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The roles of foam ceramics in suppression of gas explosion overpressure and quenching of flame propagation

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ABSTRACT

In order to substantially suppress the shock waves resulting from gas explosions in coal mines as well as to reveal the mechanism of explosion flame quenching by foam ceramics, a rectangular explosion test pipe was designed, which has a 200 mm × 200 mm cross-section and is similar in shape to the roadways in coal mines. Explosion flame propagation characteristics in empty pipe and in the presence of Al_2O_3 and SiC foam ceramics were experimentally investigated. To obtain direct observations, the flame propagation was photographed by a high-speed camera. Furthermore, the mechanism of foam ceramics affecting gas explosion propagation was analyzed. The results demonstrate that the foam ceramics attenuate drastically the maximal explosion overpressure by up to fifty percent; the interconnected micro-network structure of the foam ceramics contribute to quenching gas explosion flame and suppressing shock wave overpressure. These important findings hint that, if properly designed and deployed, this material is expected to be developed into a new suppression and isolation technique against multiple and continuous gas explosions that are presently a grave threat to production safety of coal mines across China and the rest of the world.

1. Introduction

Gas explosions pose a grave threat to the production safety of coal mines. As a consequence, it necessitates a research interest on how to effectively and reliably isolate gas explosion flame and shock wave propagation and mitigate the losses subsequent to gas explosion disasters. Domestic and overseas scholars have conducted extensive studies on explosion isolation technologies [1–5] and a variety of flame propagation suppression techniques have been proposed. At present, passive or active explosion-isolation devices are widely applied in coal mines, such as explosion-isolation water tubs and water bags. These devices adopt water mist to quench gas explosion flame propagation by cooling the flame front. Rock dust barrier is also an alternative for flame propagation suppression, which uses inert rock dust to weaken flame propagation. However, due to their operating principle, the present explosion-isolation technologies can only be installed at a distance of at least 60 m away from the ignition source. Furthermore, their disadvantages surfaced as a result of numerous gas explosion accidents that proved these devices could not effectively put gas explosions under control, thus deaths and heavy property losses were caused. Therefore, it is urgent to develop new gas explosion suppression and isolation materials and methods.

In recent years, interest was growing worldwide in investigation of porous media on their roles of gas explosion quenching, and it has emerged as a separate field of study. Porous media may present a wide range of pore sizes, porosities, pore connectivity, and specific interfacial areas between phases. This combination of a variety of length scales and physical properties allows for large thermal, chemical, and mechanical non-equilibrium among and within phases [6]. A shock propagating radially decays rapidly with distance as the energy is shared over an increasing surface area. Shocks traveling in a planar motion, such as in a tunnel, decay at significantly lower levels as they lose energy only at the edges where the wall and shock interface. This rate of pressure decay can be dramatically increased by placing material in the path of the shock. Materials that possess elements of differing shock impedance, the presence of phase boundaries and the ability to absorb energy by work done on producing irreversible changes within the material, are excellent shock pressure attenuators. Porous solid materials possessing these qualities are excellent attenuators of shock waves and therefore of blast [7]. During gas mixture combustion in inert porous media, combustion waves that move upstream or downstream along the system can be observed. The direction of these

