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Research Article

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Analysis of Explosion Characteristics and Explosion Suppression Performance of Common Fuels

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Abstract: This paper analyzes and summarizes the current state of research on fuel explosions and explosion suppression, based on a large number of relevant domestic and international literature. In recent years, numerous researchers have studied the various factors influencing fuel explosions, such as fuel type, ignition location, fuel equivalence ratio, explosion vessel size, and ignition method. The studies on common gaseous fuels like methane and hydrogen have been relatively extensive. In spherical vessels, the effect of equivalence ratio on explosions was studied by varying the ratio, and it was found that the explosion intensity was maximized when the equivalence ratio was close to 1:1. In square pipelines, the influence of different ignition positions on explosions was investigated, revealing that varying ignition locations lead to changes in the overpressure inside the pipe, resulting in different explosion pressures. To mitigate the damage caused by explosions, many studies have been conducted on explosion suppression. These include the use of $NaHCO_3$ powder, inert gases, and synthetic materials for explosion suppression. By analyzing parameters such as explosion pressure, pressure rise rate, and laminar combustion speed after the addition of suppressants, the effectiveness of different suppressants in reducing explosions was evaluated, providing reliable data for industrial safety production.

Keywords: explosive characteristics; common fuel; methane; explosion suppression; gas explosion

1. Introduction

With the rapid development of the global economy, the demand for energy continues to grow. China is not only a major energy producer but also a major energy consumer, with both energy production and consumption dominated by fossil fuels. However, China is relatively limited in fossil fuel resources. As fossil energy becomes increasingly scarce, the application of gaseous fuels in industry has become more widespread [1]. The production and transformation of light hydrocarbons, such as methane, ethylene, and ethane, play a pivotal role in the chemical industry [2]. Many processes involve high-temperature mixing and reaction between oxygen and combustible gases, such as in the production of olefins from natural gas [3]. In recent years, the large-scale exploitation and production of shale gas have significantly increased natural gas output and reduced its cost, further broadening the prospects for olefin production from natural gas [4]. However, the conversion of natural gas typically involves high-temperature and high-pressure conditions, which pose considerable safety risks [5]. The oxidation, autoignition, and explosion behavior of methane under high temperatures differ markedly from those under ambient conditions [6]. Therefore, understanding the flame propagation mechanisms of methane combustion under high-temperature and high-pressure conditions [7] and identifying safe operating boundaries at various temperatures and pressures [8] are essential to achieving intrinsic safety in oxidative coupling of methane (OCM) processes, thereby facilitating the industrial implementation of novel technologies.

Hydrogen is gaining widespread application and promotion due to its high energy density and pollution-free combustion products [9]. However, from a chemical perspective, hydrogen is classified as a Category 2 hazardous substance, making it prone to explosion accidents during storage, transportation, and usage [10]. Therefore, ensuring the safe use of hydrogen energy is a critical issue that needs to be addressed in the promotion of hydrogen energy. Although professionals in related fields have a relatively deep understanding of the risks associated with hydrogen explosions, the lack of a complete understanding of the explosion mechanisms still poses certain safety risks when conducting hydrogen explosion experiments [11]. With the development of computer technology, numerical simulations can replicate explosion parameters that are difficult to capture in current experiments, thus assisting researchers in understanding the microscopic dynamic processes and explosion mechanisms. This has led to widespread application of numerical simulations in gas explosion research.

With the continuous increase in global energy consumption and the environmental degradation caused by pollutant emissions, there is growing concern about how to improve the efficiency of traditional combustion methods to conserve energy and how to reduce pollutant emissions to protect the ecosystem. Compared with conventional diffusion flames, combustion technologies such as preheated air combustion can enhance thermal efficiency to a certain extent; however, they also lead to a significant increase in the emission of nitrogen oxides and other pollutants[12], thereby accelerating environmental degradation. Alongside rapid industrialization and ongoing scientific and technological advancements, global energy consumption has continued to rise over the past decades, with an average annual growth rate of 2.2% from 1995 to 2015. This trend is not only observed in developed countries like the United States, but also in developing nations such as China. It is projected that from 2018 to 2035, global energy consumption will continue to grow at an average annual rate of 1.3%, with China and India contributing the most to this increase. The relentless consumption of energy is not only depleting global fossil fuel reserves but also leading to increasing and cumulative emissions of CO_2 and NO_x, further deteriorating the Earth’s environment. It is estimated that by 2035, CO_2 emissions from fossil fuel usage will increase by 13%. The emission of greenhouse gases, primarily CO_2, has already led to global warming and climate anomalies such as El Niño, which have significantly altered the Earth's climate and driven many species to extinction. Energy and environmental issues have now become critical global challenges. Energy conservation and environmental protection are shared missions and responsibilities for all of humanity.

