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Study on Gas Explosion Characteristics in Urban Utility Tunnels

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Abstract

In order to study the effects of three factors, namely, premixed gas concentration, number of pressure relief ports and number of obstacles, on the overpressure characteristics of gas explosion and flame structure of gas chambers in utility tunnels, in this paper, a small and narrow experimental platform for gas explosion was constructed to study the evolution mechanism and law of the kinetic characteristics and flame behavior of gas explosion in utility tunnels, with a view to revealing the special influencing mechanism of the overpressure characteristics and flame behavior of gas explosion in utility tunnels. The results show that in the methane concentration of 9.5% when the explosion overpressure reaches its peak, and at the same time by the utility tunnel long and narrow restricted space, the explosion generated by the precursor shock wave along with the flame compression wave were superimposed on both ends of the pipeline back and forth for many times so that the overpressure waveforms are cyclic oscillatory trend, increasing the explosion hazards; compared with the closed conditions, the relief port on the overpressure characteristics of the significant impact of the maximum decrease of 57.7%, when the frequency of overpressure oscillation is reduced, the gas explosion generated by the overpressure damage is reduced; the presence of obstacles significantly affects the flow field, accelerates the flame propagation and leads to greater overpressure peaks and overpressure oscillations. The conclusions of the study can provide a basis for the safety of natural gas in utility tunnels.

Keywords: *Utility tunnels, gas explosions, explosion overpressure, overpressure oscillations, flame development*

1 Introduction

With the advancement of urban modernization, underground utility tunnels have become an important way to solve the problem of arranging various pipeline facilities [1], and gas pipelines are allowed to be included in the utility tunnel and independently into compartments [2-5]. However, in recent years, a number of gas leakage and explosion accidents in Shandong Huangdao, Kaohsiung, Taiwan, Songyuan, Jilin and other places have caused major casualties and property losses, which has sounded the alarm for the safe operation of gas compartments in utility tunnels. Therefore, how to reduce the occurrence of gas explosion accidents in utility tunnels, control the threat of gas explosion that exists at any time, and reduce the casualties and property losses that it may be caused has become one of the major topics that we urgently need to study.

Some scholars conducted experimental research on the characteristics of gas explosions and related issues in confined spaces. Wang Dongwu and Du Chunzhi [6] studied the explosion process and propagation characteristics of gas-air mixtures with different masses or concentrations. They analyzed that the peak value of the maximum explosion pressure during gas explosion is larger. Moreover, with the increase of gas volume, the position of the maximum peak pressure closer to the ignition source, and the absolute value of flame propagation speed increases significantly. Wang Quan et al. [7] studied the flame propagation characteristics of premixed methane and air gases in acrylic glass pipelines. They found that the pressure signal at the measuring point after ignition and the light signal jumped synchronously, but there was a peak pressure after the peak light moment, and the pressure duration was longer. Zheng Xingzhong et al. [8] investigated the influence of methane concentration and ignition energy on flame propagation through explosion experiments. The results showed that when the methane concentration was 10%, the explosion energy, flame propagation time, and destructive effects were the greatest. When the ignition energy was not less than 1 J, the flame length increased steadily; otherwise, the flame length would rapidly rise.

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And other scholars also investigated the flame and pressure propagation characteristics during natural gas pipeline explosions [9-11].