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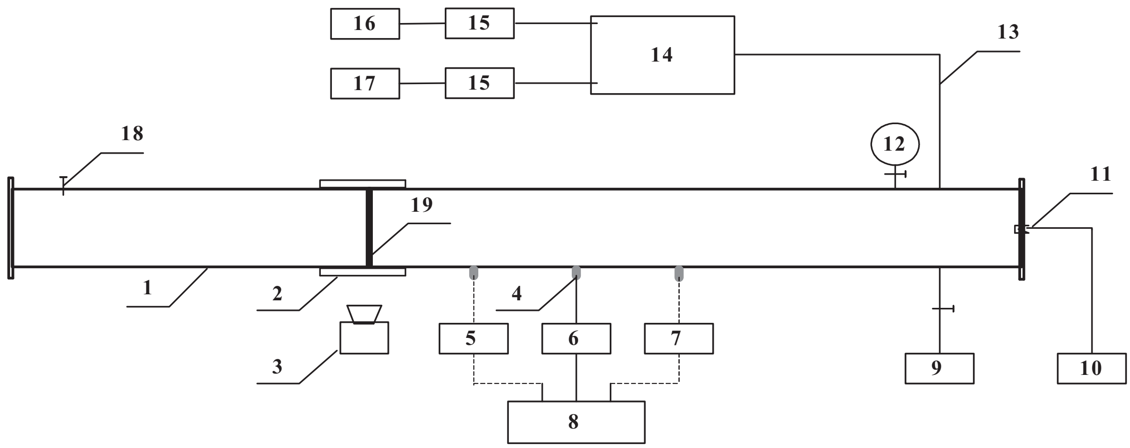

Fig. 1. Schematic of gas explosion experiment system. (1) Explosion pipe; (2) glass window; (3) high-speed camera; (4) sensors; (5–7) pressure measuring system; (8) dynamic data acquisition system; (9) vacuum air pump; (10) igniter; (11) spark plug; (12) vacuum gauge; (13) high-pressure hose; (14) gas distribution cabinet; (15) flowmeter; (16) methane; (17) compressed air; (18) air vent; (19) foam ceramics.

movements depends generally on the physical properties of both solid and gas as well as the initial speed, temperature and excess air of the mixture. Conjugating these parameters, movement speeds of said waves are achieved that are much lower to those of gas and the temperature profiles showing a very pronounced maximum in the reaction region [8].

The findings of Van Wingerden and Zeeven [9] indicated that lining of 50 mm compressible glass cotton in the experiment container could suppress the pressure peak arising from combustible gas explosion. Vasil'ev [10] experimentally discovered that in some scenarios, porous materials can significantly attenuate the pressure wave intensity, and the energy-absorption materials lined on the pipe walls can effectively suppress detonation waves. The main result of the previous work was that of Babkin et al. [11], where five of the six steady combustion regimes were identified and they proposed the following flame propagation mechanism for the high velocity combustion regime: "A positive feedback between flame acceleration and turbulence production (the flame acceleration causes turbulence, which leads to flame acceleration) is damped by local quenching of the chemical reaction due to intense heat exchange in the turbulent zone. If the characteristic time of thermal relaxation becomes less than that of chemical conversion, the flame will be quenched, since turbulent flow contains a spectrum of instantaneous gas velocities, those parts of the flame moving with maximum velocities will be quenched, resulting in a stable velocity of flame propagation."

There are reports that the placement of porous medium in combustible liquid pipe can inhibit explosions caused by chemical reactions [12]. So far, however, few reports are yet found in literatures on porous materials that contribute to suppress multiple and continuous gas explosions in coal mines. The influence of foam ceramics on gas explosion flame propagation will be experimentally revealed in this paper to develop a possibly new gas explosion suppression and isolation material and method in coal mines.

2. Experimental apparatus and procedures

2.1. Experimental apparatus

The methane explosion experiment system consists of explosion pipe, gas distribution system, ignition system, data acquisition and analysis system, pressure measuring system and high-speed camera. The experiment pipe is a rectangular pipe with 200 mm × 200 mm internal section, has 18 m length and 10 mm wall thickness and can withstand pressure up to 15 MPa. The pipe is similar in shape to the roadways in coal mines. Another advantage of such shape is that it allows an observation window to be mounted and flame propagation to be directly observed by a high-speed camera. In this experiment, eleven test points are chosen, at which pressure sensors are mounted. The pipe is placed on a support located 500 mm above the ground. The explosion pressure sensor is 211B4 piezoelectric sensor made by Kistler Instrument Ltd. of USA. Its outer shell is made of stainless steel, its response time is less than 2 μs, maximal measuring range is 200 psi (or 1.3789 MPa) and its sensitivity is controlled at 28 mV/psi. An observation window across the section is put in place, used to capture the entire flame propagation at high speed. Its schematic is shown in

Fig. 2. Gas explosion pipe and gas mixing system.

