1. INTRODUCTION

Natural gas plays an important role in the energy structure of the world and has become an essential part of almost every family. While bringing convenience to people, natural gas also poses greater safety risks. In recent years, some natural gas explosion accidents have occurred frequently, causing serious casualties and social and economic losses.\textsuperscript{1-4} At present, there are more studies on the combustion and explosion problems in the safe transportation process of large aspect ratio pipelines, concentrating on the study of the influence of characteristic parameters such as pressure relief ratio, opening pressure, opening time, and blocking ratio on the natural gas-constrained explosion process.\textsuperscript{5-11} and it was found that when the blockage ratio is set reasonably, the power generated by the explosion can be effectively reduced.\textsuperscript{9-11} Given this, how to scientifically and effectively set the shape of the vent, the blockage ratio and opening position, and other characteristic parameters have become the focus of research by many scholars.

Tang et al. studied the effect of seven opening areas under a rectangular vent on 30% hydrogen explosion characteristics and found that the effect of the blockage ratio on explosion pressure waveform was significant.\textsuperscript{12} Yao et al. concluded that when the ignition position was the same, the overpressure growth rate and the maximum overpressure decreased as the opening rate increased.\textsuperscript{13} Pan et al. studied the explosion experiments of rectangular containers with circular and square vents and found that the amplitude of flame tip propagation oscillations under circular vents was greater than that of the square ones.\textsuperscript{14} Qi et al. studied the effect of three kinds of vents of 25, 50, and 100 cm\textsuperscript{2} on the gasoline vapor-air-premixed explosion characteristics and found that the external pressure of 25 and 50 cm\textsuperscript{2} vents increased more significantly than that of the 100 cm\textsuperscript{2} vent.\textsuperscript{15} Jia et al. studied the effect of NaCL-containing ultrafine water mist with different blockage

### ABSTRACT

Given the current situation of deflagration caused by gas leakage for domestic use and the study of the single shape of the vent, the differential change law of vent parameters on the small aspect ratio of the chamber explosion flame evolution and explosion overpressure and other effects were experimentally investigated. Based on the theory of geometric similarity, the experimental platform of a small length–diameter ratio explosion chamber was designed and built, and the premixed gas explosion experiment was carried out by changing the shape (square and rectangle) and blockage ratio (0.1, 0.3, 0.5, 0.7, and 0.9). The explosion flame structure, flame front position, flame propagation speed, explosion pressure waveform, overpressure peak value, and so on were tested and analyzed. The results showed that the blockage ratio had the most significant effect on flame propagation and explosion flame evolution. With the increase of blockage ratio, the stretching degree of the flame became more and more obvious, the flame front became sharper and sharper, and the sharp flame changed from the lower part to the upper part. The position of the flame front increased rapidly, and the steepness and peak value of explosion overpressure became larger. The oscillation of the flame propagation velocity was more violent after the turn, and the speed of propagation to the outside of the chamber gradually accelerated. In the same blockage ratio, there was a difference in the time point at which the flame propagation velocity turned under the rectangular and square shape of the vent. In blockage ratios of 0.1, 0.3, 0.5, and 0.9, the peak overpressure reduction under the shape of the blast square relative to the rectangle was 41.3, 47.9, 1.03, and 27.6%. This indicated that the explosion relief effect of the square was better than that of a rectangle. The research results can provide a reference and basis for the reasonable deployment of explosion venting and explosion decompression work.
rates of pressure relief ports on the explosion characteristics, and the analysis pointed out that the explosion overpressure was enhanced with the increase of pipe blockage rate. Dong and Peng used FLUENT software to study the explosion pressure changes of methane and air mixture in containers with different venting ports and found that the rate of pressure drop in the container will be faster as the diameter of the venting port increases. Chen simulated the process of venting a 9.5% methane–air mixture in a columnar vessel and found that the farther the vent was from the ignition location, the longer the secondary pressure peak arrival time and the peak pressure duration will be. Kuznetsov et al. carried out a study of hydrogen explosions for five vent sizes and found that the peak pressure was independent of the vent opening area. Wang et al. studied the effect of obstruction ratio on hydrogen explosion in rectangular tubes with obstacles and found that the peak explosion overpressure increased with the increase of obstruction ratio.

