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Review Article

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A Review of the Development and Prevention of Explosions of Premixed Gases in Pipelines

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Abstract: Pipelines due to the constrained nature of the structure, the occurrence of gas explosions are prone to serious explosive consequences. Methane is the main component of gas and natural gas, coal mine tunnel and underground pipeline of the premixed gas explosion of methane is a serious threat to industrial production safety. Researchers have conducted many studies to clarify the development of explosions and hazards, so this paper reviews the status of domestic and international gas explosion research from two major aspects of explosion development law and explosion prevention. Explosion development is divided into explosion flame structure, flame speed and explosion overpressure; research in gas explosion prevention and control involves separate gas-phase, liquid-phase and solid-phase explosion suppression, as well as the coupling effect of different combinations of methods superior to their individual effects. Finally, future research in the field related to gas explosions is foreseen.

Keywords: methane; gas pipeline; detonation; premixed gas

1. Introduction

The application of methane-based gas and natural gas in industrial production is becoming increasingly widespread [1]. Methane air mixture can undergo a violent chain reaction when exposed to a fire source under certain conditions, producing high-temperature and high-pressure gases, accompanied by significant destructive effects. During the process of mining excavation, due to poor ventilation, gas accumulates in confined spaces and reaches the explosive limit, leading to underground gas explosions when encountering ignition sources; During the operation of the factory's gas transmission pipeline or natural gas long-distance pipeline, pipeline rupture, combustible gas leakage, etc. may occur due to internal and external corrosion, pipe design defects, technical management errors, or human damage factors, and may accumulate in confined spaces such as underground tunnels or comprehensive pipe galleries, which may also cause explosion accidents. The factors that affect the characteristics of gas explosions include initial pressure, initial temperature, ignition energy, ignition position, gas composition and concentration, mixing uniformity, flow state, container size, and the presence of obstacles. Yu Minggao et al. [2] and Pei Bei et al. [3] studied the explosion suppression effect of coupling inert gas and ultrafine water mist and found that the combination of ultrafine water mist and porous materials also has a good suppression effect on gas explosions. The methane explosion limit, as an important parameter, is influenced by various factors. Cashdollar et al. Zheng et al. [4] pointed out that with the addition of N_2/CO_2, the flame deformation of the synthesis gas-air mixture is no longer significant, the oscillation amplitude of the flame front position and flame propagation speed is correspondingly reduced, and the explosion overpressure is reduced. And CO_2 has a better inhibitory effect on the synthesis of gas air explosion than N_2. Duan et al. [5] confirmed that the quenching effect of porous media on explosive flames is closely related to its pore size and thickness. Increasing the thickness of porous media with larger pore sizes can only temporarily stop the propagation of flames, but cannot completely extinguish them. Below, this article will elaborate on different research methods from the perspectives of explosion development laws and explosion prevention and control.

2. Research on Explosion of Premixed Gas

The explosion process generally involves the reaction system entering the combustion stage through a chain reaction after the explosion occurs. Due to the large amount of energy generated by combustion, the temperature inside the system increases, which in turn leads to an increase in pressure inside the pipeline. The gas is continuously compressed, gradually forming a shock wave. The shock wave consists of two parts, namely the precursor shock wave and the accompanying combustion wave, with a gap between them, and the flame propagation speed is determined by the speed of the combustion wave. The propagation speed of shock waves is greater than the speed of sound, and they often propagate from the center of the explosion to the surrounding area in a supersonic state with the occurrence of an explosion.

1）Explosion Flame Propagation Structure

The change in flame front shape during gas explosion. Usually, high-speed photography or schlieren and shadow methods are used to record the process of flame shape changes. High speed photography was first applied to flame front observation, which is a way and research method to effectively record the development laws of high-speed motion. The four stages of premixed gas flame propagation in semi open and closed pipelines proposed by Clanet and Searby [6] are: spherical flame unaffected by wall, fingertip flame, contact wall flame, and classical Tulip flame Zhong Feixiang, Zheng Ligang et al. [7] studied the influence of initial environmental temperature fluctuations on explosion parameters in small-scale square transparent pipelines and analyzed the combustion mechanism of premixed systems. Observing the final production of tulip and non tulip flame types, and based on the unique evolutionary characteristics of tulip flames, they are further divided into T-shaped tulip flames and asymmetric tulip flames. Yu Minggao et al. [8] compared and studied the volume fraction gradient distribution of methane along the pipeline and the non-uniform premixed methane/air explosion flame propagation characteristics under different free diffusion times of methane in the pipeline using a small-scale explosion experimental platform independently built. Research has found that when non-uniform methane air is ignited in a longitudinal volume fraction gradient field of methane, it exhibits a triple flame structure, and the larger the gradient, the more pronounced the triple flame structure becomes;

