Experimental investigation on micro-dynamic behavior of gas explosion suppression with SiO_2 fine powders

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Abstract To study the effect of inert dust on gas explosion suppression mechanism, SiO_2 fine powders were sprayed to suppress premixed CH_4-Air gas explosion in a 20 L spherical experimental system. In the experiment, high speed schlieren image system was adopted to record explosion flame propagation behaviors, meanwhile, pressure transducers and ion current probes were used to clearly record the explosion flame dynamic characteristics. The experimental results show that the SiO_2 fine powders suppressed evidently the gas explosion flame, and reduced the peak value of pressure and flame speed by more than 40 %. The ion current result shows that the SiO_2 super fine powders were easy to contact with and absorb free radicals near the combustion reaction region, which greatly reduced the combustion reaction intensity, and in turn influenced the flame propagation and pressure rising. [doi:10.1063/2.1103204]

Keywords fine powder, gas explosion, explosion suppression, reaction mechanism

Gas explosion is one of the most destructive accidents in coal mine and some other process industries, which always causes large losses and serious damage. In the case of gas explosion, some inert powder sprayed over the flame profile can absorb explosion wave energy and extinguish flame propagation rapidly and finally suppress explosion evolution, which has greatly attracted many researchers.[1-3] Scientists of US Bureau of Mines have done plenty of research work in the area of gas explosion suppression. Much knowledge has been gained from the full-scale explosion research conducted by mine safety research establishments during the past two decades.[4-7] Some inertial suppressants, such as $CaCO_3$, Na_2CO_3, SiO_2, were used to suppress gas explosion flame propagation.[8,9] Many studies show that inert particles can directly decrease the explosion pressure, and the particle size and concentration play important roles in explosion suppression.[10-12]

In the previous research of gas explosion suppression, studies are mostly focused on the exterior characteristics of gas explosions, such as the maximum explosion pressure, maximum rate of pressure rise and explosion concentration limits.[13] However, few studies on the inner mechanism of explosion suppression by powder were available.[14] Especially, it is difficult to explore the interaction dynamic process and microstructure characteristics during gas explosion suppression. The flame-powder interaction may change the whole combustion process and characteristics, while a detailed physical understanding of the flame-powder interaction and micro-behavior is still lacking due to the complexity of problem itself.

The full-scale and laboratory-scale tests were conducted in Lake Lynn experimental mines of NOISH.[15] And size scaling effect on gas explosion was also discussed in detail. The results showed relatively well agreement between the laboratory and the large-scale tests in determining gas explosion process. Therefore, in this study, a 20 L laboratory explosion chamber system was set up to simulate the gas explosion flame propagation suppression. The premixed methane-air flame was observed as object and SiO_2 powder was sprayed to suppress the flame propagation. In the experiment, high speed video camera and schlieren photograph technology were used to record the process and behavior of flame propagation, and a pressure transducer was used to investigate the gas explosion pressure variation. In addition, an ion current probe was fixed up to detect the combustion reaction characteristics near the flame front region when intervened by fine powders.

The experimental system is composed of a 20 L spherical explosion chamber, an ignition system, a data recorder, a schlieren photograph system, a high speed video camera and a synchronization controller, as schematically shown in Fig. 1. A dust nozzle was put up at the bottom of the chamber. The schlieren photograph system shown in Fig. 1 consists of a 25 W mercury vapor lamp and two concave mirrors. To observe flame propagation characteristics and flame structure evolution process, part of the sides of the chamber was made of high-intensity transparent glass. Probe igniters were fixed at the chamber center, which can elicit flame propagating outwards. A high frequency-dynamic piezoelectricity transducer was set up on the combustion pipe to detect the pressure variation.

Premixed methane/air mixture was first filled into the explosion chamber, and then a certain mass of fine SiO_2 dust was sprayed through the nozzle to mix evenly with the methane-air evenly. The powder concentra-

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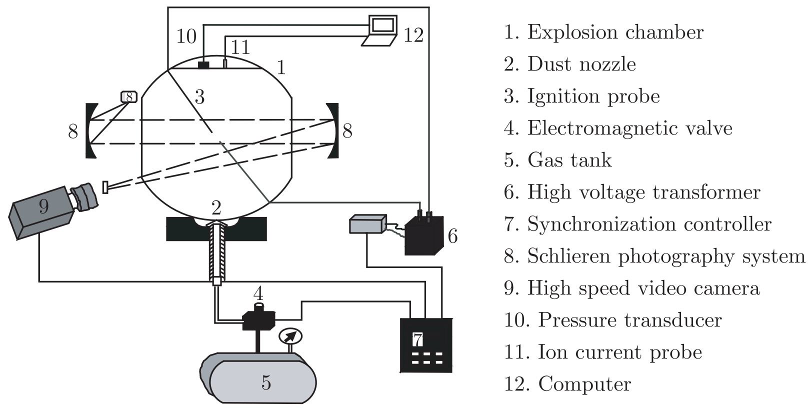

Fig. 1. Scheme of gas explosion suppression experimental system.

tion was determined from the volume of the combustion chamber and the mass of SiO_2 dust. After 50 ms delay, the mixture was ignited with a spark discharge at the center of the chamber, and then a flame propagates outwards. The flame propagation process was recorded by a high speed schlieren image system.

