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UNDERGROUND MINE GAS EXPLOSION ACCIDENTS AND PREVENTION TECHNIQUES – AN OVERVIEW

Mine gas explosions present a serious safety threat in the worldwide coal mining industry. It has been considered the No.1 killer for underground coal mining workers. The formation of an explosive atmosphere involves various factors. Due to complicated stratified geology and the coal production process, geological conditions and coal production process reasons and particular working sections underground present a high risk of an explosion that would most likely cause casualties and property loss. In this study, the basic conditions, propagation law and hazards analysis of gas explosions are reviewed, followed by a review of the typical locations where an explosion would occur. Finally, current technologies used in the mining industry for preventing gas explosions and suppressing the associated dangers were studied. Preventive gas explosion technologies mainly include gas drainage, gas accumulation prevention and gas and fire source monitoring technologies. The technologies often used to control or mitigate gas explosion hazards are usually divided into active and passive, and the advantages and disadvantages of each method are discussed and compared. This paper aims to summarise the latest technologies for controlling and suppressing gas explosion and guides mining engineers to design risk mitigation strategies.

Keywords: Coal mine explosion, Explosion protections, Control, Overview

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1. Introduction

Underground mining is often carried out to produce coal. For example, underground mines in China, at present, have an average depth of nearly 500 meters, which is increasing by an average of 8-10 meters per year. The occurrence of coal seams and conditions for underground mining is complex, the gas content in coal seams can be relatively high, and more than 50% of the coal seams contain a high content of gas. With the increase of the mining depth, the gradual increase of the gas pressure in the coal seam resulting in an upsurge in the amount of gas emission, and major malignant gas explosion accidents can occur from time to time. In most cases, coal mine explosions initially start with the ignition of the underground combustible gases caused by the violent oxidation between methane and oxygen. The characteristics of a gas explosion are affected by various factors such as the type and the concentration of mixed combustible gas, temperature and pressure. Therefore, it is particularly important to study the characteristics of a gas explosion under different conditions. In this study, the basic conditions and hazard analysis of gas explosions are reviewed. It concludes by summarising preventative and suppressive gas explosion technologies.

2. Mine gas explosion

2.1. Gas explosion conditions

The gas explosion must have three conditions at the same time:

(1) At a certain concentration, the gas will explode in a certain concentration range, the limit of gas explosion such as methane is generally set at 5%-15% in practical engineering. However, in some special cases, due to the presence of other combustible gases, the mixing of coal dust, the participation of inert gas and the initial temperature and pressure of the mixed gas, the boundary of the gas explosion limit is not constant (Gao et al. [1]).

(2) Enough oxygen concentration, if there is not enough oxygen content, a gas explosion will not occur. The gas explosion limit decreases with the reduction of oxygen concentration in the air. When the oxygen concentration in the air is diluted, the upper explosion limit will clearly drop. In practical engineering, when the oxygen concentration in the air is more than 12%, the gas will explode because of the sufficient oxygen content (Kundu et al. [2]).

(3) The ignition temperature of a certain ignition source is the lowest temperature needed to ignite the gas. And the ignition energy for gas is the lowest energy needed to ignite the gas. In practical engineering, the ignition temperature of the gas in the air is 637°C-750°C, and the minimum value of gas ignition energy is 0.28 mJ (Kundu et al. [3]).

2.2. Basic Propagation Pattern of Gas Explosion

A gas explosion can generally be divided into two states, namely deflagration and detonation. When the gas in the pipe is ignited, the forward movement of the formed flame is accelerated (Lin et al. [4], Jiang et al. [5]). Due to the exothermic combustion, the gas expands so that a pressure wave propagates at a subsonic speed and is formed ahead of the combustion front, and the superposition of the pressure wave results in a shock wave (Lewis, Elbe [6]). Such an explosion of combustible gas composed of a combustion wave and a shock wave is referred to as deflagration. When there is a sufficient amount of gas, the deflagration continues to accelerate so that the overpressure of the precursory shock wave gradually increases and the explosive gas drastically compresses, thus lead to a process in which temperature increase rapidly, after that a fierce chemical reaction is set off, which referred to as detonation (Zhang et al. [7]).

2.3. Hazard of gas explosion

The harmful factors produced by the gas explosion are mainly flame front, shock wave, and toxic and harmful gases (Ivanov et al. [8], Wang et al. [9], Tomizuka et al. [10], Pang et al. [11]).