2. Hydrogen Explosion Characteristics and Explosion Suppression Performance Analysis

Hydrogen (H_2), as one of the new energy sources, offers three major advantages: abundant resources, high calorific value, and clean, pollution-free combustion. China is currently at a critical stage of development, where energy plays a vital role in ensuring progress. Clean energy is of great significance to China’s rapid and sustainable development, and thus, hydrogen energy will play an increasingly important role in the future energy landscape. Energy is one of the material foundations for the continuation and advancement of human civilization on Earth. Conventional energy primarily comes from mineral fuels. As of 2020, 82% of global energy consumption was derived from fossil fuels, including coal, oil, and natural gas. With the growth of the global economy and the rapid development of the automotive industry, the dependency of traditional internal combustion engines on oil has led to a continuous increase in oil demand. This large demand results in the combustion of oil, producing a significant amount of pollutants that pose severe threats to both the global environment and human health. Hydrogen, as a clean energy source, has been shown in previous studies [13] to effectively reduce the emissions of pollutants such as NO_x and CO_2 when added in a volumetric fraction of 8%–30% to the currently used natural gas, without requiring modifications to existing equipment. Therefore, research related to hydrogen has become increasingly important. As a clean, sustainable, zero-carbon, and high-energy-density secondary energy source, hydrogen energy has gained significant attention for its potential to promote carbon reduction goals, enrich renewable energy storage methods, and ensure energy supply security.

Xiao, Huahua [14] used high-speed schlieren imaging and pressure sensors to experimentally study the propagation behavior and shape changes of premixed hydrogen-air flames with different equivalence ratios in semi-open and closed horizontal pipes. The study showed that, compared to other gaseous fuels, the shape changes of premixed hydrogen-air flames are more complex, exhibiting more distinct features. The dynamics of twisted tulip flames differ from those of classic tulip flames. A normal tulip flame can reform after the first deformation, whereas a twisted tulip flame’s shape change begins when pressure rises and the flame front velocity decelerates. The initiation of shape change, including quasi-planar, planar flames, tulip flames, and deformed tulip flames, is largely dependent on the hydrogen addition. Yanchao Li [15] found that methane/hydrogen fuels are widely used in internal combustion engines and gas turbines due to their increased laminar burning velocity and expanded combustion limits. To ensure safe energy utilization, the study systematically investigated the flame characteristics and explosion pressure of lean, stoichiometric, and rich flames by varying hydrogen addition and initial pressure. With the increase in hydrogen addition, the influence of diffusive heat instability and fluid dynamic instability on flame instability also increases.

3. Methane Explosion Characteristics and Explosion Suppression Performance Analysis

Methane explosions can generate enormous destructive power within a short period, causing severe damage to mining facilities and buildings. This destructive effect is closely related to the explosion shock wave generated. As a high-efficiency and clean energy source, natural gas provides convenience to people's lives, but it also poses potential hazards. During the processing, usage, and storage/transportation of combustible gases, fires and explosions occur frequently. Therefore, it is necessary to understand the development patterns of premixed flames and explosion overpressure, and to take timely preventive and control measures.

