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Different gas explosion mechanisms and explosion suppression techniques*

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Abstract

Gas explosions are characterized principally in terms of two types according to the mechanism of combustion: deflagrations and detonations; detonations can be further subdivided into unstable detonations and stable detonations. All these three kinds of explosions are possible in confined underground coal mine roadways, so corresponding explosion suppression techniques shall be available. The effectiveness of water barriers commonly used in today's coal mines is in doubt in views of catastrophic gas explosions occurring from time to time. In this paper, different gas explosion mechanisms are theoretically investigated; the adequacy of current explosion suppression measures is explored. Along with the explosion suppression materials generally used in other process industries, their possible applications in coal mine roadways are discussed. It is concluded that porous medium is a promising material. If they are used with water barriers together, explosion accidents may be diminished to the minimum and production safety be guaranteed to the maximum.

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Keywords: gas explosions; deflagration; detonation; water barriers; porous medium

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1. Introduction

Gas explosion is the first concern in production safety in coal mines. China is the biggest victim of gas explosions, as the coal mine gas explosions were responsible for hundreds of deaths in recent years. This cannot be separated from a large number of its highly gassy coal mines. Moreover, an important reason is that the present explosion suppression techniques have been proven inefficient to suppress the most violent gas explosions, especially continuous and multiple explosions. So the current suppression means are intrinsically imperfect **[1]**. Take the water barriers commonly applied in mine roadways as an example. It is a passive means, namely, when the preceding shock waves from gas explosions arrive and trigger rows of water tubs to pour water into the air, water mist will seal the entire roadway section, which will remove the heat released from chemical reactions of gas/air mixture and cool down the temperature in the flame front, making the flame temperature decrease below its ignition temperature and consequently the flame extinguishes **[2]**.

Flame arrestors are commonly used in the chemical industry to prevent the escalation of accidental combustible mixture ignition to a violent explosion. An important part of a flame arrestor design is the use of porous media, such as wire mesh, ceramic beads, sand, or other high surface area heat sinks **[3]**. Expanded aluminum mesh and polymer foam materials have been used for explosion suppression and slosh mitigation baffles in US aircraft fuel tanks and dry bays for over 30 years. These materials are also being used for other explosion suppression applications in portable fuel containers, military vehicle fuel tanks, armored limousine and racing car fuel tanks, fuel tanks in certain types of boats, and some stationary flammable liquid storage tanks and manholes **[4]**. Zhou Cong et al experimented with the metal mesh structure for its suppression of explosion waves in duct, whose findings show that, with appropriate geometrical parameters, materials, number of layers and spacing, metal mesh can satisfactorily suppress flame propagation and decay the transverse waves and thus degrade detonations to deflagrations **[5]**. NIE Bai-sheng et al experimented with porous medium Al_2O_3 and SiC foam ceramics, finding that gas explosion max-overpressure can be attenuated by fifty percent or so after flames propagate through the foam ceramics; flame propagation velocity is substantially suppressed from 50m/s in smooth pipe to 2.2m/s in foam-ladern pipe **[6,7,8]**. In view of the successful applications of these porous materials in other process industries, it is reasonably expected that if they are properly designed with respect to coal mine practicalities and by taking into account gas explosion propagation characteristics in mine shafts, a new explosion suppression technique may be developed and applied in coal mine roadways to ensure the maximum safety.

2. Different gas explosion mechanisms

2.1. Deflagration

In deflagration, the combustion rate is controlled by the supply of oxygen to the explosion front which travels at subsonic velocities in the unburnt gas. The propagation mechanism is a heat transfer effect. The combustion reactions are strongly dependent on heat and mass diffusion in the region of energy release **[9]**.

In coal mine roadways, most of gas explosions occur in the form of deflagrations.

In strong deflagrations, combustion wave is preceded by shock wave which is formed by the expansion of combustion products left behind. Combustion wave consists of preheat zone and reaction (or oxidation) layer. Heat and mass transfer occurrs in the inner layer, where temperature rapidly rises; CH_4 and O_2 are consumed as shown in Fig. 1.

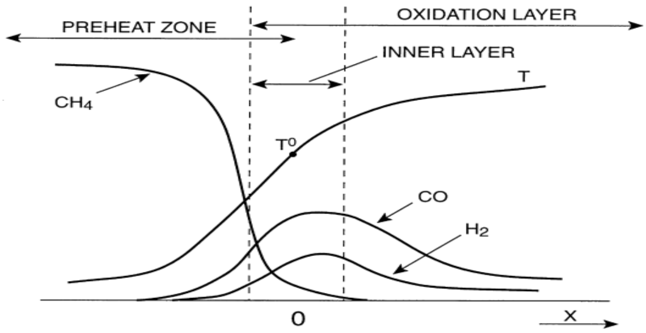

Fig. 1 Schematic of preheat zone, oxidation (reactive) layer, and temperature change in CH_4 explosions

Gas explosion can be simplified as an one-step, exothermic chemical reaction, as shown in Formula 1:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 886.2\text{kJ/mol} \qquad (1)$$

But in fact, the explosion is a very complicated branching chain chemical reaction. As given by American National Lawrence Livermore Lab, there comprises 53 species and 325 reactions **[10]**.