In the study of the influence of vent characteristic parameters on explosion overpressure, many scholars have done a lot of experimental research on the explosion with a single vent shape, but there were few reports on the influence of different vent shapes, especially on the indoor premixed natural gas detonation in confined spaces such as kitchens (which can be called combustion chambers with a small height–width ratio). Based on this, this paper, combined with previous description, based on geometric similarity and certain conditions of simplification, a small aspect ratio chamber was designed and built, as shown in Figure 1, to carry out and analyze the systematic study of the explosion overpressure and explosion fire propagation of small aspect ratio space natural gas under the effect of different vent shapes and blockage ratios.

The experimental system consisted of a PMMA small aspect ratio explosion chamber, a pressure relief surface, a gas distribution and ignition system, and a data monitoring system. The small aspect ratio chamber has a cross section of 300 × 300, a 600 mm long rectangular body, and a chamber wall thickness of 30 mm. The upper part of the chamber was set with two threaded holes: the left threaded hole was the pressure sensor hole, whose center was 70 mm from the left end face, and the right threaded hole was the exhaust ball valve hole, whose center was 100 mm from the left end face. The lower part of the chamber had a pressure sensor hole, whose center was 70 mm from the left end face.

Figure 2 shows the design and physical drawings of the small aspect ratio chamber. The pressure relief surface was composed of a Q235 ordinary carbon structural steel plate with a thickness of 10 mm, a sealing rubber gasket, and a PE film. The installation steps of the three components and the main body of the chamber are as follows: laying the PE film along the left side of the chamber pressure relief end → placing the sealing rubber gasket → placing the Q235 ordinary carbon structural steel plate → wearing the hexagonal bolts and fastening, as shown in Figure 3.

2. EXPLOSION SYSTEM OF A SMALL ASPECT RATIO CHAMBER

2.1. Experimental System Composition and Function. In the construction field, the L/D ratio is generally defined as the ratio of the longest dimension in the geometric profile to the product of its cross-sectional circumference (denoted by l) and 4 times the cross-sectional area of the building (denoted by d). When the L/D ratio ≤ 3, it is a small L/D ratio, and kitchens in current residential buildings can usually be considered as small L/D ratio chambers. In addition, kitchen windows can generally be divided into square and rectangular, combined with the previous description, based on geometric similarity and certain conditions of simplification, an experimental platform of a small aspect ratio natural gas explosion chamber was designed and built, as shown in Figure 1, to carry out and analyze the systematic study of the explosion overpressure and explosion fire propagation of small L/D ratio space natural gas under the effect of different vent shapes and blockage ratios.

Figure 1. Test system diagram.
2.2. Naming Rules of the Experimental Working Conditions. Due to the many experimental conditions, to facilitate subsequent analysis and reader’s understanding, the development of naming rules is shown in Figure 4. The vent shape with the letters Z and C, respectively, represents the shape of the blast for the square and rectangular vents; blast area with $A_v$, the area by blockage ratio ($\phi = 1 - S$ blast area/ chamber cross-sectional area), taking values of 0.1, 0.3, 0.5, 0.7, and 0.9. The blast area is shown in Table 1. The shape of the relief opening and the blockage ratio are determined by the opening in the horizontal chamber section of the relief steel plate corresponding to the PMMA chamber. $a$ and $b$ determine the top left vertex of the opening, and $c$ and $d$ determine the bottom right vertex of the opening. Figure 5 shows the pressure relief steel plate at $\phi = 0$, the unit in the figure: millimeter (mm). $a = b = 70$ (mm) and $c = d = 70$ (mm) for $\phi = 0$.