1) High temperature

Studies have shown that when the gas concentration is 9.5%, the instantaneous temperature generated during an explosion can reach 1850-2650°C. Such high temperatures will not only injure people and damage equipment but may also ignite wood, supports and coal dust, then causing catastrophe situations such as fire and coal dust explosion accidents.

2) High pressure

The sudden increase of the gas temperature during the explosion will cause the gas pressure to build suddenly, thus forming a high-pressure shock wave through experimental and theoretical calculations. The gas pressure after the gas explosion is 7-10 times bigger than before.

3) Toxic and harmful gases

After the gas explosion, the amount of oxygen was greatly reduced, and a large amount of toxic gas was generated (He et al. [12]). According to the analysis, the gas composition after the gas explosion is as follows: oxygen 6%-10%, nitrogen 82%-88%, carbon dioxide 4%-8%, carbon monoxide 2%-4% (up to 6%) (Cui et al. [13]).

3. Recognition of Mine Gas Explosions Hazard in underground coal mine

A gas explosion often requires three components that must exist simultaneously, namely, a combustible gas, oxygen and a source of ignition (Meng et al. [14]). The combustible gas often refers to methane in an underground coal mine (Cheng et al. [15], Cheng et al. [16], Cheng et al. [17], Geretto et al. [18]). Due to the coal production, the coal seam is gradually mined out, and methane continually emits into the underground working sections, which causes a high explosion risk that mineworkers suffer in some regions. The following sites in the underground locations are the most likely where an explosion could take place (Ghosh, Wang [19]).

4. Mine Gas Explosions Prevention and Control

There are mainly three approaches to prevent and control mine gas explosion, namely avoiding gas accumulation and overrun, preventing gas ignition and inhibiting the further expansion of gas accidents. Gas explosion prevention and control technologies mainly include preventive

TABLE 1

locations where an explosion could take place

Locations	Explanations	Case
Underground Working Faces or inside the Driving Face	The mining work is advancing	the Upper Big Branch (UBB) mine in 2010 in the US (Davis et al. [20])
Tunnels with Electrical Equipment	The underground chambers and some tunnels are often used to place electrical equipment	the Tunlan coal mine gas explosion in 2009 in China (Cheng, Wei [21])
Mine Gob Areas	The mined-out area when the coal seam is extracted	an explosion occurred in the sealed A Left Section of the Darby Mine No. 1 of the US
Manual Blasting Place of Mine	Manual detonation for loosening and crushing mines as well as coal and rock masses on the site	a major gas explosion occurred in Baijiagou Coal Mine, Faku County, in 2008, in China (Li [22])

and suppressive technical measures. Preventive technical measures optimise ventilation networks and systems, prevent gas accumulation, conduct gas drainage and strengthen the monitoring of gas and fire source to avoid accidents. Suppressive measures are primarily designed to limit or control the propagation of gas explosion waves. According to the different suppression methods, the suppressive technical measures can be divided into active and passive ones. The active technology is that the explosion wave directly triggers the action of the explosion suppression device; the passive technology is triggered by the explosion pressure or flame signal detected by the sensor of the explosion suppression device.

The following sections are going to discuss the prevention and control methods used in coal mines.

4.1. Preventive Measures for Gas Explosion Accidents

4.1.1. Gas Drainage Technology

Gas drainage is not only a fundamental solution to gas emission from mines and gas explosions, but also an important means of developing and utilizing gas energy as well as protecting the atmosphere. Wang classified gas drainage technologies into different types according to different locations, principles and roadway layouts. According to the source, the methods can be divided into the drainage in the mining layer, adjacent layer, goaf and surrounding rock. According to the principle, it can be classified into gas drainage in the non-gassy coal seam, the gassy coal seam for mining and the coal seam where the pressure is artificially drained. According to the relationship between gas drainage and mining time, it can be divided into gas drainage during and after mining. According to the drainage process, it can be divided into borehole drainage, roadway drainage and mixed drainage via borehole and roadway. According to the drainage construction location, it can be classified into ground drilling gas drainage and underground gas drainage. To improve the gas drainage efficiency, new gas drainage technology and equipment should be improved and developed.