In the inner layer, branching chain reactions take place, where huge quantities of free radicals (activation centers) are generated, such as CH_3, OH, O, and HCO. They are responsible for flame self-sustaining. Some major free radical species are shown in Fig.2 **[11]**.

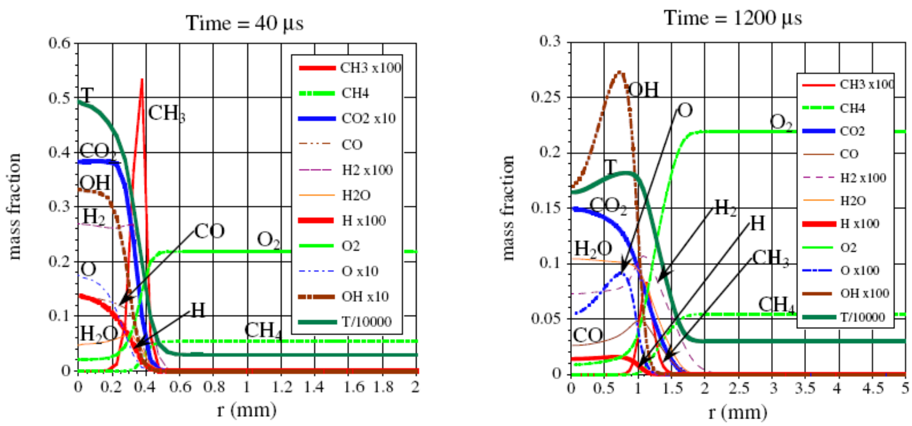

Fig. 2 Change of some major species in the reactive zone with time (courtesy of F. A. Williams)

2.2. Detonations

Detonations, where the combustion is initiated by the pressures and temperatures associated with the shock wave, travel at supersonic velocities in the unburned gas ahead. Propagation is due to compression effects (by shock compressive heating of the unreacted gases ahead of the propagation front). Detonations generate high pressures and are usually much more destructive than deflagrations. Detonations can be further subdivided into two types: 1. Stable detonations, which occur when the detonation progresses through a confined system without significant variation of velocity and pressure characteristics; 2. Unstable detonations, which occur during the transition of a combustion process from a deflagration into a stable detonation. The transition occurs in a limited spatial zone where the velocity of the combustion wave is not constant and where the explosion pressure is significantly higher than that in a stable detonation.

In the worst case scenario, where the mine shaft size and the combustible mixture conditions are conducive, the deflagration can transition to a detonation wave **[12]**. The velocity can be up to 2000 m/s, and the maximum pressures produced are close to 20bar that cause huge destruction of underground roadways and equipments.

In simple terms, a detonation wave can be described as a shock wave immediately followed by a flame (ZND theory). The shock compression heats the gas and triggers the combustion, as shown in Fig.3.

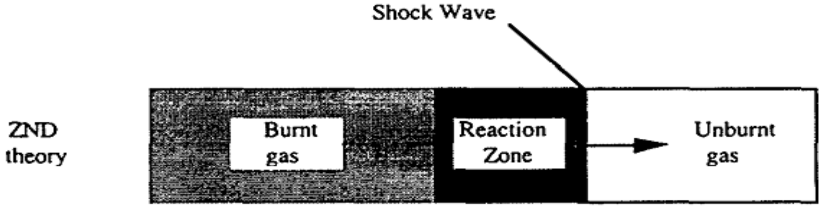

Fig.3 Detonation wave described by a shock wave immediately followed by a flame

3. Gas explosion suppression by water mist

Water barriers are commonly used in coal mine roadways for suppressing gas explosions. It is a passive suppression device, instead of an active one. The principle is, the shock wave ahead of combustion wave breaks or pulls down the water bags suspended on the roof, the water mist thus formed will diffuse and seal off the entire roadway section. The water mist will cool down the subsequent flame front and stop the chemical reactions. Thus flame extinguishes. Fig. 4 shows the arrangement of water barriers in the roadway.