Meanwhile, some scholars conducted experimental and simulation studies on actual engineering of utility tunnels, exploring the effects of external factors such as relief vents and obstacles on gas explosions within the tunnels. G.Tomlin [12] conducted 38 explosion experiments with a gas concentration of 9.5% to study the influence of different venting areas on the degree of container explosion damage. It was found that too small venting areas or excessively large venting valve thresholds would exacerbate the explosive damage effects. Moen [13] and Barry [14] et al. utilized a computer model combining the discrete vortex method with flame interface algorithm to study the acceleration of premixed flames propagating through stagnant obstacles in planar channels. The research findings revealed that obstacles caused a sudden contraction of airflow, resulting in initial acceleration of the flame. Combustion generated airflow forming turbulent recirculation zones downstream of the obstacles, where the flame interacted with turbulent vortices, increasing the combustion rate. Consequently, the velocity field within the channel intensified, further accelerating the flame. Jiang Jiahong [15] conducted numerical simulations of gas chamber explosions in utility tunnels using FLUENT. The results indicated that the length of accumulated premixed gas in the sealed utility tunnels had the most significant influence on the explosion intensity, while the impact of the tunnel cross-sectional shape was negligible. The size of openings in partially open utility tunnels would affect the overpressure intensity within the tunnels, with the venting effect strengthening as the opening size increased. Xu et al.[16] utilized FLACS to investigate four different designs of venting layouts while simultaneously conducting gas dispersion and explosion simulations. The research findings indicated that under the action of venting, the size of the leaked gas cloud primarily depended on the distance from the leakage point to the vent. Properly setting up venting layouts could significantly reduce the maximum explosion overpressure from 2.23 bar to 1.97 bar. Wang et al. [17] developed a numerical model for gas explosions in large tunnels. Their study revealed that gas explosions in utility tunnels could be divided into three stages based on pressure and flame development: the combustion-induced rise stage, the oscillation rise stage, and the oscillation fall stage. Furthermore, setting up side ventilation ports near the end of the tunnels could reduce peak pressure by 42%～78% and oscillation peak by 35%～87%. In summary, researchers both domestically and internationally focused their studies on the characteristics of gas explosions within confined spaces. However, unlike typical confined spaces, utility tunnels due to their elongated structure, are highly susceptible to transitioning from deflagration to detonation in the event of a gas explosion [18]. However, researchers have primarily utilized numerical simulation methods for studying the combustion and explosion characteristics of utility tunnels, lacking consideration for factors such as the complex layout of auxiliary facilities and dynamic ventilation conditions within the tunnels. Moreover, there is insufficient experimental data available. Therefore, to support accident consequence assessment and the formulation of safety protection strategies in the event of explosions in utility tunnels, there is an urgent need to conduct gas explosion experimental research that conforms to real tunnel scenarios. This will provide essential data with high confidence levels required for validating numerical computational models, thereby offering crucial insights for disaster prevention and mitigation designs in urban utility tunnels.

This study aimed to address the characteristics of gas explosions in utility tunnels. By referencing national standards and literature, key influencing factors of gas explosion characteristics in utility tunnels were identified. Subsequently, a small-scale, elongated, confined space explosion experimental platform was constructed to analyze the behavior of explosion flames and changes in overpressure characteristics under the influence of these key factors. The objective was to reveal the evolutionary patterns and mechanisms of gas explosion flame characteristics within elongated underground spaces systematically. Ultimately, this research seeks to enhance the theoretical understanding of gas explosions in elongated confined spaces and provide technical support for the safety management of gas explosion accidents in urban utility tunnels.

2 Explosion Experimental Platform

2.1 Experimental system

Due to the complexity of factors affecting methane-air explosions in elongated confined spaces, and the coupled effects among various parameters, the explosion development process is inherently complex. Describing the explosion characteristic parameters within elongated spaces is therefore challenging [19]. Therefore, this paper relied on the Oil and Gas Fire and Explosion Dynamics Laboratory, considering the spatial elongation and complex internal structure of the gas chamber in utility tunnels, constructed a small-scale elongated pipeline gas explosion experimental platform, as shown in Figure 1.

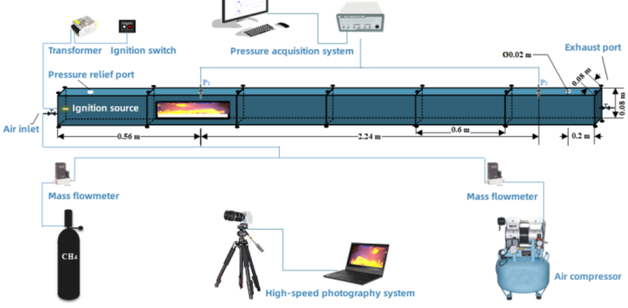

Figure 1 Schematic Diagram of the Experimental Setup

2.2 Experimental setup

The small-scale elongated pipeline gas explosion experimental platform mainly consists of the experimental pipeline, pressure acquisition system, image acquisition system, gas distribution system, and ignition system. Some of the components are shown in Figure 2.