In the test, the startup time of the high speed video camera (Photron, Fastcam SA1.1), the high speed digital data recorder (HIOKI, 8826 Memory Recorder) and the high voltage igniter were controlled by a synchronization controller. The detailed experimental conditions were given as follows.

Equivalence ratio of the premixed methane-air in the mixer tank: ϕ=1.0; SiO_2 dust mass: 3.0 g; dust diameter: 10−20 μm; dust density:1.5 g·cm^{-3}; Ignition voltage: 20 000 V; Recording speed of the high speed video camera: 10 000 fps; Sampling rate of the data recorder: 100 kHz.

Schlieren photographs were obtained based on the light refraction from the flow, which can be used to reflect the gas explosion flame structure characteristics.[16] Therefore, the explosion flame propagation can be clearly recorded by the high speed schlieren photograph system.

Figure 2 is a series of typical high speed schlieren photographs showing the explosion flame propagation and flame front structure behavior. As shown in Fig. 2, the burned and unburned gases were separated by a thin flame front. Meanwhile, the convex flame front propagated from ignition point toward outside in a regular spherical wave shape. Based on the flame front radius, the flame propagation speed was obtained from the following expression,

$$v_f = \frac{\mathrm{d}r}{\mathrm{d}t},$$

where, v_f is the flame propagation speed, m/s; r is the flame front radius, m; t is the flame propagation time after ignition.

Therefore, based on the high speed schlieren photographs of explosion flame propagation, the accurate explosion flame speed can easily be obtained. Figure 3 shows the explosion flame speed under different conditions. Curve A describes pure gas flame speed with time, and curve B the flame propagation speed when influenced by fine powders. Curves A and B demonstrate that the pure gas flame speed increased quickly, and reached a peak value $v_f = 119$ m/s at 53 ms after the ignition, while the maximum flame speed was attained at 72 ms, and the peak value was about $v_f = 80$ m/s when sprayed with fine SiO_2 powders. When influenced by fine powders, the peak value of flame propagation speed dropped quickly and the flame acceleration rate decreased too.

Figure 4 shows the gas explosion pressure variation with time. Under the condition of pure CH_4-Air explosion, the explosion pressure rose quickly to a peak value, and then began to decline, accompanied with sharp fluctuations. When the mixture of CH_4-Air and SiO_2 powder was ignited, both the explosion pressure and its rising rate decreased obviously. The explosion pressure of mixture was no more than half that of pure gas explosion pressure, and the time of peak value occurrence was delayed about 27 ms. It is obvious that just the fine powder made explosion pressure depressed.

Some researchers have obtained similar results, but detailed investigations on internal evidence were rarely available. Therefore, to explore the inherent mechanism of combustion dynamics and propagation behavior, the ion current probe technology was used to detect the characteristics of flame structure and combustion reaction zone. Theoretical inference is based on the fact that the hydrocarbon produces some medial ion after combustion reaction, such as [H], [OH] and [CH_3], and thus the fluctuations of ion current show the reaction intensity and further characterize the reaction zone structure[17,18]. Therefore, the ion current probe technology can be used to study the characteristics of combustion reaction region.

The scheme of the ion current probe measurement is illustrated in Fig. 5. The ion current probe consists of a sensor and a reference electrode, which were made up of 0.1 mm diameter and 2.0 mm long platinum wires with high temperature resistivity, anti-oxygenic property and good conductivity, set to be parallel with each other approximately 1.0 mm apart.

As shown in Fig. 6, the current signal of pure propane-air flame started about 49.1 ms after ignition

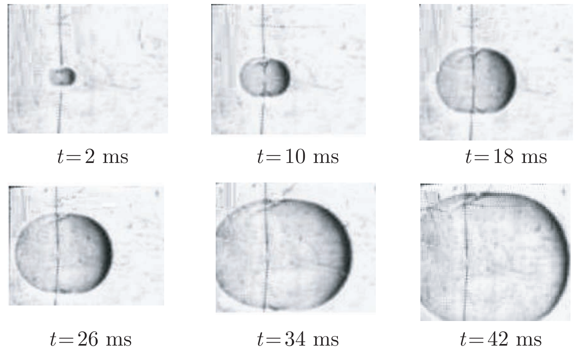

Fig. 2. Explosion flame propagation based on high speed schlieren photographs.