2）Flame propagation speed

The flame propagation speed refers to the speed at which the flame front advances along the normal direction of the flame relative to the unburned combustible mixture. Flame velocity measurement methods include measurement system speed measurement, particle image speed measurement, and high-speed photography technology to record the characteristics of gas flame propagation speed measurement. Wang Fahui et al. [9] studied the propagation characteristics of methane detonation flames under oxygen rich conditions, and the results showed that the flame propagation speed first increased, then decreased, and then increased again. This phenomenon is mainly caused by changes in flame structure. The deceleration stage of the flame occurs from the side of the "finger shaped" flame front contacting the wall to the initial formation of the "tulip" flame. The enhanced heat transfer between the flame and the wall, as well as the reduced contact area between the burned and unburned gases, collectively lead to a decrease in flame propagation speed. Zhang Xinmin et al. [10] conducted methane/air premixed explosion tests in variable cross-section pipelines with volume fractions of 7.5%, 8.5%, and 9.5%, respectively. They found that flames would wrinkle and deform under turbulent excitation, and the flame surface area and combustion rate would increase, leading to an increase in flame propagation speed and overpressure, thereby increasing the explosion release speed and generating greater turbulence. Zhou Yonghao et al. [11] used a gas powder two-phase mixture explosion experimental system and recorded flame propagation images using a high-speed camera under conditions below the lower limit of methane explosion. They studied the effects of coal dust types and methane volume fraction on the propagation characteristics of methane/coal dust composite flames. The results showed that with the increase of volatile matter content, the combustion mode gradually shifted from diffusion combustion to gas-phase premixed combustion, the combustion reaction was enhanced, the flame propagation speed increased, and the flame temperature increased.

3）Explosion overpressure and pressure rise

The change in overpressure caused by gas explosion in pipelines. Explosion overpressure is a frequently studied characteristic parameter in explosion research, which refers to the pressure difference between the pressure on the detonation wavefront and atmospheric pressure. In the experiment, data is collected through pressure sensors, acquisition cards, computers, etc. The pressure signal is converted into an electrical signal and transmitted to a pre written program on the computer for calculation and storage. Later, data processing software such as Origin and Excel is used to process and plot the trend of pressure over time or propagation distance. Cashdollar et al. [12] studied the explosion limits of different states and types of ignition sources in 20 and 120 L explosive devices, and found that container size had a significant impact on the rate of increase in explosion pressure. Cao et al. [13] conducted experiments and numerical simulations on methane air explosions, including the effects of methane concentration and explosion pressure on internal pressure dynamics and explosion characteristics. Studied the effects of methane concentration and explosion pressure on internal pressure dynamics and exhaust characteristics. At a concentration of 7vol%, there was almost no pressure oscillation observed in the internal pressure curve. But at concentrations ranging from 9vol% to 13vol%, pressure oscillations are evident on the internal pressure curve. ZHANG et al. [14] studied the flame propagation characteristics of hydrogen and air under non-uniform premixed volume fraction gradients in a vertical channel through experiments and numerical simulations. Research has shown that mixtures with positive volume fraction gradients have higher flame acceleration and faster explosion overpressure rise rates compared to homogeneous mixtures or mixtures with negative volume fraction gradients.

3. Research on Explosion Suppression of Premixed Gas

1）Gas phase explosion suppression

Inert gas explosion suppression technology is to inject inert gas into the explosion source during gas explosion prevention and control, dilute the volume fraction of CH_4 and O_2 in the explosion source, and reduce the intensity and danger of gas explosion. The currently widely used inert gas explosion suppression materials are mainly N_2 and CO_2. Some scholars have conducted extensive experimental research on the effects of N_2 and CO_2 on gas explosions. Zhang Yingxin et al. [15] studied the effects of CO_2 and N_2 on the explosion characteristics of mine gas, and the results showed that both CO_2 and N_2 can reduce the concentration of gas and narrow the range of gas explosion limits; But at the same volume fraction, CO_2 has a better explosion suppression effect, leading to a greater decrease in peak gas explosion pressure and explosion index. It is pointed out that with the addition of N_2/CO_2, the flame deformation of the synthesis gas air mixture is no longer significant, the oscillation amplitude of the flame front position and flame propagation speed is correspondingly reduced, and the explosion overpressure is reduced. And CO_2 has a better inhibitory effect on the synthesis gas air explosion than N_2. Ren et al. [16] used CHEMKIN software to model and investigate the effect of different concentrations of CO_2 on laminar premixed flames of methane/air mixtures. From the perspective of fluid flow, the process of gas explosion will undergo changes from laminar to turbulent flow, and different combustion modes will be produced depending on the flow state of premixed gas. After the explosion, the initial premixed gas flow rate is relatively stable, and the flame is basically a laminar flame, with a smooth combustion surface. As the process develops and changes, the up and down disturbances during the premixed gas flow make the combustion unstable. In the later stage of the explosion, a turbulent flame with fast propagation speed will be formed, and the flame surface will be wrinkled, stretched, and deformed. The characteristic parameters during the explosion propagation process will change with the stage changes.