When the shape of the vent hole is square, the position for the upper opening with different blockage ratios corresponds to the pressure relief steel plate, as shown in Table 2. When the shape of the vent is rectangular, the opening position for the upper part of the different blockage ratio corresponds to the pressure relief steel plate, as shown in Table 3. Because the position of the explosion opening is in the upper part, the fixed parameter $B$ (the top left) was selected as a constant value of 70 mm so that explosion experiments with different vent areas can be conducted. As the shape of the vent is square, with the decrease in the vent area, the parameters $a$, $c$, and $d$ would be increased accordingly; and with the increase of parameters $a$, $c$, and $d$, the value of $b$ remains unchanged, and the shape of the vent hole moves up as a whole, so the centroid of the vent hole moves up on the cross section. When the vent shape is rectangular, with the reduction in the vent area, calculated by the rectangular area formula, the parameters $a$, $b$, and $c$ would remain constant at 70 mm, and the parameter $d$ would gradually become larger, leading to a vent hole in the cross section of the center of mass, which would gradually move upward.

In the experiment, first, we should connect the experimental equipment as shown in Figure 1, adjust the position and focal length of the high-speed camera so that it can clearly shoot the whole experimental platform, and then calculate the values that meet the adjustment range of the mass flow meter for CH$_4$ and air when the methane-to-air equivalent ratio is 1 (i.e., the volume fraction of methane was 9.5%), according to Dalton’s law of partial pressure, and adjust the mass flow meter for CH$_4$ and air. By the commissioning data acquisition system and ignition system, we should install the pressure relief surface and

![Figure 2. Design (a) and physical drawings (b) of the chamber.](image)

![Figure 4. Test condition naming method.](image)

| Table 1. Blockage Ratio |
|-------------------------|
| chamber cross-sectional area/m$^2$ | chamber volume/m$^3$ | $\phi$ | $A_v$/m$^2$ |
|-------------------------|------------------|-----|---------|
| 0.09                    | 0.054            | 0.1 | 0.081   |
| 0.3                     | 0.063            | 0.5 | 0.045   |
| 0.7                     | 0.027            | 0.9 | 0.009   |

![Figure 3. Pressure relief surface installation diagram.](image)
then work on gas distribution; an experimenter should open the exhaust ball valve and the gas distribution ball valve and another experimenter should open the high-pressure cylinder screw valve and the air compressor ball valve. We should press the stopwatch timing, allow ventilation for 15 min, and finally work on ignition and experimental raw data collection and maintenance. After conducting an experiment, we should replace the pressure relief surface to change the experimental conditions in order to determine the reliability of experimental data, and each experimental condition was repeated three times.

3. RESULTS AND DISCUSSION

3.1. Effect of Detonation Parameters on the Evolution of the Explosion Flame Structure. Figure 6a,b shows the full local view of the evolution of the explosion flame structure within the small aspect ratio chamber with different blockage ratios for square and rectangular vent shapes, respectively. The evolution of the explosive flame structure within the small aspect ratio chamber was divided into two stages, namely, before and after the rupture of the detonation film as the node. In the first stage, before the bursting of the vent membrane (the moment when the PE membrane bulges to its limit), the premixed natural gas inside the chamber was successfully ignited by the ignition system, and the explosion flame was not constrained by the chamber walls for an initial period of time and propagates as a spherical flame. Later, as the combustion continues, it developed into a finger-shaped flame constrained by the chamber walls. With the generation of explosive combustion products and the exothermic combustion making the gas expand, the blast film was gradually bulged to the deformation limit state by the force. In the second stage, when the PE film reached the limit of the detonation membrane rupture (in the shape of the detonation rectangle, the blockage ratio of 0.3, and the detonation membrane rupture was more obvious), in the internal and external pressure difference and unburned premixed natural gas inertia under the dual role of unburned combustible premixed natural gas exhaust, resulting in a change in the internal flow field of the chamber, when the finger-shaped flame began to stretch deformation, and with the rupture of the detonation membrane, spread to the chamber outside the chamber. Under different experimental conditions, due to the difference in vent area and vent shape, the pressure-flow field generated in the combustion chamber during the explosion was not equal, the gas burning rate was inconsistent, the flame propagation speed was also different, and the flame propagation time was inconsistent. Additional note: for the safety of small aspect ratio chamber explosion experiments, the PMMA chamber wall thickness selected was thicker, as well as the camera’s FPS was lower, so the clarity of the shot to the interior of the chamber was lower.