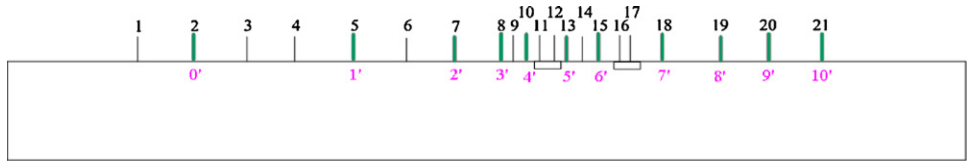

Fig. 3. Positions of 11 pressure sensors (0′, 1′, . . ., 10′).

Fig. 1. Fig. 2 illustrates the physical arrangement of the experiment system. Fig. 3 demonstrates the layout of pressure sensors.

The ignition device releases 70 J energy each time at a frequency of 6–12 times/s, used along with 3 W–4 A model DC regulated power supply. The high-speed camera was manufactured by RedLake Ltd. in USA, which can achieve acquisition rate up to 100,000 frames/s and resolution of 1504 × 1128. By constantly shooting the photos of flame passing the window, the contour and structural change of the flame can be visually observed, and the propagation velocity of the flame front can be computed as well.

2.2. *Experiment procedures*

The experiment was conducted when the mixture was ignited on the front end, the latter end was confined and methane was at a concentration of 9.5%. In two scenarios: (1) methane/air mixture is fully filled in empty pipe; (2) methane/air mixture is fully filled in the pipe in the presence of foam ceramics (the foam ceramics is placed 10.338 m away from the ignition point).

The Al_2O_3 and SiC foam ceramics used in the experiment are both porous material that can resist high temperature up to 1600 °C. The pore diameters of the two materials are: 10 ppi (big pore), 20 ppi (middle pore) and 30 ppi (small pore), (note: ppi means the quantity of pores per inch, the larger ppi, the smaller pore diameter), respectively, with sizes of 200 mm × 200 mm × 15 mm, 200 mm × 200 mm × 30 mm and 200 mm × 200 mm × 50 mm, respectively, porosity of 80–90%, and density of 0.45 g/cm^3, as shown in Fig. 4.

3. Experiment results and analysis

3.1. *The characteristics of gas explosion flame propagation in the absence of obstacles*

For the comparison purpose, Fig. 5 illustrates the photos shot by the high-speed camera for full 9.5% methane/air mixture explosion in empty pipe. The photographing speed is 1000 frames/s, and the resolution of the photos is 1024 × 768. Twenty typical images are displayed here.

These pictures show that, at 3 ms the flame front appears on the window. At 40 ms, the flame is the brightest, which hints the chemical reaction is the most violent, the concentration of free radicals is the largest, and the flame temperature is the highest at this time. Then, the flame fades out, hinting chemical reactions become weaker and weaker and gas mixture have been used up.

3.2. *The influence of foam ceramics on explosion flame propagation*

Fig. 6 illustrates the images about the motions of gas explosion flame for full 9.5% methane/air mixture when 50 mm Al_2O_3 foam ceramics at 30 ppi (small pore) was placed at 10.338 m away from the ignition point (just in the middle of the window). Foam ceramics is represented by a black bar in Figs. 7–9. Photographing speed is 2000 frames/s, and the resolution of the photos is 1024 × 768. Fifteen typical images are displayed below.

It is noticeable from Fig. 6 that the flame front appears in the window at 1.5 ms. Then the flame becomes brighter and brighter. At 20.5 ms the flame front arrives to the surface of the ceramics. At 25.5 ms, the flame is the brightest. Afterwards, the flame seems to reside on the surface of the ceramics and does not penetrate it.