2）Liquid phase explosion suppression

Fine water mist acts on the gas explosion reaction zone from both physical inhibition and chemical inhibition, inhibiting the continuous progress of the gas explosion reaction. Fine water mist has a high heat capacity, and it quickly vaporizes under the action of high-temperature flames, taking away a large amount of heat, reducing the temperature of the reaction zone, and suppressing the continuation of the gas explosion chain reaction. After vaporization into water vapor, the volume of fine water mist rapidly expands. At this time, water vapor acts as an inert component, reducing the volume fraction of intermediate products such as free radicals, O_2, and CH_4 in the gas explosion reaction zone, lowering the transmission speed of the gas explosion reaction chain, and suppressing the progress of the gas explosion reaction. Gu Gongtian et al. [17] conducted a study on the suppression of gas-liquid two-phase flow in gas and coal dust explosions by pre mixing gas gas in pipelines. They compared the suppression effects of single fluid fine water mist and gas-liquid two-phase flow on explosions. The flame propagation status after suppression can be collected through high-speed imaging through the glass window at the end of the pipeline, revealing the flame development under different fine water mist conditions. It was determined that CO_2 gas-liquid two-phase flow fine water mist has the highest suppression efficiency, with a maximum reduction of 59.1% in flame propagation speed. Zhou Xihua et al. [18] developed a pipeline experimental system for suppressing gas explosions with explosion-proof water curtains, and conducted comparative experiments on the effectiveness of explosion-proof water curtains with and without water curtains, different gas concentrations, and different flow rates through the experimental system to study the barrier effect of explosion-proof water curtains on gas explosions. The research results indicate that the explosion-proof water curtain has a good barrier effect, and the best explosion-proof effect is achieved at a gas concentration of 9.5% and a nozzle spray flow rate of 16.4 L/min. Wang

3）Solid phase explosion suppression

Porous media, as a new type of material, have attracted the attention of researchers. The unique pore structure endows it with the high surface area and volume ratio required for quenching explosive flames. It has the characteristics of high porosity, large specific surface area, high temperature resistance, impact resistance, and strong buffering ability. When the explosion flame passes through porous media, its combustion wave and shock wave can be greatly weakened after passing through countless pores, and even the explosion flame can be extinguished, playing a role in explosion protection. Porous explosion suppression media mainly include metal wire mesh porous media and foam filled porous media. Duan et al. [19] confirmed that the quenching effect of porous media on explosive flames is closely related to its pore size and thickness. Increasing the thickness of porous media with larger pore sizes can only temporarily stop the propagation of flames, but cannot completely extinguish them. Yu Jianliang [20] explored the propagation and extinguishing characteristics of detonation flames in cracks and multi-layer wire mesh, and established corresponding flame quenching models. Nie et al. [21] found that the material properties of porous media affect its ability to quench the flame. The interconnection network structure of foam ceramics helps extinguish the explosion flame, suppress the shock wave, and the peak value of explosion overpressure decreases by 50% significantly. Wen et al. [22] experimentally studied the behavior of quenching gas explosion flames in porous media with three different material properties. The results show that compared with foam Al_2O_3 and SiC, foam aluminum has better flame quenching and overpressure attenuation capabilities.

4. Conclusion

(1) Premixed gas explosion process and flame propagation characteristics: In pre mixed gas explosion, the rapid energy release inside the system leads to the formation of shock waves, including precursor shock waves and accompanying combustion waves. The flame propagation structure is diverse, and different forms of flames can be observed through techniques such as high-speed photography, such as spherical flames, tulip flames, etc. These forms are influenced by the pipeline structure and initial conditions. The speed of flame propagation is influenced by various factors, including the uniformity of the mixed gas, turbulent conditions, and wall effects. Research has shown that turbulence and uneven volume fraction gradients accelerate flame propagation and increase explosion overpressure.

(2) The influencing factors of flame propagation speed and explosion overpressure: Flame propagation speed is crucial for understanding the destructive power of an explosion, as it is influenced by various factors such as the composition of the mixed gas, the geometric structure of the container, and the initial temperature. The flame propagation speed will first increase and then decrease under certain conditions, which is related to the changes in flame morphology and structure. The interaction between flames and walls can cause a decrease in flame propagation speed, while turbulent conditions can increase flame surface area and combustion rate, thereby enhancing explosion intensity and overpressure.

(3) Application of gas-phase and liquid-phase explosion suppression technology: Gas phase explosion suppression technology reduces the intensity and danger of explosions by injecting inert gases such as N_2 or CO_2, with CO_2 showing better explosion suppression effects in certain situations. Liquid phase explosion suppression technology utilizes the physical and chemical inhibition effects of fine water mist to

reduce flame temperature and suppress the continuation of chain reactions. Fine water mist not only reduces the reaction temperature by taking away heat, but also generates inert gas effect through volume expansion, effectively suppressing the propagation of explosive flames.

(4) The role of porous media and multiple combined explosion suppression methods: Porous media effectively suppress the propagation of explosive flames through their high surface area and high temperature resistance and can absorb shock waves and weaken flame energy. In addition, combining porous media with other methods such as fine water mist and inert gas can further enhance the explosion suppression effect. This multi-pronged strategy works synergistically to reduce explosion overpressure, slow down flame propagation speed, significantly improve the overall effectiveness of explosion suppression, and reduce the risk of secondary disasters.

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