From Figure 6a,b, it can be seen that the experimental conditions of the vent shape and blockage ratio on the explosion flame structure evolution will have a certain degree of influence, but the degree of influence will have a difference depending on the working conditions: under the square shape, \( \varphi = 0.1 \) and 0.3, stretching deformation of the explosion flame...
from the lower part of the detonation membrane rupture; $\phi = 0.5$, from the middle of the detonation membrane rupture; and $\phi = 0.7$ and 0.9, from the upper part of the detonation membrane rupture spread outside the chamber; Under the rectangular vent shape, $\phi = 0.1$, from the middle of the blast film rupture; and $\phi = 0.3, 0.5, 0.7$, and 0.9, from the upper part of the blast film rupture propagation to the cavity outside, indicating different blast shapes; the location of the explosion flame from the blast film had differences. In the same vent shape, with the increase of the blockage ratio, the explosion flame stretching deformation became more and more obvious, and the front end of the flame with the increase of the blockage ratio became increasingly sharp. Due to the rupture of the detonation membrane after the change in the flow field within the chamber and the superposition of reflected waves, through the detonation port propagation to the chamber outside the explosion flame also became more and more elongated, the

Figure 6. Flame structure evolution in the chamber under the different blasting area at the square (a) and rectangular (b) vents.

Figure 7. Flame front position (a) and flame propagation velocity (b) in each working condition chamber under the conditions of square explosion vents.
shape of the flame also evolved from the lower tip to the upper tip.

3.2. Influence of the Detonation Parameters on the Position and Propagation Speed of the Flame Front. Figures 7 and 8 show the position and propagation velocity of the blast flame front with time within the small aspect ratio chamber with different blockage ratios for square and rectangular vent shapes, respectively. In the same shape of the venting, changing the blockage ratio, before the rupture of the venting film, whether square or rectangular shape, the change in the blockage ratio (0.1, 0.3, 0.5, 0.7, and 0.9), and the explosion flame front position almost had no effect on the five conditions of the flame front position almost overlap. After the rupture of the detonation film, it began to show significant variability. The position of the flame front was the most forward when the blockage ratio was 0.7, and the position of the flame front was the most lagging when the blockage ratio was 0.1. The same shape of the vent, the location of the flame front with the increase of the blockage ratio, and the growth rate showed a clear trend of acceleration.

From Figures 7 and 8, the explosive flame propagation speed can likewise be considered as a node before and after the rupture of the venting film. Before the rupture of the vent membrane, the ignited explosive flame started with a large initial velocity due to the instability of the initial stage of combustion of the explosive flame; in the spherical flame to finger-shaped flame evolution stage, the explosive flame propagation velocity with the development of time showed a trend of oscillation and lasted for a certain period of time (about 20 ms or so). With the explosion flame shape turned into finger-shaped flame propagation, the explosion flame speed had basically a stable value, until the moment of rupture of the vent membrane. After the rupture of the vent membrane, the vent opening, due to flame combustion expansion and flame stretching deformation (the formation of flame cell structure, i.e., flame self-acceleration and flame instability), so that the explosion flame propagation for the second time showed an oscillation trend and lasts for a certain period of time, and compared to the vent membrane rupture before, the oscillation of flame propagation speed increases significantly.

In addition, it can be seen from the analysis of Figures 7 and 8 that after the rupture of the blast film, the opening of the vent, the different shape of the vent on the impact of the explosion flame propagation speed showed some differences. In the rectangular vent shape, the flame propagation velocity turned time relative to the square vent shape, there was a certain delay phenomenon, the explosion flame propagation velocity oscillation amplitude was also more dramatic, especially when the blockage ratio was 0.7 and 0.9, and the difference in oscillation amplitude was more and more significant. The blockage ratio also had a certain effect on the explosion flame propagation and the experimental conditions, and the blockage ratio for the explosion flame propagation rate after the rupture of the vent film also had a significant effect. The same venting shape and the flame propagation speed after the turn of the oscillation amplitude with the increase of the blockage ratio showed a more intense trend, and the propagation to the chamber outside the speed was also gradually accelerated.