The images illustrate that the foam ceramics can somewhat suppress the flame propagation. Compared with the corresponding experiment as shown in Fig. 5, in case foam ceramics is absent, the propagation velocity of the flame on the observation window is about 50 m/s, whilst, when foam ceramics is put in place, the velocity rapidly decreases to 11 m/s or so. It is evident that the flame propagation velocity in the presence of Al_2O_3 foam ceramics significantly drops, which indicates that presence of foam ceramics in the pipe can suppress flame propagation. The placement of foam ceramics clearly influences the gas dynamics behavior.

In order to further validate the roles of foam ceramics in gas explosion flame suppression, other experiments, where foam ceramics with different porosities and thicknesses are placed, were separately performed. The gas explosion propagation was found to be similar to those shown in Fig. 6. The foam ceramics can likewise suppress explosion flame propagation.

3.3. *Influence of foam ceramics on gas explosion overpressure*

Gas explosion max-overpressure reflects the energy distribution of explosive waves in their propagation process. Extent of

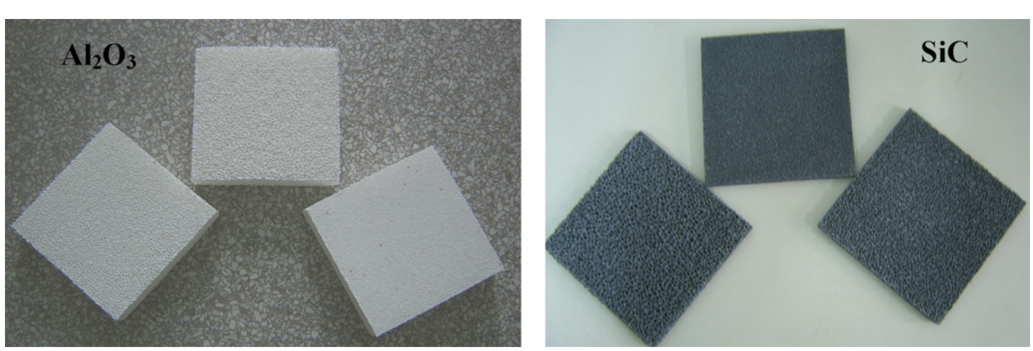

Fig. 4. Al_2O_3 and SiC foam ceramics.