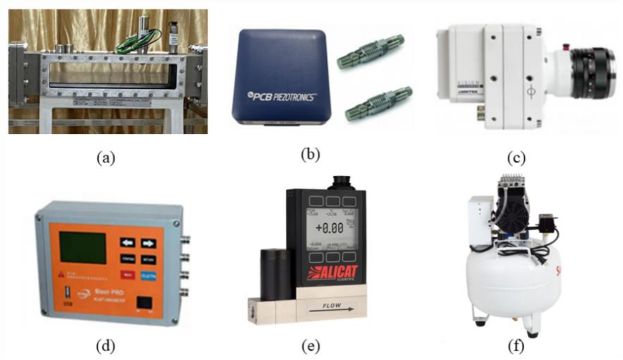

Figure 2 Experimental Equipment

(a) Experimental pipeline (with viewing window); (b) Pressure sensor; (c) High-speed camera;(d) Pressure collector; (e) Flow meter; (f) Air compressor

2.3 Experimental conditions

Before the experiment, it is necessary to check the airtightness of the pipeline and ensure that the system is functioning properly. After confirming that everything is in order, gas distribution can begin. The gas is regulated by gas flow meters to achieve the desired gas concentration, and a mixed gas equivalent to four times the volume of the experimental pipeline is continuously introduced. After the gas is introduced, both valves on the sides are closed, and the system is left to stabilize for 30 seconds to ensure uniform mixing of the premixed gas inside the pipeline. The electric igniter switch is then turned on to ignite the gas, while simultaneously collecting image and pressure data. To ensure the repeatability of the experimental results, each set of experiments is conducted at least three times.

Table 1 summarizes the experimental conditions for studying the gas explosion characteristics in utility tunnels. A 3.6m small-scale elongated gas chamber model was used as the experimental object, and the experimental design followed the requirements of GB50838-2015 standards. In this setup, air intake and exhaust vents were placed at both ends of the pipeline. Various premixed gases (with methane volume fractions ranging from 7.5% to 12.5%) were chosen to determine the methane-air concentration that had the greatest impact on the explosions. Two types of ventilation ports, bolt-sealed and thin polyvinyl chloride (PVC) film vents, were selected to investigate the effects of the number of vent openings. Additionally, obstacles were introduced into smooth pipelines with gas chamber structures (as shown in Figure 3) to study the influence of obstacle quantity. These configurations aimed to identify the methane-air concentration that had the greatest impact on the explosions and to explore the effects of the number of vent openings and obstacles on the experimental results.

Table 1 Experimental Conditions Configuration

Impact Factors	Experimental Conditions
Methane Volume Fraction	7.5%-12.5%
Number of Vent Openings	0; 1(Front); 1(Rear); 2
Number of Obstacles	0; 1; 2; 3