4.1.2. Prevent gas accumulation and overrun

Gas accumulation and overrun during coal mine production are major hidden dangers threatening the safe production in the mine (Moridis et al. [23]). Gas accumulation is most likely to occur temporally and spatially in the part where the mining machine blasts the coal in the mining face, the drilling rig sees the coal or the gas source, during the process of coal blasting, in the downstream wells where the gas is drained, in the top-coal caving region, within the confined areas and poorly ventilated areas (including corner areas), in the blowing-out and windless areas (including the blowing-out area in a dead-end roadway) and positions itself with the gas emission, a sudden outflow of large amounts of gas and outbursts of coal (Wang et al. [24]). The principle of preventing gas accumulation and overrun is to maintain good ventilation, timely deal with locally accumulated gas and strengthen the inspection of gas concentration. In fact, with diverse geological conditions and coal seams, there are big differences between various mines when it comes to gas accumulation and overrun. When solving related problems, a specific analysis should be conducted with scientific-based methodologies adopted (Zhang et al. [25]).

4.1.3. Ventilation Methods

The mine ventilation system is composed of the ventilation network, main fans and ventilation structures. Due to the influence of the environment and mining activities, the ventilation system constantly changes, which will affect the mine ventilation capacity and ventilation reliability. With the development of science and technology, mine ventilation automation is improving. An example of this is the CTT63 / 43 automatic monitoring system, which can effectively deal with safety hazards; the combination of refrigeration and cooling technology with ventilation system can improve the operation efficiency; the mine ventilation management system based on Visual C++ 6.0 can simulate and calculate the situation; the technology of ventilation and dust removal can be enhanced by installing a dust collection device with the combination of a Coanda type air duct in the working face. The commonly used ventilation methods in China include partition ventilation, checkerboard ventilation, comb ventilation network, local ventilation, etc. In recent years, the development of multi-stage fan station technology, energy-saving fan and network energy-saving optimisation control and other ventilation methods improve the efficiency and safety of underground ventilation. The more accurate and intelligent automatic ventilation system has become the main research direction (Cao [26]).

4.1.4. Stoppings and Seals

The stoppings and seals are used as ventilation control devices, which usually placed to isolate goaf, fire zones and areas susceptible to spontaneous combustion. In America, ordinary seal construction practice was to construct two solid block stoppings about 0.3 ~ 0.6m apart with concrete, earth or sand-filled in between. The standard seal design is illustrated in figure 1. Materials of stoppings and seals required non-combustibility, and their average flexural strength must be at least “39 pounds per square foot” for three walls. The impermeability is an important factor that must be considered in their design — in other words, the ability to prevent or reduce the exchange of gases from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after the explosion tests and compared to Mine Safety and Health Administration (MSHA) established guidelines: for pressure differentials up to 0.25 kPa, air-leakage through the seal should not exceed 2.8 m^3/min; for pressure differentials over 0.75 kPa, air leakage should be less than 7.1 m^3/min. Besides, the seal must meet an explosive rating of 140kPa (Gillies, Wu [27]).

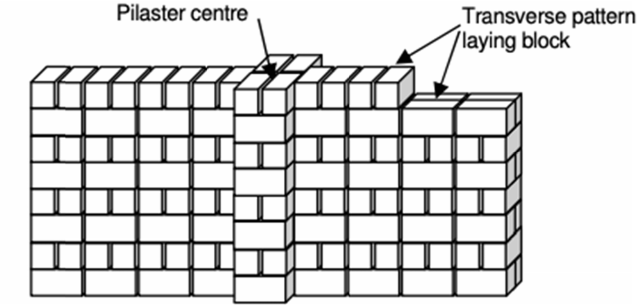

Fig. 1. Standard type, solid-concrete-block seal

4.1.5. Pressure Balancing

The pressure balancing method is reducing oxygen supply by reducing air leakage to make a high-temperature area or fire area stop oxidation. In coal mining face, combined pressure balancing of fan and air window can inhibit the oxidation of residual coal in goaf. Adjusting air window, balancing air chamber or connecting pipe can adjust the pressure difference inside and outside the closed wall. However, complex ventilation systems, personnel and mining activities may destroy the pressure balanced state, resulting in air leakage in goaf or fire areas. The new balance can only be achieved through artificial adjustment. However, if the pressure adjustment is not accurate, timely or the pressure balancing effect is not ideal, the air leakage can not be effectively controlled. It is one of the important research directions of intelligent mine to adjust the pressure balance quickly and accurately as well as maintain the balance state. The automatic control pressure balancing fire prevention and extinguishing system can realise the automatic control and adjustment of fan speed and adjust the area of wind window air outlet so that the pressure-balancing area can always maintain a pressure balance and effectively improve the pressure equalising effect.