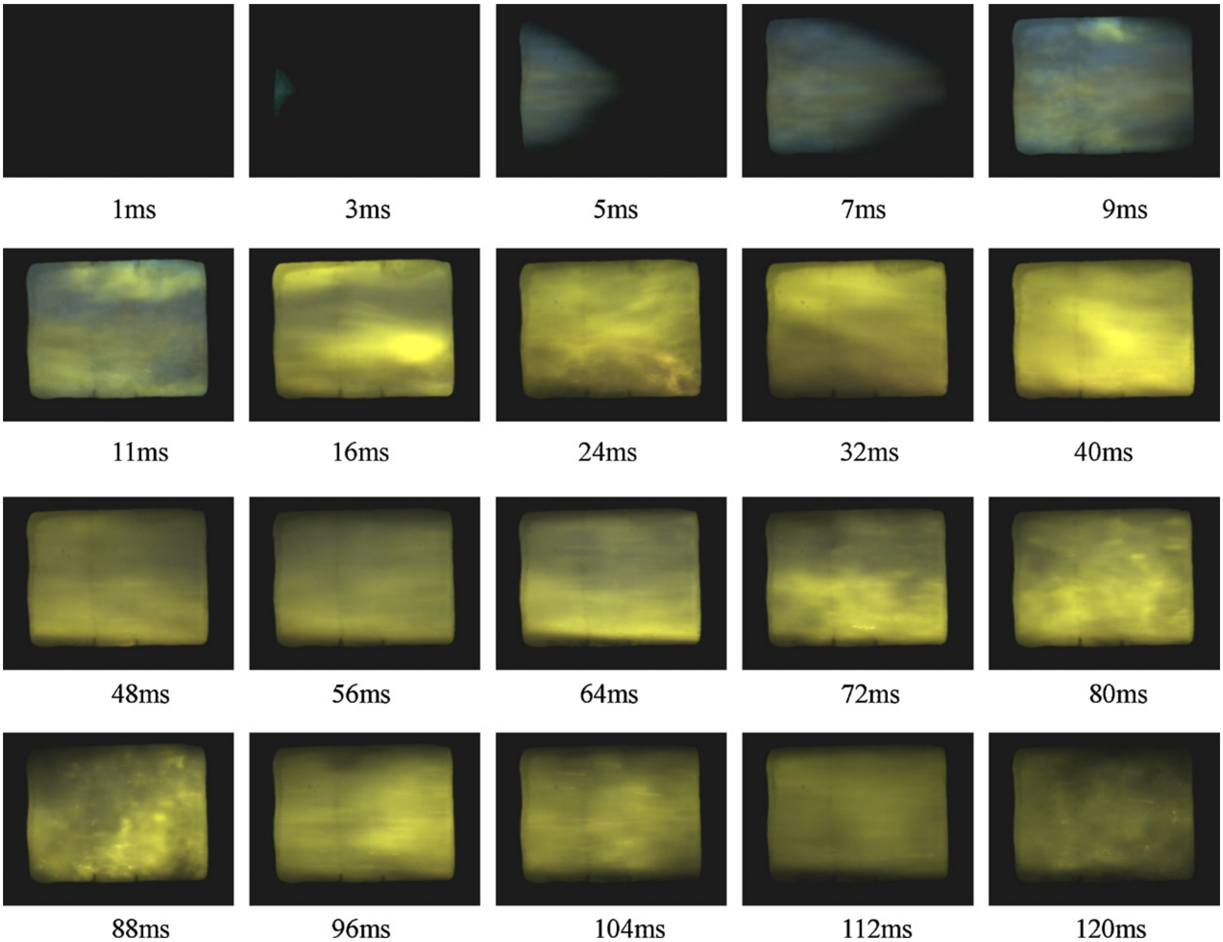

Fig. 5. Explosion flame propagation images of full methane/air mixture in the pipe.