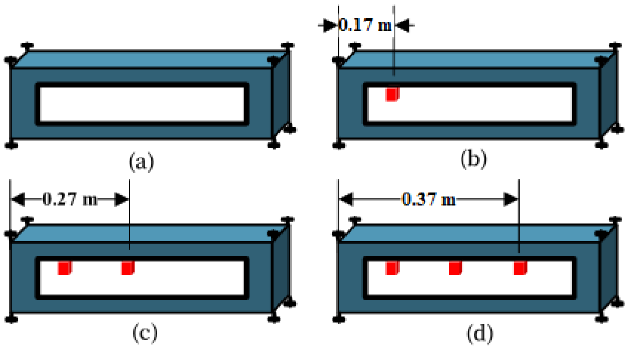

Figure 3 Schematic Diagram of Obstacle Placement

3 Results and Discussion

3.1 Influence of methane volume fraction

From the analysis of the hazards of gas explosions in utility tunnels, it is evident that the shockwave and flame front pose the greatest threat to the gas chamber. Therefore, capturing the changes in overpressure and flame propagation-related characteristic parameters during the gas explosion process becomes particularly important [20-22]. Explosion overpressure is an important indicator used to assess the consequences of gas explosion accidents [23-25]. Figure 4 shows the overpressure characteristic curves under different premixed gas concentrations. Taking 9.5% CH_4 volume fraction as an example, it can be observed from the graph that the pressure variation curve at the outlet exhibits a periodic oscillatory state, with multiple overpressure peaks occurring. This phenomenon occurs because intense chemical reactions occur in the experimental pipeline containing combustible gas after ignition, leading to rapid expansion of combustion products and acceleration of pressure wave generation. The precursor shockwave propagates forward, breaking through the PVC film at both ends to release combustion products, gradually reducing the pressure inside the pipeline and forming the first pressure peak, creating a pressure drop zone. As the flame propagates forward, the surrounding gas undergoes rapid heating, accelerating the expansion rate of combustion products beyond the venting rate of the pipeline. At this point, the pressure at the measurement point rises, creating the second overpressure peak. However, as the precursor shockwave propagates forward, it continuously attenuates due to friction with the gas and the pipe wall, resulting in excessive expansion of the explosion products and the formation of a negative pressure zone due to inertia. At this moment, the surrounding gas moves towards the center of the explosion, compressing the unburned gas again to form a flame compression wave. This wave, along with the flame propagation, accelerates the precursor shockwave. However, when the precursor shockwave hits the wall, it reflects and forms a reverse airflow, which superimposes with the flame compression wave, gradually increasing the pressure and creating the third overpressure peak. Subsequently, the precursor shockwave, accompanied by flame compression waves, oscillates back and forth multiple times at both ends of the pipeline until the maximum overpressure peak (P_{max}) is reached, gradually oscillating smaller until it approaches zero.

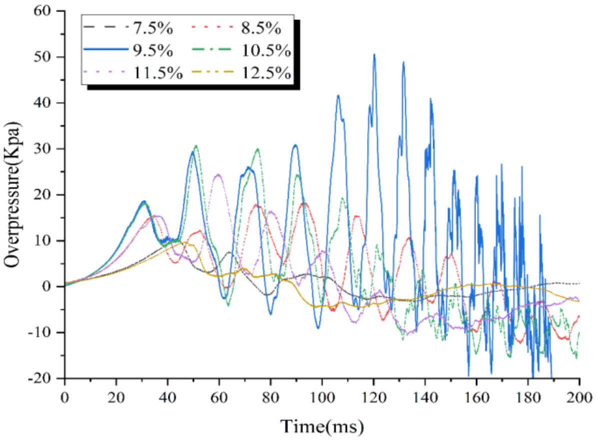

Figure 4 Overpressure Distribution under Different Methane Volume Fractions

As shown in Table 2, when the methane volume fraction is 9.5%, both P_1 and P_2 reach their maximum values. This phenomenon indicates that when the methane volume fraction approaches the stoichiometric ratio (9.5%), the severity of the gas explosion in the experimental pipeline becomes more intense. It is worth noting that the peak overpressure values at 10.5% and 11.5% are still greater than the peak overpressure value at 7.5%. This suggests that in the event of a gas explosion in an utility tunnel, higher volume fractions of natural gas leakage will result in more severe consequences. Additionally, influenced by the narrow and confined space of the utility tunnel, when an explosion occurs within the channel or pipeline, the flame propagation rate increases due to the confinement of the pipeline walls. This accelerates the stacking of precursor pressure waves along the pipeline, ultimately leading to severe pressure oscillations or even detonations. Without proper mitigation, this could result in significant destructive force [26].

Table 2 Comparison of Peak Overpressure under Different Methane Volume Fractions

Experimental Condition	Peak Overpressure P_1/kPa	Peak Overpressure P_2/kPa
7.5% CH_4	9.9425	9.8695
8.5% CH_4	16.0739	18.0850
9.5% CH_4	32.0092	48.1285
10.5% CH_4	19.8956	30.6564
11.5% CH_4	13.0647	24.3866
12.5% CH_4	7.1211	9.5695