4.1.6. Gas Concentration and Fire Source Monitoring Technology

4.1.6.1. Real-time Automatic Monitoring of Gas Concentration and Fire Source

Real-time automatic monitoring of gas concentration and fire source is crucial to prevent gas explosion (Cheng et al. [28], Wang et al. [29]). For example, figure 2 shows the structure of a goaf coal spontaneous combustion monitoring system. The initial state of the probe is the dormant mode, which can reduce energy consumption. A clock controlled system interrupt generator sends the interrupt wake-up command to make the probe into the normal operating mode. After that, the probe detects the current position point temperature and then converts it from analogue to digital before sending it out, according to the corresponding wireless transmission protocol. The probe also has a routing function where data will be passed out fast and accurately from the goaf to the wireless receiving station and transmits it to the ground control centre (Qin et al. [30]). As for methane, a monitoring system based on ZigBee, with methane sensor nodes and controllers, has been tested. The sensor detected methane and sent voltage to carry on A/D conversion. Then the node would alarm, display and transmit data to its controller, which will transmit data to the monitoring station by CAN bus. The results show that all errors are less than 0.05%, which are acceptable to the rules for error in a coal mine (Liu et al. [31]).

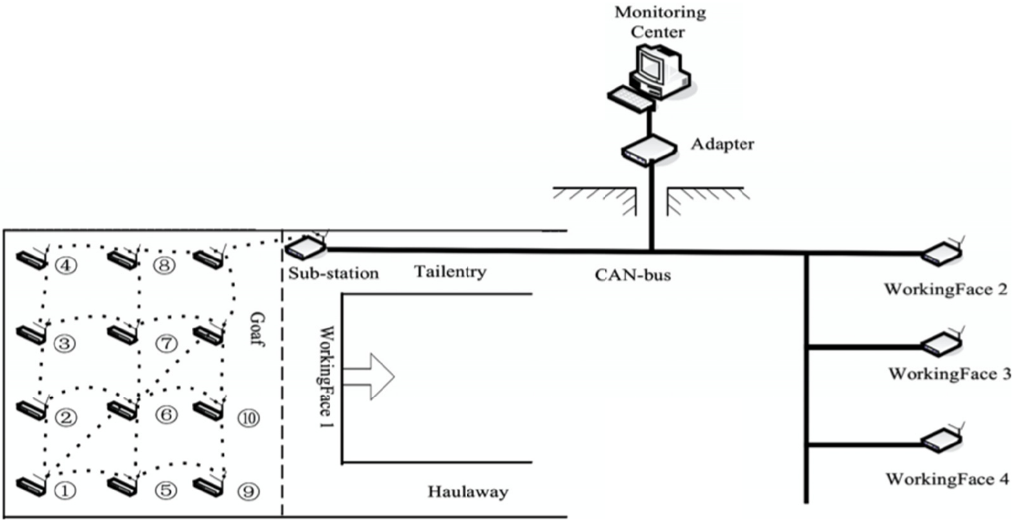

Fig. 2. The structure of goaf coal spontaneous combustion monitoring system

Most fire disasters and gas explosions occur because the gas concentration reaches the explosion limit. When the concentrations in different components reach the explosion limit by calculation, it means that the mine is currently in a dangerous state where an explosion may occur at any time. Hence, the gas concentration in the downhole air exerts a crucial impact on predicting the downhole safety status.

4.1.6.2. Underground Fire Source Control

A series of measures should be taken to prevent and control high-temperature heat sources in coal mines, such as blasting sparks, mechanical shocks and so on (Shao, Ma [32], Li et al. [33], Guo, Zhang [34]). In addition, fire sources and gas accumulation must be prevented from appearing together. For example, the gas concentration should be detected before the blasting. With the development of technology, more new materials, e.g. various resins, plastics, liquid fuels and hydraulic fluids, have been used, and the number of electromechanical equipment has been on the rise, which has increased the possibility of mine fires. To prevent gas explosions, first of all, it is important to avoid using flammable materials and eliminate high-temperature heat sources at the same time. Secondly, fire disasters should be monitored, and fire hazards ought to be timely detected. Thirdly, the fire extinguishing system should be established and improved. In addition, the management of open flames should be strengthened, and the fire safety system should be strictly followed to eliminate the sources that might ignite the gas.