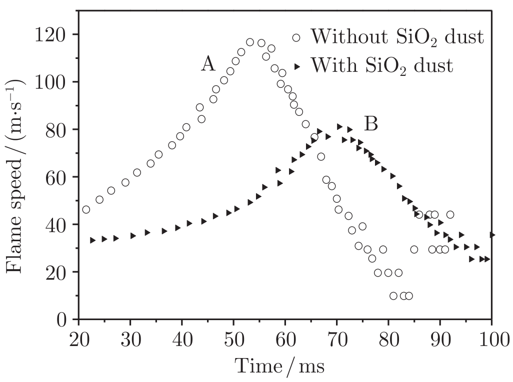

Fig. 3. Gas explosion flame speed variation with time.

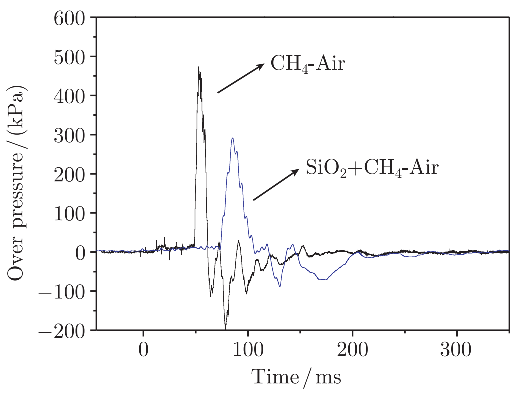

Fig. 4. Gas explosion pressure variation with time.

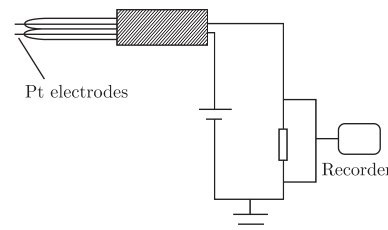

Fig. 5. Sketch of ionization current probe.

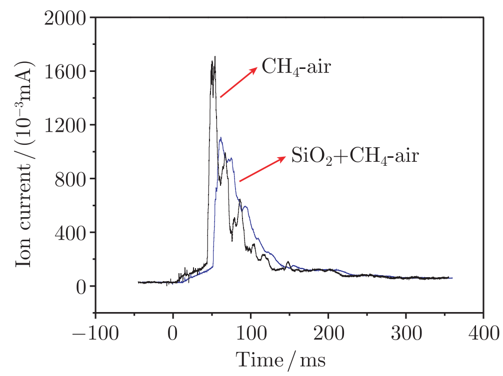

Fig. 6. Combustion reaction intensity variation with time.

and reached the peak value at 53.6 ms. Thereafter, the ion current value fell sharply when the chief combustion reaction was accomplished. At about 60 ms after ignition, obvious fluctuations appeared on the curve. According to the turbulence combustion theory and relevant literature, the fluctuation in the descending stage of ion current curve arises mainly from vortex combustion, which means that the combustion reaction is strong enough. When sprayed with SiO_2 powder, the peak value of ion current dropped to no more than two thirds of that of pure gas flame, which indicated that the reaction intensity fell quickly due to the SiO_2 powder suppression effect in reaction region.

Based on the radical chain reaction theory, propane-air explosion reaction produces many free radicals such as [O], [H], [CH_3] and [OH]. According to the ion current curve given above, the fall of combustion reaction intensity can be attributed to the process that the SiO_2 fine powder directly reduced the reaction degree of free redicals in the combustion reaction region. Owing to high specific surface area of fine powders, the fine particles are easy to contact with and absorb free radicals; secondly, the fine particles are more inclined to pyrogenation near the combustion region, all of which provide particles chance to compound with free radicals in the combustion reaction region, reducing thus the free radical concentration.

It can be drawn that the inertial SiO_2 powder does not directly react with the gas explosion flame, but reduces free radical concentration and reactivity character, which in turn depresses the combustion reaction rate, and finally suppresses the explosion flame effectively.

To study gas explosion suppression mechanism by fine particles, SiO_2 fine powders were sprayed to suppress CH_4-Air explosion flame propagation in a 20 L explosion chamber. In the experiment, the inherent reaction mechanism and propagation behavior of the explosion flame were studied in detail. Some conclusions were drawn as follows.

SiO_2 fine powders can distinctly suppress gas explosion. When sprayed with 10-20μm SiO_2 particles, the peak values of explosion pressure and flame speed dropped to no more than two thirds of those of pure gas explosion. In addition, the occurrence time of peak values of explosion pressure and flame speed was delayed greatly (it takes more than 30% time for the explosion pressure and flame speed to reach their peak values).

The inertial SiO_2 particles don't react with CH_4-Air explosion flame, but because of their high specific surface area, the fine particles are easy to contact with and absorb free radicals near the combustion reaction region, which directly reduces the combustion reaction intensity and in turn depresses the explosion flame speed and pressure wave.

In this study, the diameters of SiO_2 powers applied to the explosion suppression were in the range of 10-20μm. To explore the influence of particles size on flame behavior, particles of different sizes will be adopted to extinguish gas explosion flame in further studies.

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