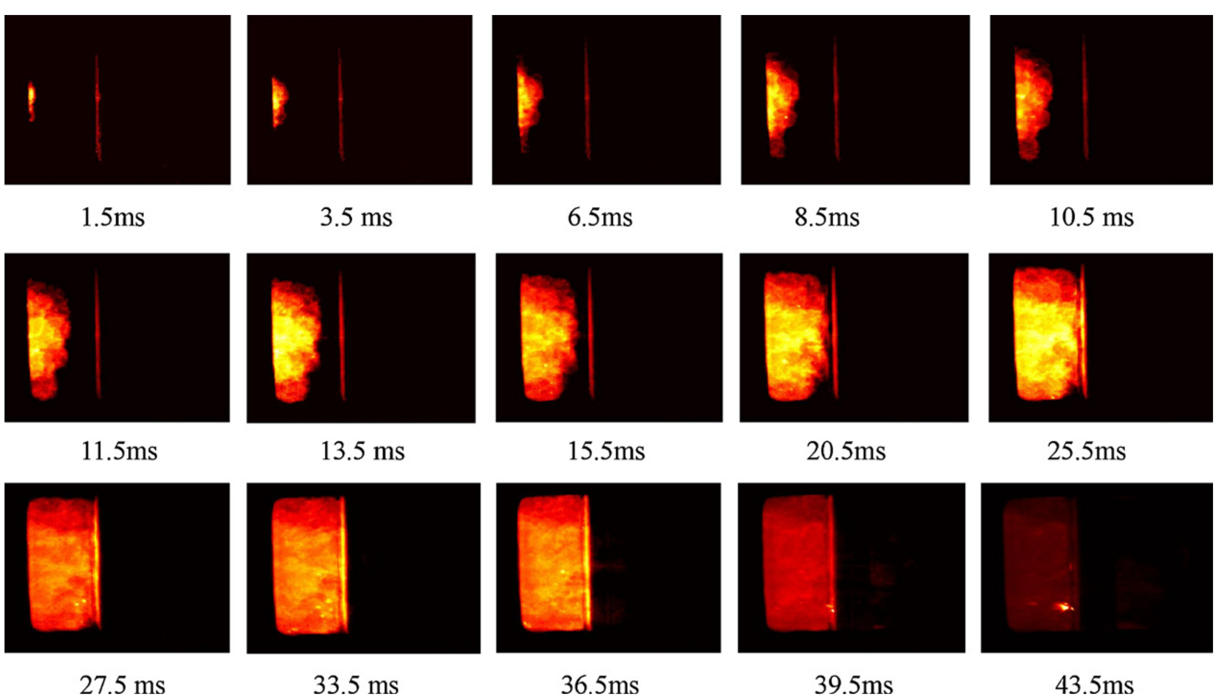

Fig. 6. Explosion flame propagation images in the presence of Al_2O_3 foam ceramics at 50 mm thickness.

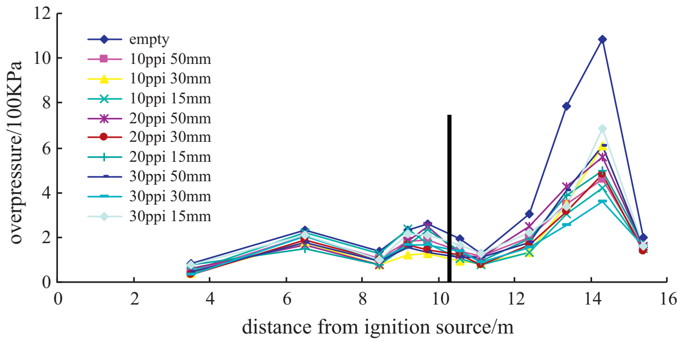

Fig. 7. Effect of Al_2O_3 ceramics on max-overpressure.

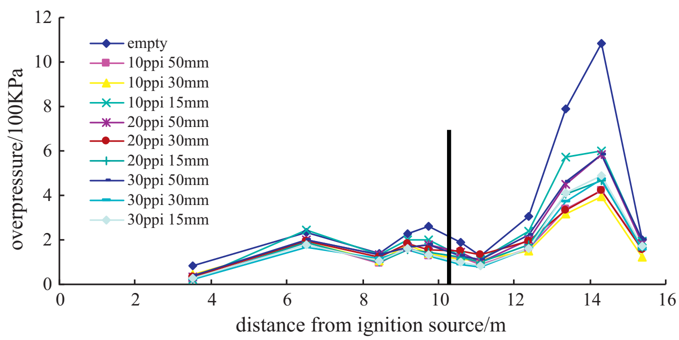

Fig. 8. Effect of SiC ceramics on max-overpressure.

attenuation of max-overpressure can approximately represent the suppression effect of foam ceramics on explosive wave energy. Figs. 7 and 8 illustrate the distribution of max-overpressures along the pipe in the experiments of empty pipe and in the presence of Al_2O_3 and SiC. It can be found that, whether in the empty pipe or in the presence of foam ceramics, max-overpressure in the latter section of the pipe is generally higher than that in other locations. In the empty pipe, max-overpressure on the four test points in the latter section of the pipe ranges from 200 kPa to 1.084 MPa; max-overpressure at the point of 14.31 m from the ignition source is the largest, being 1.084 MPa in the empty pipe experiment, and being 519.44 kPa, 507.61 kPa and 659.63 kPa in the presence of 50 mm, 30 mm and 15 mm Al_2O_3 ceramics, respectively, and being 590.71 kPa, 467.35 kPa and 598.86 kPa in the presence of SiC ceramics of three thicknesses, respectively. Max-overpressure drops by about fifty percent, which suggests that foam ceramics drastically attenuate explosion max-overpressure.