4.2. Inhibitory technical measures

4.2.1. Rock dusting

Proper rock dusting in underground coal mines can effectively eliminate the two conditions for coal dust to participate in the explosion. The inert rock dust can function as an isolator, physical heat sink and chemical energy absorber. The heavier rock dust applied over the lighter coal dust can serve as an isolator to prevent the coal dust underneath from becoming easily airborne. The isolator is most likely to function only when the explosion flaming front has not reached the supersonic velocity. If the deposited coal dust is not suspended into the mine air, it is very unlikely for coal dust to reach the lower explosive limit (Harris et al. [35]).

In a methane explosion event, the explosion propagation can quickly become supersonic and thus generates a shock wave. The shock wave is well capable of suspending the settled coal and rock dust into mine air. Under this condition, the suspended rock dust along with the unexploded coal dust can act as a physical heat sink and absorb the heat in the passing hot air, creating a temperature equilibrium between the dust and air. Based on the law of energy conservation, a simplified model can be derived for assessing the heat sink effect of rock dust. For example, a coal dust load is assumed to be 1.2 kg per meter length of a 2 m high and 6 m wide mine entry, so a coal dust concentration of 100 g/m^3 (higher than the coal dust's lower explosive limit) can be created when all coal dust is suspended in the air. To demonstrate the heat sink effect of rock dusting, the entry is dusted with limestone powder at 0.00, 2.23 and 4.80 kg per meter of entry to create 0%, 65% and 80% rock dust concentrations, respectively. The suspended coal and rock dust (originally at an ambient temperature of 16°C) absorb the heat from the hot air and decrease its temperature (Zhang et al. [36]).

Rock dusting has been widely used in major coal-producing countries. However, the quality and quantity standards for the rock dust vary to some degree (Man, Teacoach [37]). The bases for the variations could be related to the coal dust size, methane concentration in mine air, rank of coals, etc. In China, it is required that the incombustible content of combined coal and rock dust must be at least 60% or 90% when the CH_4 concentration is over 0.5%. Besides, rock dust must meet the following quality requirements: (1) the combustible content <5%, (2) the content of free silica (SiO2) <10%, (3) free of any toxic or harmful mixture. The rock dust should entirely pass through a 50 mesh sieve (<300 μm in sizes), and 70% of it passes through a 200 mesh sieve (<75 μm in sizes) (Luo et al. [38]).

4.2.2. Stone dust Barriers

The explosion travels within an underground mine roadway that consists of three stages: slow deflagration, fast deflagration and detonation. The initial laminar flame speed is only 3 m/s, however, with the slow deflagration accelerates, the turbulent flame speed might increase to about 300 m/s (McPherson [39]). The combustion front acts as a piston, compressing the unburned gas in front of the flame front. Between this shock wavefront and the flame front, the unburned gas acquires velocity to the left, and the static pressure inside this region will increase. This pressure increase ahead of the flame front is termed as “pressure piling”.

In the beginning, a stone dust barrier was popularly used to control explosion travelling in the underground roadways. Stone dust barriers are boards supported on pivots across the airway, usually near the roof, and loaded with stone dust. Dust loadings vary from 30 to 60 kg per metre length of the board. Several boards are located close together within a short length airway to form the complete stone dust barrier. The intention is that the boards and their contents will be dislodged by the shock wave of an explosion to produce a high concentration of airborne stone dust at the time the flame front arrives and, hence, prevent its further propagation.

4.2.3. Water mist curtain

Water mist refers to the diameter of water droplets less than 400 μm, which are mainly produced by high pressure when the range of pressure is between 5~20 MPa. A water mist system has been used as a fire protection system for a long time. The small water droplets allow the water mist to be easily controlled, as well as suppress or extinguish fires by: (1) cooling both the flame and surrounding gases by evaporation; (2) displacing oxygen by evaporation; (3) attenuating radiant heat by the small droplets themselves (Linteris et al. [40], Koshiba et al. [41], Cao et al. [42]).

The effectiveness of a water mist system in fire suppression depends on its spray characteristics, which include the droplet size distribution, flux density and spray dynamics.