3.3. Effect of the Explosion Parameters on the Explosion Pressure Waveform and Overpressure Peak. Figure 9 shows the Z-0.1S working condition, in which "O"
represents the pressure waveform at the top and “Ø” represents the pressure waveform at the bottom. To facilitate the analysis of pressure waveforms and overpressure peaks, the Z-0.1S working condition was used as an example, and a more detailed description was given to prepare for the subsequent analysis of pressure waveforms and overpressure peaks.

It is clear from Figure 9 that there were multiple pressure peaks, that is, \( P_{b} \), \( P_{ext} \), \( P_{mfa} \), and \( P_{rev} \). In the early stages of the explosion, with the combustion reaction, the combustion exotherm made gas expansion, the pressure inside the chamber gradually increased and for the first time reached the peak \( P_{b} \); the explosion venting membrane was subjected to the limit state rupture, heating, and mixed gas exhaustion, so that the pressure inside the chamber was rapidly reduced. When the vent was opened, the pressure shock rose due to the change of the flow field in the chamber, causing the occurrence of Helmholtz shock,\(^{26,27}\) part of the premixed natural gas inside the chamber leaks out from the broken membrane under the action of pressure outflow, and the gas cloud formed outside was ignited,\(^{28,29}\) causing a secondary explosion, resulting in a dramatic change of the pressure inside the chamber and the formation of the characteristic pressure peak \( P_{ext} \). With further

Figure 10. Pressure waveform in the chamber of each working condition under the condition of square (a) and rectangular (b) explosion vents.
time, when the explosion flame propagated to the walls of the chamber, the pressure continued to increase to reach a peak, which in turn formed a pressure peak $P_{mfa}$. In the late stages of deflagration exhaust, due to the role of negative pressure, a certain amount of fresh air and flame was sucked into the chamber, and the remaining unnatural gas began to burn, resulting in an increase in pressure, the formation of peak pressure $P_{rev}$. Finally, at the end of the explosion in the chamber, the pressure value showed a negative value and did not return to the zero value, which was the result of the high temperature generated by the explosion acting on the pressure sensor.

**Figure 10a,b** shows the blast pressure waveforms and blast overpressure peaks with time in small aspect ratio chambers with different blockage ratios for square and rectangular vent shapes, respectively. In the figure, “P” indicates the peak pressure waveform measured by the upper pressure sensor, and “p” indicates the peak pressure waveform measured by the lower pressure sensor.

As can be seen in **Figure 10**, different blockage ratios had a significant effect on the explosion pressure at the same vent shape. The blast overpressure curve generally showed a sudden rise, followed by a fall, then a sudden rise, and finally a fall back to a steady state, which was mainly related to the explosion reaction and propagation process; the magnitude of the blast overpressure and the blast overpressure waveform measured by the pressure sensors arranged above and below obviously had certain variability. In the same vent shape, with the increase of the blockage ratio, the explosion overpressure peak gradually increased, and the sudden increase in magnitude also increased significantly. This was mainly due to the opening of the vent, and the pressure change of the combustion chamber was mainly affected by the interaction of two processes: one was the combustion of combustible gas in the combustion chamber caused by the increase in temperature and pressure, which was mainly affected by the flame surface area and combustion rate; second, the combustible gas is released from the vent to the external space, resulting in the temperature and pressure drop, which is mainly determined by the area of the vent and the pressure within the combustion chamber. When the blockage was relatively large (the area of the vent was smaller), the gas in the combustion chamber was impacted by the high-speed air flow, and the high pressure generated by the vent cannot be discharged on time, and the pressure accumulates at the vent. Therefore, the explosion overpressure at the vent will rise.

