细水雾抑制甲烷爆炸的过程,并且对现象进行了分析。采用四个E12-1-K型快速响应热电偶获取超细水雾抑爆过程中四个不同位置的温度变化情况,并且讨论了甲烷浓度和超细水雾体积对爆炸延迟时间的影响。实验结果表明,超细水雾对甲烷爆炸的抑制效果是与水雾的体积和甲烷浓度紧密相关的。初步确定了超细水雾抑制甲烷爆炸的临界体积。

关键词:甲烷爆炸;抑爆;爆炸延迟时间;超细水雾

中图分类号:X932　　文献标识码:A