A reported comparative study (You et al. [43]) shows, by analysing the flame images with/without the application of water mist, the area and brightness of the flame are both weaker when applying the water mist, which means the methane/air mixture explosion is significantly suppressed by water mist.

4.2.4. Closed vacuum chamber

The basic idea of the closed vacuum chamber is to absorb the explosion energy in the burned and unburned gas to the vacuumed man-made chamber for explosion suppression by reducing explosion overpressure and flame propagation velocity in tunnels (Wu et al. [44]).

Currently, it can be used as explosion protection for underground or surface gas pipelines. Also can be used to control the explosion in the tunnels, but care must be taken when engineering the design for this. The chamber is vacuous but sealed by a fragile plane, which can be easily broken by the pressure difference between the inside and outside (Wu et al. [45]).

There are two basic elements for the suppressing effects. One is the suction capacity of the chamber, and the other is the fragile plane which can be broken sensitively. The vacuum chamber should not only have a certain vacuum degree but also have a certain volume. Once the explosive pressure is high enough to break the fragile plane, the chamber decompresses the explosion overpressure. Therefore, the selections of the fragile plane material and control of breaking are also carefully designed and require thorough research (Jiang et al. [46]).

4.2.5. ExploSpot Active suppression system

One of the characteristics of an explosion is the flashlight, which is also a result of the explosion flame. The light travels faster than the flame or overpressure wave, which makes it possible to detect the light intensity to determine the gas explosion. The flame sensor is installed on the system to detect the gas/coal dust explosion at the beginning stage. The physical signal is then interpreted into a digital signal by the sensor for double-checking. Once the digital signal is verified, the high-pressure vessel is triggered by the system. The stored explosion suppressive agent in the container is released instantly to form a physical barrier in the underground tunnels to stop the flame propagation so that the explosion and the generated harmful gases can be controlled within a small region (Späth et al. [47]).

There are two important parameters for the performance of an ExploSpot active suppression system. One is the explosion suppressant agent, where the quantity of agent highly depends on the geometry of underground tunnels and the desired agent distribution density in the air and the scale of the explosion. Insufficient agent released in the underground would not control the spreading of the explosion. The other one is the system jetting pressure, which influences the desistance that the suppressant agent can reach. In other words, the 'thick" of the barrier is initially controlled by the jetting pressure. Therefore, to improve the explosion control effects, technical parameters of the system for different field applications should be optimised (Wang et al. [48]). In addition, materials used to make the agent is also an effective method to improve the control efficiency.

4.2.6. Suppressing Gas Explosion by Fluorinated Fire Extinguishing Agent

The fluorinated fire extinguishing agents mainly consists of two types, i.e. fluorinated halogenated hydrocarbon fire extinguishing agent and fluorinated surfactant fire extinguishing agent. The fluorinated fire extinguishing agent is highly efficient and only require a small dosage. Fluorinated ketone is a macromolecule that decomposes under high-temperature conditions as found in an explosion reaction zone, and the broken chemical bonds can absorb part of the energy produced in the explosion reaction. In addition, it will generate fluorine-containing free radicals that have a gas-phase reaction with active radicals that produce chain reactions during the explosive combustion reaction of methane, thereby interrupting the transmission of chemical chain reactions and suppressing the explosion of methane. From the perspective of the thermal explosion mechanism, the physical-chemical reaction of the gas-air mixture generates the accumulation of heat, which promotes the continuous acceleration of the reaction. As the circulation continues, the gas explosion is triggered once the energy stored in the gas-air mixture exceeds a specific limit. When adding the agent, more heat will be absorbed, which slows down or stops the heat accumulation during the reaction so that the energy will not exceed the threshold above in which the methane-air explosion will be triggered, thereby suppressing the explosion (Deng et al. [49]).

4.2.7. Gas Explosion Suppression Technology

Nitrogen, carbon dioxide, argon and CCl4 are currently the most widespread inert gases, featuring a wide range of sources and low formation (Borowski et al. [50]). The principle and advantages for nitrogen to extinguish the fire and suppress explosion are as follows:

1) Explosion suppression effect: Neither is nitrogen combustible nor does it support combustion. Therefore, when it's exposed to high-temperature fire sources, it does not chemically react with combustible substances or gases.
2) Smothering effect: There is a certain proportional relationship between the content of oxygen and the thermal energy generated during gas combustion. The smaller the oxygen content is, the greater the energy required to trigger a possible explosion. When the oxygen concentration drops below 3%, the combustion will stop.