Fig. 9. Picture of Al_2O_3 ceramics showing length scale indicators.

4. Gas explosion suppression mechanisms of foam ceramics

4.1. Micro-characteristics of foam ceramics

Fig. 9 illustrates the structure of Al_2O_3 foam. It can be seen that, the foam ceramics consist of pore and strut. The strut is composed of the triangular pore on the strut center and surrounding porous pore walls. The strut wall is characterized by three-dimensional interconnected network structure similar to foam. Moreover, foam ceramics are equipped with uniform pore channels, relatively regular crystalline grains and compact sintering. The spatial skeleton structure is three-dimensional network structure, with sound connectivity and large porosity. The large specific surface area hints increased heat dissipation. These characteristics play an important role in gas explosion suppression.

4.2. Possible mechanisms of foam ceramics' flame propagation suppression

According to literatures, the flame propagation suppression may result from several factors. When flame propagates in narrow gaps or channels, if the interval of the gaps or the diameter of the channels is adequately small, the flame will automatically extinguish after it propagates for a certain distance within them, which is known as quenching. Foam ceramics is a kind of porous medium. When flame passes through the micro-channels of the ceramics, the wall effect will result in abrupt reduction of free radicals involving in combustion and terminate the chemical reactions. Moreover, numerous honeycomb "cells" are available in the ceramics, combusting flame has to penetrate these "cells" and exchange heat with the pore walls of the ceramics. Consequently, the heat dissipates through the pore walls and adjoining structures, thus the flame temperature quickly drops below quenching temperature, quenching occurs and flame propagation is suppressed [13]. A likely explanation is that as soon as the combustion front attempted to completely enter the porous media, it was quenched by the very effective radiative heat transfer from the solid [14].

4.3. Mechanism of foam ceramics attenuating explosion wave

Foam ceramics can suppress the transverse waves generated from gas explosions. What detonation waves can self-sustain attributes to generation and development of transverse waves. Foam ceramics have a large quantity of networked pore structures. When explosive shock waves are incident on their surface, a majority of the shock waves will enter the interior of the foam ceramics along "labyrinth" pore channels, propagate within the pores and give rise to vibration of the air in the pores, and be frictional with very coarse ceramic struts on the surface of the pores. Some acoustic energy is converted into thermal energy, and some reflected into the foam ceramics when it arrives to the rigid walls, shock waves will re-enter the pore channels and cause the air to be frictional with the ceramic struts, thus acoustic energy being continuously converted and consumed. Interaction of the two effects allows the foam ceramics to effectively consume the incident acoustic energy and to markedly suppress the generation and development of transverse waves.

5. Foam ceramics in larger practical applications

From the above experimental findings, we have found the foam ceramics is a promising material. If properly designed and arranged,

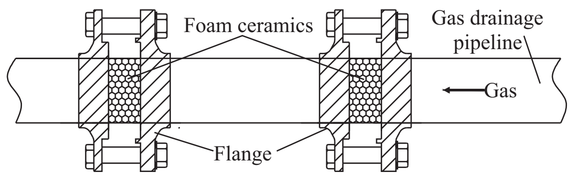

Fig. 10. Schematic of foam ceramics isolating explosion in gas drainage pipeline.

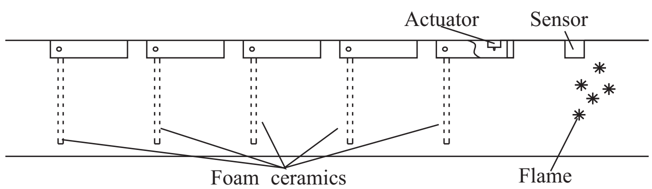

Fig. 11. Schematic of foam ceramics in roadways at normal time and at accident.