3.2 Influence of the number of vent openings

In previous studies, it has been found that vent openings in utility tunnels can effectively reduce the structural safety risks. As concluded in Section 3.1, the explosion accident is most severe when the methane volume fraction is 9.5%. Therefore, in this section, taking a methane volume fraction of 9.5% as an example, the gas explosion characteristics under closed conditions and different venting conditions are compared and studied. Figure 5 depicts the flame propagation images of gas explosions in the second section (0.6m to 1.2 m) of the utility tunnel gas chamber model under different numbers of vent openings. It can be observed that the flame propagation of the premixed gas explosion undergoes four stages: "spherical flame - finger-shaped flame - flat flame - tulip flame". At the time from t=6ms to t=15ms, When the number of vent openings is 0 (n=0), due to the frictional force generated by the wall, there is a velocity gradient in the fluid motion. The burned gas (low-density fluid) experiences significant changes in velocity compared to the unburned gas (high-density fluid), leading to increased entrainment of unburned gas and enlarging the burning area. Consequently, the velocity difference between them increases, intensifying the flame propagation speed and deepening the concavity of the flame front inward [27]. Under the influence of buoyancy, the upper part of the flame front moves slightly faster than the lower part, resulting in a bright flame color and a mild explosive sound. When n=1(Front), the flame propagation speed is faster, and the explosion sound is louder. This is because the vent opening at the front end releases the internal gas from the opening, promoting the acceleration of flame propagation. This results in the flame front speed at the upper side being greater than that at the lower side. When n=1(Rear), the flame structure has transitioned from "Jet-Type" to "Tulip-Type". The flame propagation speed is slowest, and the flame color is brighter. The explosion sound is also louder. Different gas explosion overpressure distributions under different numbers of venting ports are shown in Figure 6. The overpressure oscillation under ventilation conditions is significantly reduced compared to closed conditions, as shown in Table 2. For the gas chamber model under different opening conditions, the reduction rates of the overpressure peaks at P1 compared to closed conditions are 47.5%, 57.7%, and 38.4%, respectively. The reduction rates of the overpressure peaks at P2 compared to closed conditions are 29.4%, 54.5%, and 35.2%, respectively. From the above data, it can be seen that compared to the closed condition, the peak overpressure values in the open conditions are significantly reduced. Additionally, due to the superposition of the compression wave, expansion wave, and shock wave at the rear end, the reduction rate of the peak overpressure at P2 is smaller than that of the peak overpressure at P1 in the corresponding conditions. Furthermore, when the number of venting ports is 1 and located far from the ignition end, the reduction rate of the pipeline's peak overpressure is the highest. Therefore, venting ports have a significant impact on the overpressure and flame effects of gas explosions in utility tunnels. The explosion hazards under open conditions are lower than those under closed conditions. According to the "Technical Code for Urban Utility Tunnel Engineering" (GB50838-2015), utility tunnels are required to have design requirements for inlet and exhaust ports. In the past, numerical simulations of gas explosions in utility tunnels mainly focused on closed, narrow-space models, leading to overestimation of the explosion characteristics. Therefore, considering factors such as inlet and exhaust ports based on the structural characteristics of utility tunnels is beneficial for accurately predicting the hazards of gas explosions in utility tunnels.

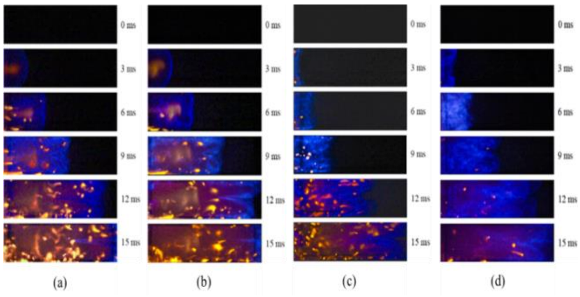

Figure 5 Flame Propagation Images with Different Venting Port Numbers

(a) n = 0, (b) n = 1 (Front), (c) n = 1 (Rear), (d) n = 2

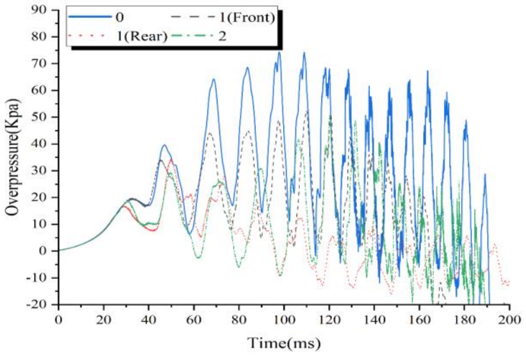

Figure 6 Pressure Distribution under Different Venting Port Numbers

Table 2 Comparison of Peak Pressure under Different Venting Port Numbers

Experimental Condition	Peak Overpressure P1/kPa	Peak Overpressure P2/kPa
n=0	48.7234	74.2330
n=1(Front)	25.5690	52.4069
n=1(Rear)	20.6287	33.7838
n=2	32.0092	48.1285