**From Figure 10**, the peak explosion overpressure measured by upper and lower pressure sensors in different working conditions were extracted, as shown in Figures 11 and 12.
It can be seen from Figures 11 and 12 that under the same shape of the vent, the blockage ratio had a significant influence on the explosion overpressure peak value. With the increase of blockage ratio, the overall trend of the explosion overpressure increases (except for some pressure points). This was primarily attributed to the fact that when the surface of the explosion flame touched the wall of the combustion chamber, due to the restriction of the wall and the airflow disturbance caused by the reduction of the vent area, the flame gradually stretched along the wall, accelerating combustion, resulting in an increase in pressure. Compared with Figures 11a and 12a, the peak explosion overpressure \( P_1 \) and \( P_2 \) of the square and rectangular vents was at the maximum blockage ratio of 0.9 and the maximum peak overpressure of 167.01 and 230.58 mbar, respectively. By comparing Figures 11b and 12b, the peak explosion overpressure of the square vent \( p_1 \), \( p_2 \), and \( p_3 \) reached the maximum overpressure of 39.81, 56.24, and 119.2 mbar at the blockage ratios of 0.9, 0.9, and 0.7, respectively. The explosion overpressure peaks \( p_1 \), \( p_2 \), and \( p_3 \) of the rectangular vent reached the maximum at the blockage ratios of 0.9, 0.9, and 0.7, respectively, with maximum overpressure peaks of 78, 48.43, and 68.14 mbar. Therefore, there was a strong relation between blockage ratios and the explosion overpressure. For further analysis of the difference in the maximum overpressure peak of the square and rectangular vent under different blockage ratios, the maximum overpressure peak under different working conditions was elected from Figures 11 and 12, as shown in Figure 13.

![Figure 13. Maximum overpressure in each working condition under square and rectangular vents.](image)

From Figure 13, it can be seen that under the same blocking rate, different shapes of the vent had significant influence on the peak overpressure. Rectangular vent under the peak overpressure increased significantly higher than the square, rectangular vent under the peak overpressure with the increase in the blockage ratio showed a first rising, then a falling, and a rapidly rising trend, and the peak overpressure under the square vent with the increase in the blockage ratio showed a rising trend. The rate of the peak overpressure rise was smaller when the blockage ratio was lower than 0.7, above which the peak overpressure surged sharply. This result can be attributed to the amount of unburnt gas discharged through the varying venting area. In addition to the blockage ratio of 0.7 working conditions, in the same blockage ratio, the square venting effects were better than the rectangular venting effect; the blockage ratios were 0.1, 0.3, 0.5, and 0.9; and the peak overpressure reductions were 41.3, 47.9, 1.03, and 27.6%, respectively.

### 4. CONCLUSIONS

1. In the same vent shape, flame stretching deformation became more and more obvious as the blockage ratio increased, the front end of the flame became more and more pointed, pointed flame was also followed by the lower to the upper transformation, the flame array position increased with the increase of blockage ratio, and the growth rate showed a significantly accelerated trend.

2. In the rectangular vent shape, the flame propagation velocity turned time relative to the square, and there was a certain delay; when the blockage ratio was 0.7 and 0.9, the difference in propagation velocity oscillation amplitude was more and more significant. In the same venting shape, with the increase of blockage ratio, the flame propagation velocity after the turn of the oscillation amplitude showed a more intense trend; the propagation to the cavity outside the speed was also gradually accelerated.

3. In the experimental conditions, the explosion flame in the explosion vent membrane before the rupture in accordance with the form of spherical flame, finger-shaped flame evolution, and rupture after the explosion flame violent shock, the flame became wrinkled. Explosion overpressure curve was the first sudden surge, then dropped back, then a sudden rise, and finally returned to normal pressure. In the same venting shape, with the increase of blockage ratio, the explosion overpressure increased the steepness, and the explosion overpressure peak became larger.