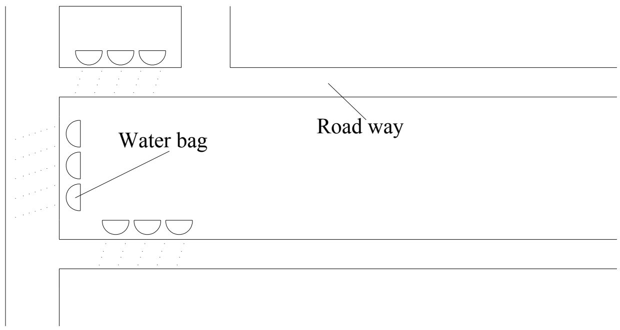

Fig.4 Arrangement of water barriers in roadways

The key for water barriers to suppress and isolate gas explosions depends on a lot of factors, such as water tub sensitivity to shock wave, water quantity, droplet size, time of atomization in the entire roadway section, duration of suspension in roadways. XIE Bo et al's experiments indicated that inadequate water quantity and inappropriate arrangement could not help to suppress flame propagation and decay shock waves **[13]**.

WANG Congyin et al. **[1]** conducted an experiment in a gas explosion duct. The experimental results indicatd that, explosion has very strong cohesive force, the flame kernel will gradually shift from the duct center to the duct bottom. As such, the flame continued to propagate the suppression zone and cannot be extinguished by the water mist. Consequently, the flame will ignite the gas mixture ahead.

4. Research on porous medium explosion suppression and their applications

Flame arrestors are commonly used in the chemical industry to prevent the escalation of accidental combustible mixture ignition to a violent explosion, where flame is forced to pass through the interconnected foam pores, where flame extinction can occur. As a consequence, in the reaction waves propagating through the gas-filled non-reacting foam, the losses in momentum and heat are significantly greater, as is the gas flow turbulization. Fig.5 shows expanded aluminum mesh and foam ceramics used in flame arrestors.

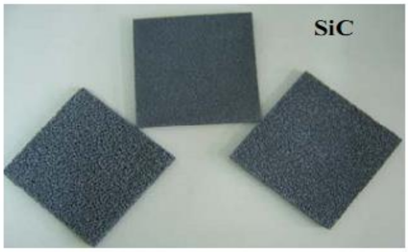

Fig.5 Expanded aluminum mesh and foam ceramics

The experiments show that, the fractional pressure rise values are approximately half the values that would occur if there were no foam or mesh in the arrestor volume of the test apparatus. Thus, the values ensure that the arrestor actually quench the flame rather than allow it to propagate through a substantial portion of the mesh/foam.

NIE Baisheng et al used foam ceramics in their experiments to prove the materials' gas explosion suppression properties. The results showed that, the flame was quenched and the shock wave was decayed by half **[6]**.

5. Assumptions of co-use of water barriers and porous medium in mine roadways

Presently, water barriers concentrate on cooling down the heat in flame front in case of gas explosions, while shock waves cannot be substantially attenuated. But in fact, shock waves are also responsible for casualties and huge destruction of the underground equipments. Moreover, if deflagration transitions to detonation, because of high pressures and velocities of the detonation waves, the apparatus used for quenching a deflagration will not be suitable for attenuating a shock wave, the control of which requires special equipment. Therefore, porous medium is proved an ideal material in suppressing gas explosions in mine roadways.

According to the roadway practicalities, the authors come up with a new arrangement of passive water barriers and active porous medium in the roadways, as shown in Fig.6.

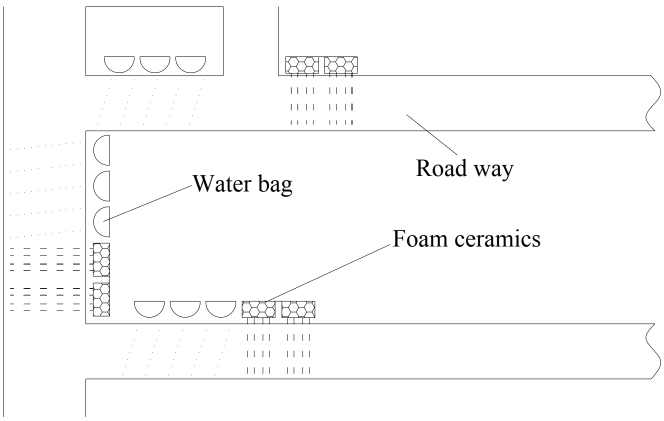

Fig.6 Arrangement of water barriers and porous medium in mine roadways

Such arrangement can make use of the respective advantages of passive and active explosion suppression devices. When the water barriers are pulled down by the preceding shock waves and produce water mist to cool down the flame front, the porous medium will be triggered and drop to seal off the entire roadway section to attenuate shock waves and suppress combustion waves.

6. Conclusions

Water barriers generally used nowadays in coal mine roadways are inherently inadequate to cope with gas explosions in different mechanisms. When deflagration has very quick velocity or even transitions to detonation, the high velocities and overpressures produced cannot be suppressed any more, which will inevitably lead to serious accidents. Porous medium is a promising material to be used in mine roadways to effectively quenching combustion wave while dramatically attenuating shock waves. If water barriers and porous medium are used together, their respective advantages can be made use of to secure production safety in coal mines.

Acknowledgments

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