3.3 Influence of obstacle quantity

In practical engineering, the gas chambers of utility tunnels often contain equipment such as pipelines, brackets, and lighting systems, which differ significantly from other chamber spaces or tunnel structures [28]. Figure 7 shows images of flame propagation under different obstacle quantities. Compared to the smooth gas chamber model, when the obstacle quantity is 1 (o=1), the flame on the upper side is obstructed by the obstacle surface, resulting in a reduction in the flame front area and burning rate. This leads to a decrease in the propagation speed of the upper flame, with the lower flame propagating slightly faster than the upper flame. From t=9ms to t=15ms, after the flame passes through the obstacle, the folding of the flame intensifies. Under the influence of turbulent pulsations and Rayleigh-Taylor instability, the lower flame is drawn upwards, increasing the flame burning area and promoting an increase in flame propagation speed. The brightness of the flame intensifies, accompanied by an increase in the intensity of the explosion sound. When o = 2, the pattern of flame passing through the second obstacle is consistent with that of passing through the first obstacle. The flame propagation speed increases, and the growth rate shows a trend of first increasing and then decreasing. The brightness of the flame enhances significantly, appearing as an orange-yellow flame, and the explosion sound becomes particularly loud. When o = 3, the flame propagation speed and brightness decrease slightly. This is because when passing through the third obstacle, the flame propagation speed temporarily decreases due to the obstruction of the obstacle wall, resulting in a smaller flame propagation distance than the preceding case. Subsequently, as the turbulence level of the flow field increases, the flame accelerates propagation again, resulting in an orange-yellow flame and particularly loud explosion sound. It can be observed that the peak overpressure increases gradually with the increase in the number of obstacles, and the oscillation trend of the overpressure waveform becomes more pronounced. Comparing with the smooth pipeline condition, the increase rates of peak overpressure at P1 are -16.7%, 98.0%, and 176.2% respectively, while at P2, the increase rates are 127.8%, 237.6%, and 293.7% respectively. Both P1 and P2 peak overpressure values significantly increase with the increase in the number of obstacles. However, due to the proximity of sensor P1 to the obstacles and the significant superimposition of explosion waves at the tail end, the increase rate of P2 peak overpressure is greater than that of P1 in the corresponding conditions. Additionally, when o = 1, indicating a small number of obstacles, the effect of wall obstruction at the P1 measurement point in the flow field is greater than the acceleration effect of turbulence disturbance on the flame front. This leads to the opposite result in the increase rate of peak overpressure. Considering that there are many pipelines and supports in the gas chamber of the utility tunnel, it is crucial to plan the pipelines, supports, and other obstacles in the gas chamber for the safe operation of the utility tunnel.

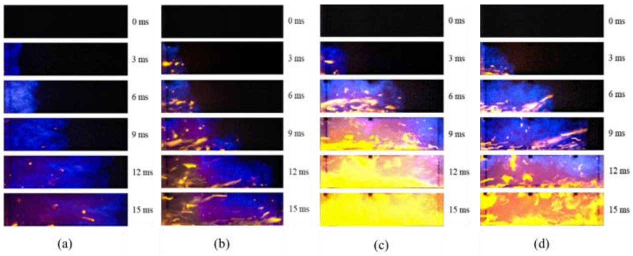

Figure 7 Flame propagation images under different obstacle quantities conditions

(a) o= 0, (b) o = 1, (c) o = 2, (d) o = 3

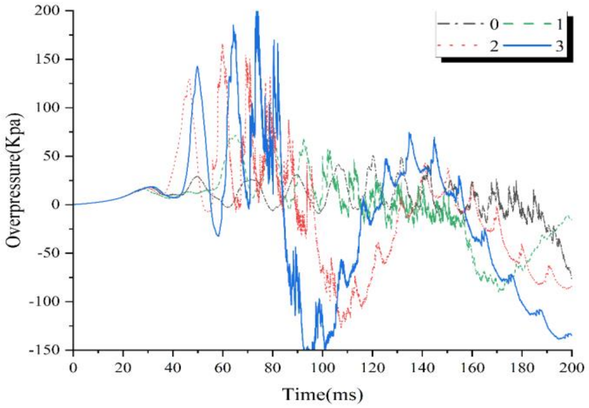

Figure 8 Overpressure characteristics curves under different obstacle quantities conditions.