In recent years, many scholars have conducted extensive experiments on methane/air premixed gas explosions, mainly focusing on the study of flame propagation and explosion overpressure. Research has shown that the flame propagation speed is determined by the combustion velocity of the combustible gas and the diffusion velocity of the airflow. A higher airflow diffusion velocity can trigger turbulence inside the pipe, which increases the flame's combustion area during combustion, significantly accelerating the energy release rate. This causes the flame to accelerate and the pressure to increase, resulting in severe damage to production equipment and buildings. Feixiang Zhong et al. [16] investigated the $CH_4/O_2/CO_2$ premixed system in a small-scale square transparent pipe, conducting a series of explosion experiments to explore the impact of initial environmental temperature fluctuations on explosion parameters. They analyzed the combustion mechanism of the premixed system and found that oxygen concentration significantly affects flame structure and propagation mode. The flame speed curve and explosion overpressure curve are closely related to the relative oxygen concentration (γ), and the fluctuation of the initial environmental temperature (T_0) affects explosion intensity. Dai Liu et al. [17] conducted experimental studies on laminar flame propagation speeds of $CH_4/H_2/O_2/CO_2$ premixed gases at ambient temperature and pressure using a Bunsen burner method. They used a flame image-based comprehensive area method to calculate the laminar flame propagation speeds. The study concluded that the laminar flame propagation speed of the $CH_4/H_2/CO_2/O_2$ mixture reached its maximum between an equivalence ratio of 1.0 to 1.1. As the oxygen volume fraction increased, the flame propagation speed increased, with the rate of increase gradually becoming more pronounced. Under low hydrogen content conditions, the laminar flame propagation speed increased slowly with the hydrogen volume fraction, showing a linear relationship between the two. Yalei Wang et al. [18] completed methane explosion experiments under various constrained end-face conditions, studying the explosive characteristics of methane under different concentrations. They concluded that the nature of the constrained end-face significantly affects the development of the methane explosion flame and overpressure. The morphology of the rupture after the constrained end-face differs greatly depending on the material, and the curves of flame front positions with time during the early stages of flame development overlap to different extents. However, as the constrained end-face ruptures, they gradually separate. Additionally, under high-pressure constrained end-face conditions, the explosion overpressure of methane with different concentrations is the same. In this case, the peak pressure is the explosion overpressure for methane of varying concentrations. Furthermore, under the same constrained end-face, the overpressure oscillation curve after membrane rupture for methane at different concentrations overlaps completely during the first half of the pressure decay cycle. Fangming Cheng et al. [19] reviewed domestic and international literature on gas explosion suppression materials and mechanisms. They summarized and analyzed research on gas, water mist, powder, and multiphase composite suppression materials and their mechanisms, proposing innovative trends for future development. Qin Yi et al. [20] proposed an explosion overpressure model to avoid explosion accidents in confined spaces with combustible premixed gases. They established a fractal combustion theory-based explosion overpressure prediction model, considering flame wrinkles and turbulent flame propagation, and compared it with experimental results. The results showed that when the volume of the confined space is larger, the relative error between experimental and theoretical peak pressure estimations using the wrinkled and turbulent flame theory was 10.4% and 11.1%, respectively, which is a significant improvement compared to the smooth laminar flame model, where the error was reduced by 72.3% and 50.6%. Maria Mitu et al. [21]

examined the explosion pressure and maximum pressure rise rates under varying initial pressures (50 to 200 kPa) and environmental initial temperatures, using methane concentrations within the combustible limits. Under a constant CH_4/O_2 ratio, explosion pressure and the maximum rate of pressure rise showed a linear relationship with initial pressure. The initial pressure is determined by the increase in the amount of combustible gas in the unit volume and the higher heat released during combustion.

To investigate the suppression effect of the combined use of trifluoroiodomethane (CF_3I) and carbon dioxide (CO_2) on methane explosions, Fangming Cheng et al. [22] studied the impact of CF_3I and CO_2, both individually and in combination, on methane explosion pressure characteristics. The results showed that after adding CF_3I and CO_2, the methane explosion limit range gradually narrowed, with CF_3I having a more significant effect on the methane explosion limits. When the volume fractions of CF_3I and CO_2 reached 5.5% and 32.0%, respectively, the upper and lower explosion limits of methane coincided, and the critical oxygen volume fractions were 17.85% and 12.50%. This indicates that CF_3I is much more effective at suppressing methane explosions than CO_2. When comparing the decrease in maximum explosion pressure and maximum explosion pressure rise rate at a 9.5% methane volume fraction, the explosion suppression effect of 5.0% CF_3I was approximately six times and five times more effective than an equal volume of CO_2.

Gas explosions in coal mines are one of the major disasters in China, with significant destructive power. According to statistics, 90% of major accidents in Chinese coal mines, resulting in more than 10 fatalities annually, are caused by gas (and coal dust) explosions, leading to enormous economic losses and posing a severe threat to miners' safety. Therefore, research into effective methods for preventing and controlling gas explosions is of great importance. Chengjie Ji [23] used a 20 L multifunctional spherical explosion experimental device to select C_3HF_7 gas and $NaHCO_3$ powder as explosion suppressants. The study analyzed the suppression law and effectiveness of these agents on gas explosions, providing fundamental experimental data for the development of gas-solid composite suppressants for gas explosions and offering some guidance for gas explosion prevention and control.