4. In the shape of the different vents, the peak overpressure of the explosion was maximum in a blockage ratio of 0.9, but the maximum peak overpressure of the square and rectangular shape of the venting was different, respectively, 167.01 and 230.58 mbar. The square venting effect was usually better than the rectangular venting effect; the blockage ratios were 0.1, 0.3, 0.5, and 0.9; and the peak overpressure reductions were 41.3, 47.9, 1.03, and 27.6%, respectively.

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Notes
The authors declare no competing financial interest.

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REFERENCES

(1) Pang, L.; Hu, Q. R.; Ma, F. F.; Lv, P. F.; Yang, K. Influence of characteristic parameters of explosion relief surface on overpressure peak value of natural gas explosion. J. Saf. Sci. Technol. 2020, 16, 126–131.

(2) Yu, M.; Wan, S.; Xu, Y.; Zheng, K.; Liang, D. Suppressing methane explosion overpressure using a charged water mist containing a NaCl additive. J. Nat. Gas Sci. Eng. 2016, 29, 21–29.

(3) Li, A.; Si, J.; Zhou, X. Experimental Research on Rapid Fire Zone Sealing and Explosion Venting Characteristics of an Explosion Venting Door Using a Large-Diameter Explosion Pipeline. ACS Omega 2021, 6, 27536–27545.

(4) Liu, J.; Yu, R.; Ma, B.; Tang, C. On the Second Explosion Limits of Hydrogen, Methane, Ethane, and Propane. ACS Omega 2020, 5, 19268–19276.

(5) Xu, J. N.; Ni, Z. H.; Lu, J.; Xu, J. F.; Sun, H. J.; Zhou, J.; Jiang, X. S. Experimental study on explosion and suppression of gasoline-air mixture in large length-diameter ratio pipeline. J. Saf. Sci. Technol. 2021, 17, 77–83.

(6) Tang, X. S.; Wei, X.; Zhao, Y. D.; Li, J. Y.; Li, J.; Yu, B. B. Oil and gas explosion experiment of long and narrow pipelines with different length-diameter ratio. Oil Gas Storage Transp. 2020, 39, 879–884.

(7) Zhang, Y. M.; Zhang, H. J.; Qin, K. Analysis of space explosion accident of oil and gas pipeline with large length-diameter ratio — Taking “8.7” wellhead explosion accident of heavy oil thermal recovery in Xinjiang Oilfield Company of PetroChina as an example. J. Saf. Environ. 2008, 03, 93–96.

(8) Zhang, S.; Zhang, Q. Effect of vent size on vented hydrogen-air explosion. Int. J. Hydrogen Energy 2018, 43, 17788–17799.

(9) Pang, L.; Hu, Q.; Zhao, J.; Lv, P.; Sun, S.; Yang, K. Numerical study of the effects of vent opening time on hydrogen explosions. Int. J. Hydrogen Energy 2019, 44, 15689–15701.

(10) Ren, S. F.; Chen, X. F.; Wang, Y. J.; Li, D. K.; Liu, J. Experimental study on the influence of unconstrained explosion venting on methane/air flame propagation characteristics. China Saf. Sci. J. 2013, 23, 84–88.

(11) Huang, Z.; Chen, X. F.; Dong, L. H.; Li, Z. Experimental study on gas explosion of industrial containers. J. China Coal Soc. 2013, 38, 388–392.

(12) Tang, Z.; Li, J.; Guo, J.; Zhang, S.; Duan, Z. Effect of vent size on explosion overpressure and flame behavior during vented hydrogen–air mixture deflagrations. Nucl. Eng. Des. 2020, 361, 110578.

(13) Yao, Z.; Deng, H.; Zhao, W.; Wen, X.; Dong, J.; Wang, F.; Chen, G.; Guo, Z. Experimental study on explosion characteristics of premixed syngas/air mixture with different ignition positions and opening ratios. Fuel 2020, 279, 118426.

(14) Pan, C.; Wang, X.; Li, G.; Liu, Y.; Jiang, Y. Influences of a square and circular vent on gasoline vapor explosions and its propagation: Comparative experimental study. Case Stud. Therm. Eng. 2021, 27, 101225.