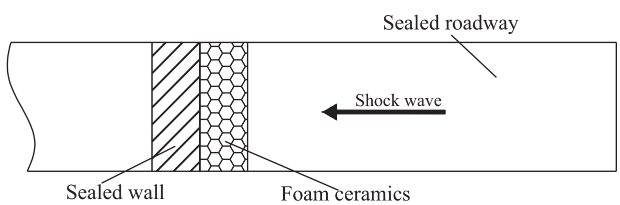

Fig. 12. Schematic of foam ceramics in sealed roadway.

the material is likely to be developed into a new gas explosion suppression and isolation device in coal mines. Some typical layouts in coal mine are supposed, as illustrated below.

In case of any breakage, gas drainage pipeline is prone to combustion or explosion because of the presence of high concentration gas. Placement of foam ceramics at intervals can suppress flame propagation and prevent flame and shock wave spreading into other roadways, as indicated in Fig. 10.

Foam ceramics are designed into curtain-like device and suspended on the roof of roadway (solid line). When the sensor ahead detects the flame or pressure change, it will send signals to the actuator that swiftly pushes the foam ceramics down to cover the whole roadway cross-section, as shown in Fig. 11 (dotted lines). In real mine shaft, gas explosions are more violent than in experiment pipe, so it is appropriate to arrange several layers of foam ceramics, as indicated in Fig. 11.

Coal gas accumulates in sealed roadway. In case of air leakage, proper oxygen concentration is formed and explosion limit is reached, explosion is highly possible within the sealed roadway. In such case, shock wave may destroy the sealed walls. Provision of foam ceramic ahead of the sealed wall can damp the shock wave and protect the sealed wall, as indicated in Fig. 12.

6. Discussions

However, before its practical use in real coal mine roadway, there are some problems to be addressed in our future experimental research.

(1) The experiments found 50 mm foam ceramics (the thickest one used in our experiments) can withstand the shock waves and basically be kept intact, the 30 mm one comes the second, and the 15 mm is the poorest. It seems one layer of such foam ceramics cannot withstand multiple and continuous impact by the shock waves in the gas explosions in real mine roadway. How to design such device for practical use in coal mines? How many layers of such foam ceramics are optimal in suppressing flame propagation and attenuating shock wave overpressure, especially when the large transient dynamic loading of the leading shock wave is taken into account? Perhaps its use together with other present devices in coal mines should be verified.

(2) In our present experiments, we only tested the performance of the foam ceramics in suppressing pure gas explosions. But in fact, if the coal dust is carried along by natural ventilation and penetrates into the foam and the pores be blocked, would its explosion suppression performance be compromised subsequently? Our preliminary idea is to design the material into a curtain-like device, which is normally "hidden", to avoid blockage. Or if multiple and continuous gas explosions occur and coal dust is carried into the pores, what change will its performance have? These are the focus of our future experiments.

7. Conclusions

(1) Experimental investigations of Al_2O_3 and SiC foam ceramics have been conducted for their influence on gas explosions. The results suggest that, due to their distinctive structures, foam ceramics can significantly attenuate gas explosion max-overpressure by up to fifty percent. When the flame penetrates the micro-channels of the foam ceramics, it produces wall effect with the pore walls, which makes the flame temperature quickly reduce below the quenching temperature, and thus effectively suppresses flame propagation.

(2) Some possible mechanisms attributable to flame suppression and overpressure attenuation are explored. Chain reaction theory, thermal explosion theory and transverse wave suppression mechanism may combine to cause flame extinction, which need further validation experimentally.

(3) A host of larger practical applications in coal mine are supposed. If experimentally proved feasible in real roadways, foam ceramics can be developed into a new suppression and isolation technology against multiple and continuous gas explosions in coal mines.

Acknowledgments

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