4. Other Fuel Explosion Characteristics and Explosion Suppression Performance Analysis

Polyethylene is one of the most widely used synthetic resin materials. However, during the production process of polyethylene, high concentrations of polyethylene dust clouds can form, which may lead to dust explosions in localized areas. Several explosion incidents caused by polyethylene have occurred, making the research on explosion prevention and control technology of polyethylene crucial for the production safety of polyethylene-related industries. Ordinary automobiles primarily use gasoline as fuel. Guochun Li et al. [24] conducted research on gasoline engines using a gasoline-ethanol mixture, and Chunhua Bai [25] also carried out related studies. The supply and demand conflict of fossil fuels, as well as the air pollution caused by motor vehicles, have become one of the major issues faced by countries worldwide. Seeking alternative fuels for petroleum has become a key research area in the engine and combustion fields. Propane, the main component of liquefied petroleum gas, has a low boiling point, a high octane rating, and easily forms a uniform mixture with air, enabling complete combustion. Hydrogen has a high flame propagation rate, a wide combustion limit, and is easily ignited. In addition to NOx, no other combustion pollutants are emitted, making it considered one of the most promising alternative fuels. Recent studies show that hydrogen combustion in engines can improve engine power economy, reduce emissions, enhance lean combustion properties, and reduce CO emissions. Research has reported the basic combustion characteristics of propane-air and hydrogen-air mixtures. However, there is less research on the basic combustion characteristics of propane-hydrogen-air mixtures. The laminar burning rates of propane-hydrogen mixtures with ratios of 1:2 and 1:8 at the theoretical equivalence ratio were measured. Based on the assumption that the small amount of hydrogen added to propane burns completely, equivalence ratios and hydrogen blending ratios were defined, and the laminar burning rate of propane-hydrogen-air mixtures was obtained. It was found that the laminar burning rate increased linearly with the increase in the hydrogen blending ratio. From a combustion safety perspective, research has been conducted on the addition of a small amount of propane to hydrogen to suppress combustion. The results indicate that adding a small amount of propane can significantly reduce the flame propagation rate and combustion temperature. The flame morphology, flame pulsation, flame temperature, and flame radiation fraction of the propane/hydrogen flame were studied, and the relationship between these characteristics and the propane proportion in the fuel was established. The results show that, when the heat release rate of the heat source is constant, the total flame height and flame diameter have no significant correlation with the propane proportion, while the height of the blue flame increases as the propane proportion decreases. A quantitative analysis of the blue flame height was conducted using the blue flame height fraction, and a dimensionless prediction model for the blue flame height fraction was established based on the previously established carbon black volume fraction model. Furthermore, the propane proportion affects the flame pulsation frequency. Based on the dimensionless numbers proposed by previous researchers and combined with experimental data, an empirical formula for flame pulsation frequency was fitted and compared with previous data.

Common explosion prevention techniques include explosion suppression, explosion isolation, and explosion venting. Among these, explosion suppression is a more proactive and efficient explosion prevention method, and the key to its effectiveness lies in the performance of the suppressive agents. Wang Yan et al. [26] selected four powders—$NaHCO_3$, $KHCO_3$, $Na_2C_2O_4$, and $K_2C_2O_4$—and analyzed their ability to suppress polyethylene dust explosions from two aspects: flame structure and flame propagation speed. The study also explored the suppression mechanisms by combining the physicochemical properties of the suppressive powders. The results showed that all four suppressive powders were capable of inhibiting flame propagation in polyethylene dust explosions, and the suppression effect was enhanced as the concentration of the suppressive powders increased.

In recent years, research on modifying nano SiO_2 through methods like hydrothermal synthesis has become relatively mature. The modified SiO_2 is a low surface energy, superhydrophobic material, with a static contact angle of up to 158.0°±5.4°, demonstrating excellent hydrophobicity. To investigate the coupling relationship between explosion velocity and pressure of butane under the influence of nano-hydrophobic SiO_2 powders as flame retardants and flow enhancers, Xie Jibiao et al. [27] conducted experiments using a custom-designed explosion testing platform based on a LabVIEW control system. The results showed that adding hydrophobic SiO_2 reduced the repose angle of the mixed powder, enhanced its flowability, improved the powder's diffusion effect and storage capacity, and significantly affected the combustion reaction by changing the powder mixture ratio and concentration. Within a certain concentration range, the powder's large specific surface area and the free radicals of the pyrolysis-combined combustion region led to a significant decrease in flame propagation speed and explosion overpressure. However, excessively high powder concentrations promoted early-stage explosions. Moreover, the synergistic effect of the two powders in suppressing explosions was superior to that of a single powder.

5. Conclusion

(1) Key Factors Affecting Explosion Characteristics: The paper summarizes the explosion characteristics of common fuels such as methane and hydrogen, highlighting those factors such as fuel type, ignition location, equivalence ratio, and container size have a significant impact on explosion intensity. For example, the explosion intensity is maximized when the equivalence ratio is close to 1:1, and different ignition locations can lead to variations in explosion overpressure.

(2) Effectiveness of Explosion Suppression Technology: The study analyzes various explosion suppression methods, such as $NaHCO_3$ powder, inert gases, and fine water mist, demonstrating that these methods can effectively reduce explosion pressure, rate of pressure rise, and flame propagation speed. For instance, trifluoroiodomethane (CF_3I) exhibits superior suppression performance for methane explosions compared to carbon dioxide (CO_2).

(3) Future Research Directions: The paper points out that, although existing research has made certain progress, further exploration is still needed, especially in understanding the explosion mechanisms of hydrogen. Combining numerical simulations with experimental studies is an important direction for future research, as it can provide more reliable data support for industrial safety.

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