Table 3 Comparison of peak overpressure values under different obstacle quantities.

Experimental Condition	Peak Overpressure P1/kPa	Peak Overpressure P2/kPa
o=0	32.0092	48.1285
o=1	26.6799	72.9017
o=2	63.3863	162.492
o=3	88.3959	189.4782

4 Conclusion

This study utilized a small-scale experimental platform based on the structural characteristics of gas chambers in utility tunnels. Through high-speed photography and pressure sensors, precise capture and collection of explosion characteristic parameters in small-scale narrow pipes were conducted. The influences of methane volume fraction, venting port quantity, and obstacle quantity on the explosion characteristic parameters of methane-air premixed gas in the pipes were analyzed. The following conclusions were drawn:

(1) As the methane volume fraction increases from 7.5% to 12.5%, the peak explosion overpressure in the experimental pipes shows a trend of initially increasing and then decreasing. When the methane volume fraction reaches 9.5%, the maximum peak overpressure generated by the gas explosion is observed. Additionally, due to the constrained space of the utility tunnel, explosions lead to an acceleration in flame propagation rate, resulting in the continuous superposition of precursor pressure waves along the pipes, ultimately leading to severe pressure oscillations or even detonations. It is necessary to implement suppression measures to ensure the safe operation of the utility tunnel.

(2) Compared to the closed conditions, the peak overpressure under ventilated conditions was reduced by up to 57.7%. At this point, the frequency of overpressure oscillations decreases, thereby reducing the overpressure damage to the tunnel structure caused by gas explosion accidents. Therefore, it is essential to regularly inspect the functionality of pressure relief devices during the operation of the utility tunnel to ensure the rapid and effective release of gases within the tunnels in the event of accidents. Additionally, during numerical simulations, considering factors such as the structure of the utility tunnel gas chamber and the presence of inlet and outlet vents would facilitate accurate prediction of the hazards posed by gas explosions in utility tunnels.

(3) The auxiliary facilities within the utility tunnel gas chamber accelerate the development of flames and also contribute to an increase in peak overpressure, amplifying the trend of overpressure oscillations, thereby leading to more significant explosion disasters. Therefore, proper planning of auxiliary facilities such as pipelines and supports within the utility tunnel gas chamber is of vital importance for the safe operation of the utility tunnel.

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References

[1]Yiping BAI, Rui ZHOU, Jiansong WU, et al.. Hazard identification and analysis of urban utility tunnels in China[J]. Tunnelling and Underground Space Technology, 2020,(103):103584.

[2]LUO Y, ALAGHBANDRAD A, GENGER T K, et al.. History and recent development of multi-purpose utility tunnels[J].

Tunnelling and Underground Space Technology, 2020,103:103511.

[3]CHEN Z-L, CHEN J-Y, LIU H, et al.. Present status and development trends of underground space in Chinese cities: Evaluation and analysis[J]. Tunnelling and Underground Space Technology, 2018(71):253-270.

[4]Jingpeng WANG. Overview of the role-playing of underground utility tunnels construction in urban development[J]. Housing & Real Estate, 2020(9):257.

[5]Hang LIU. An overview of the application of internet of things technology in the construction of urban utility tunnels[J]. Modern Information Technology, 2020,4(4):170–173.

[6]Dongwu Wang, Chunzhi DU. Experimental study on the propagation law of tunnel gas explosion[J]. Journal of Mining and Safety Engineering, 2009,26(4):475-485.

[7]Quan WANG, Ziru GUO, Zhiming LI, et al.. Experimental Study on the Propagation Characteristics of Methane-Air Premixed Flame in a Confined Tube[J]. Coal Science and Technology, 2007(11):95-97+100.

[8]Xingzhong ZHENG, Dan ZHENG. Experimental Study on the Influence of Methane Concentration and Ignition Energy on the Length of Gas Explosion Flame[J]. Fire Technology and Product Information, 2015(03):12-15.

[9]Shengguo CHEN, Yansong ZHANG, Jian LIU, et al.. Experimental Study on the Propagation Law of Natural Gas Explosion Flame and Pressure Wave in Pipeline[J]. China Safety Science Journal, 2013,9(10):43-48.