(15) Qi, S.; Du, Y.; Wang, S.; Zhou, Y.; Li, G. The effect of vent size and concentration in vented gasoline-air explosions. J. Loss Prev. Process. Ind. 2016, 44, 88–94.

(16) Jia, H. L.; Xiang, H. J.; Li, D. H.; Zhai, R. P. Suppression of explosion in pipelines with different blockage rates by ultra-fine water mist containing NaCl. Explo. Shock Waves 2020, 40, 34–43.

(17) Dong, B. Y.; Peng, X. Influence of explosion relief area on pressure in explosion relief process of cylindrical vessel. Ind. Saf. Environ. Protect. 2012, 38, 47.

(18) Chen, Z. H. Numerical analysis of the influence of vent parameters on the venting process of cylindrical vessels. Chin. Min. Mag. 2015, 24, 138–140+156.

(19) Kuznetsov, M.; Friedrich, A.; Stern, G.; Kothchourko, N.; Jallais, S.; L’Hostis, B. Medium-scale experiments on vented hydrogen deflagration. J. Loss Prev. Process. Ind. 2015, 36, 416–428.

(20) Wang, Q.; Luo, X.; Li, Q.; Rui, S.; Wang, C.; Zhang, A. Explosion venting of hydrogen-air mixture in an obstructed rectangular tube. Fuel 2022, 310, 122473.

(21) Li, T. X. Study on the influence of square and rectangular vent on explosion overpressure. Fire Protect. 2020, 6, 67–68+70.

(22) Xiao, H.; Makarov, D.; Sun, J.; Molkov, V. Experimental and numerical investigation of premixed flame propagation with distorted tulip shape in a closed duct. Combust. Flame 2012, 159, 1523–1538.

(23) Chen, D. L.; Sun, J. H.; Liu, Y.; Ma, H. F.; Han, X. B. Propagation characteristics of premixed methane-air flames. Explos. Shock Waves 2008, 28, 385–390.

(24) Sun, S.; Qiu, Y.; Xing, H.; Wang, M. Effects of concentration and initial turbulence on the vented explosion characteristics of methane-air mixtures. Fuel 2020, 267, 117103.

(25) Mokhtar, K. M.; Md Kasmani, R.; Hassan, C. R. C.; Hamid, M. D.; Emami, S. D.; Nor, M. I. M. Reliability and applicability of empirical equations in predicting the reduced explosion pressure of vented gas explosions. J. Loss Prev. Process. Ind. 2020, 63, 104023.

(26) Carcassi, M.; Schiavetti, M.; Pini, T. Non-homogeneous hydrogen deflagrations in small scale enclosure. Experimental results. Int. J. Hydrogen Energy 2018, 43, 19293–19304.

(27) Schiavetti, M.; Carcassi, M. Maximum overpressure vs. H2 concentration non-monotonic behavior in vented deflagration. Experimental results. Int. J. Hydrogen Energy 2017, 42, 7494–7503.

(28) Yao, N.; Bai, C.; Wang, L.; Liu, N. Investigation on the Explosion Characteristics of an Aluminium Dust-Diethyl Ether-Air Mixture. ACS Omega 2021, 6, 18868–18875.

(29) Zhang, Y.; Chen, K.; Yang, J.; Chen, J.; Pan, Z.; Shi, W.; Meng, X.; Zhang, X.; He, M. The Performance and Mechanism of the Green Explosion Suppressant SGA for Coal Dust Explosion Suppression. ACS Omega 2021, 6, 35416–35426.

(30) Chen, Y.; Li, Z.; Ji, C.; Liu, X. Effects of hydrogen concentration, non-homogenous mixtures and obstacles on vented deflagrations of hydrogen-air mixtures in a 27 m³ chamber. Int. J. Hydrogen Energy 2020, 45, 7199–7209.

(31) Zheng, L.; Li, G.; Wang, Y.; Zhu, X.; Pan, R.; Wang, Y. Effect of blockage ratios on the characteristics of methane/air explosion suppressed by BC powder. J. Hazard. Mater. 2018, 355, 25–33.