Explosion suppression technologies such as nitriding and nitrogen injection can quickly control the conditions required for gas combustion, safely and rapidly smother and extinguish gas explosions at the coal mining face.

4.2.8. Explosion-proof and Fire-tight Confinement

Once the gas explosion in the goaf destroys the closed wall used in the goaf for fire and explosion protection, the underground ventilation system will be completely disordered (Zhang et al. [51]).

The explosion-proof and fire-proof closed system aims to prevent related structures of the chamber system from being damaged by the instantaneous high temperature, continuous high temperature and a side explosion shock wave in the fire or explosion accident. The system can also stop toxic and harmful gases from penetrating the chamber. The round log, based on yellow mud, was used to construct the anti-impact wood section wall of the system because of its mechanical properties. The pressure relief opening reserved on the anti-impact wood section wall was tightened by a leather pad, which not only reduced air leakage but also absorbed the energy of an impact event to relieve the damage on the wall. Compared with the traditional brick wall, this wall features greater compressive strength, prevents air leakage from the confined fracturing to the goaf, prevents the closed wall from being damaged by the impact of ground pressure (Dong et al. [52]).

4.2.9. Aerosol materials

Composed by nano or sub-micron solid and liquid particles, aerosol materials are colloidal dispersion systems suspended in gaseous media. There are currently three types of aerosol materials, i.e. hot aerosol, cold aerosol and composite aerosol. Hot aerosol extinguishes fire mainly with the chemical suppression of solid particles (40% carbonate and metal oxides) and physical suppression of gas-phase media (60% CO_2, N_2 and water vapour) as a supplement. As for cold aerosol, the main components of the fire extinguishing agent are made into superparticles, compressed inert gases, which serve as the power source and gas source. The fire extinguishing particles are usually sodium bicarbonate, ammonium dihydrogen phosphate etc. The principle of composite aerosol fire extinguishing agent, e.g. $NaHCO_3/SiO_2$ composite particle aerosol fire extinguishing agent, aparting from the application of cold or hot aerosol fire extinguishing agent, other fire extinguishing agents, fire retardants or specific inert gases are added to improve the fire extinguishing effect and reduce the side effects of the aerosol fire extinguishing agent (Qu [53], Chen et al. [54]).

4.2.10. Suppressing Gas Explosion by Core-shell Red Mud-based Composite Powder

The core-shell red mud-based composite powder is a type of explosion-proof composite powder material. Cheng ([55]) analyzed the physical and chemical inhibition effects of red mud-based composite powder. The physical inhibition effect after the structure of the core-shell red mud-based powder was damaged in the explosion and the quenching effect and the endothermic reaction of the carrier particles were found in the red mud matrix material. The void structure of the material was also enlarged. When it comes to the chemical inhibition effect, during the process of capturing reactive radicals by gaseous products after the decomposition of carrier particles and more pore structures distributed on the material surface, a large amount of explosive reactive radicals were consumed. The above resulted in the interruption of the explosive chain reaction and reduction of the explosion intensity.

4.2.11. Porous medium materials

Foam ceramics is a kind of porous medium, the structure of which consists of pore and strut. The spatial skeleton structure could induce a large specific surface area which increases heat dissipation to absorb the gas explosion energy. Besides, it is hard for the explosion flame to propagate in narrow gaps or channels because the flame would lose energy, and its propagation would not be sustained. The foam ceramic can also attenuate the explosion waves, and pore structures make the shock waves reflect within coarse ceramic struts on the surface of the pores, resulting in the energy being either consumed or converted into thermal energy. The potential applications in the underground mine are also proposed by the design of curtains that are suspended on the roof of the tunnels with a sensor placed ahead for detecting any arisen explosion flames. The above can trigger the actions of unfolding a series of foam ceramics curtains to cover the tunnel's cross-sectional area, thus reducing the intensity of the explosions.