[10]HARIHARAN A, WICHMAN I S. Premixed Flame Propagation and Morphology in a Constant Volume Combustion Chamber[J]. Combustion Science and Technology, Taylor & Francis, 2014,186(8):1025–1040.

[11]Jinsheng XU, Yang LIU, Xianfeng CHEN, et al.. Influence of Methane-to-Air Mass Concentration Ratio on Flame Structure and Propagation Characteristics[J]. China Safety Science Journal, 2014,24(9):64-69.

[12]TOMLIN G, JOHNSON D M, CRONIN P, et al.. The effect of vent size and congestion in largescale vented natural gas/air explosions[J]. Journal of Loss Prevention In The Process Industries, 2015(35):169-181.

[13]MEON I. The influence of Turbulence on Flame Propagation in Obstacle Environments[C]. Montreal, Prof of First International Specialist Meeting on Fuel, Air Explosions, 1981.

[14]Barry P K. Acceleration of a flame by flame-vortex interactions[J]. Combustion And Flame, 1990(82):115-125.

[15]Jiahong JIANG, et al.. Study on the Distribution Law of Gas-Cloud Explosion Field in Urban Comprehensive Pipe Gallery[D]. Nanjing: Nanjing University of Science and Technology, 2018.

[16]XU Y, HUANG Y, LI J, et al.. A risk-based optimal pressure relief opening design for gas explosions in underground utility tunnels[J]. Tunnelling and Underground Space Technology, 2021(116):104091.

[17]WANG S, LI Z, FANG Q, et al.. Numerical simulation of overpressure loads generated by gas explosions in utility tunnels[J]. Process Safety and Environmental Protection, 2022(161):100-117.

[18]Xinsheng JIANG, Wei XIE, Yadong ZHAO, et al.. Experimental Study on Oil and Gas Explosion in Long and Narrow Pipelines with Different Length-to-Diameter Ratios[J]. Oil & Gas Storage and Transportation, 2020,39(8): 879-884.

[19]Zhenmin LUO, Jing SHI, Tao WANG, et al.. Study on the Influence of NH_3 on CH_4 Explosion Characteristics and Reaction Kinetics[J]. Journal of Safety Science and Technology, China, 2020,30(9):51-58.

[20]L PANG, T WANG, Q ZHANG, et al.. Nonlinear distribution characteristics of flame regions from methane–air explosions in coal tunnels[J]. Process Safety and Environmental Protection, 2014(92):193-198.

[21]J WEERHEIJM, J VERREAULT, M. VAN DER VOORT, et al.. Quantitative risk analysis of gas explosions in tunnels[J]. Fire Safety Journal, 2018(97):146-158.

[22]L WANG, H MA, Z SHEN, et al.. A comparative study of the explosion behaviors of H2 and C2H4 with air, N2O and O2[J]. Fire Safety Journal, 2021(119):103260.

[23]LIY C, BI M S, ZHOU Y H, et al.. Experimental and theoretical evaluation of hydrogen cloud explosion with built-in obstacles[J]. International Journal of Hydrogen Energy, 2020,45(51):28007-28018.

[24]GUO C W, JIANG S G, SHAO H, et al.. Suppression effect and mechanism of fly ash on gas explosions[J]. Journal of Loss Prevention in the Process Industries, 2022(74):104643.

[25]WANG Q H, SUN Y L, JIANG J C, et al.. Inhibiting effects of gas-particle mixtures containing CO2, Mg(OH)2 particles, and NH4H2PO4 particles on methane explosion in a 20-L closed vessel[J]. Journal of Loss Prevention in the Process Industries, 2020(645):104082.

[26]DU Y,ZHANG P L,ZHOU Y,et al.. Suppressions of gasoline-air mixture explosion by non-premixed nitrogen in a closed tunnel[J]. Journal of Loss Prevention in the Process Industries, 2014(31):113-120.

[27]Tingxi XU, Xuede WANG, Xiaobo ZHANG, et al.. Numerical Study on the Influence of Air Intake Position on Inerting Characteristics of Fuel Tanks[J]. Aeronautical Computing Technique, 2015,45(4):105–108.

[28]Shuwang WEI, Xinsheng JIANG, Biao HE, et al.. Experimental Study on the Inhibition of Oil and Gas Explosions in Narrow and Confined Spaces by C_3HF_7 [J]. China Safety Science Journal, 2016,12(7):128–133.