4.2.12. Suppression powders

Sometimes the efficiency of inert gas is not good enough to control the severity of the accident. Hence, researchers either use fine powders only or mixes fine powders with inert gases to enhance the effects of explosion suppressions. All of the powders are inert and can absorb the energy when an explosion happens. Powders including $CaCO_3$, Na_2CO_3, SiO_2, ABC dry powder (mainly $NH_4H_2PO_4$), Al(OH)3, Mg(OH)2 and Urea (mainly $CO(NH_2)2$) have experimentally examined for the effects of the explosion suppression effects (Jiang et al. [56], Luo et al. [57], Liu et al. [58], Chen et al. [59], Yu et al. [60]). The main function for the agents to control mine explosion is to chemically absorb the thermal energy in a calcination process, which can reduce the temperature and intensity of the gas explosion (Zeman [61]). Currently, the suppression powder is used to extinguish a coal fire. Generally, a low-velocity applicator is used to ensure the powder is fully applied efficiently and effectively to the burning material and prevents the swarf from spreading. However, the powder can cause breathing problems, and it is hard to clear up.

5. Discussion

Passive explosion suppression technologies like explosion-proof rock powder bags, water belts and water tanks are all characterised as limited practical applications. In some cases, it is difficult for the explosion wave ahead of the explosion flame to have enough impact force to timely trigger the action of the passive explosion-proof device. For example, the container containing rock powder or water poured on the explosion-proof shed cannot be broken or overturned by the shock wave, the flame damper and explosion suppressor inside are scattered to form a high-concentration rock powder area or explosion suppressor area in the roadway to prevent the explosion from spreading forward continually. Spraying rock powder onto the roadway can make the gases inert, thus significantly preventing gas explosions. When a gas explosion or airflow shock occurs, the rising rock dust can absorb the heat of the explosion flame and prevent the explosion from spreading forward. But ordinary rock powder is susceptible to moisture, so the rock powder should be frequently replaced, which requires more effort and time. Since rising rock dust may affect the operating environment underground and cause occupational diseases, the rock powder has gradually been made redundant.

When a gas explosion occurs, the automatic explosion suppression device driven by an initiative measure is rapidly triggered to timely extinguish the fire source and attenuate the explosion. This device accurately distinguishes the explosion signal and overcomes the shortcoming of the passive explosion-proof device, which relies on sufficient shock waves to extinguish the fire source.

The fluorinated ketone fire extinguishing agent is a new type of fire extinguishing agent currently in the research stage. Many studies on fire extinguishing, thermal decomposition, and flame retardant of fluorinated ketone fire extinguishing agents have been carried out worldwide. This agent is widely used in aviation and other fields. Although these domestic studies in China on fluorinated ketone still focus on fire suppression and synthesis, the fluorinated ketone fire extinguishing agent will be recognised and applied by more people in the future around the world. In addition, with excellent performance in flame retardance and explosion suppression being continuously discovered, the fluorinated ketone fire extinguishing agent will finally be applied in real life.

The explosion-proof and fire-proof closed wall can prevent the underground high temperature, shock waves and harmful gases from causing greater losses and casualties after the gas explosion. The closed wall is the "first barrier" against gas explosion. Whether the closed wall can maintain its stability and integrity while being affected by the powerful effects of explosion shock waves is of great safety significance to underground operators. Currently, in China, there is no specific requirement on the explosion-proof performance of closed walls. Engineering analogy and empirical calculation methods are frequently used to set closed walls, but such methods lack theoretical guidance and are against the safety and economic practicalities of the closed walls.

Due to the importance of the safety issue, prevention strategies of mine gas explosions must be carefully planned and designed for mining engineers. The only basis of field considerations and features that each explosion control method has is to ensure that management can be performed sufficiently. Therefore, it is highly recommended that more than two methods should be used when controlling the mine gas explosion. In addition, combining preventive measures can effectively reduce risks, such as gas drainage, ventilation system, stoppings and seals, pressure balancing and monitoring technology. Most of these are required to update for an intelligent mine.

Reviewing all the technologies to control or mitigate the mine gas explosion, it can be concluded that each method has both advantages and disadvantages. The ExploSpot Active suppression system is an effective one, but the high cost may limit its extensive usages.

6. Conclusions

Preventing or mitigating the gas explosion is an important job and measures for mine safety production, which should be performed regularly. This paper provides the recognition of mine gas explosions in underground coal mines, as well as reviewing the technologies, their applications and basic methods that used to control the coal gas explosions in the major coal-producing countries worldwide. The capabilities and limitations of selected explosion protection strategies can be explicitly realised. The complicated conditions in the underground coal mines require the mine operators to carefully choose the explosion protection management, which will increase the likelihood of achieving the safety objectives.

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