INVESTIGATION OF THE EXPLOSION CHARACTERISTICS OF ETHYLENE-AIR PREMIXED GAS IN FLAMEPROOF ENCLOSURES BY USING NUMERICAL SIMULATIONS

by

Dong LI[a,b*], Shijie DAI[a], and Hongwei ZHENG[c]

[a] School of Mechanical Engineering, Hebei University of Technology, Tianjin, China
[b] CNOOC Tianjin Chemical Research and Design Institute Ltd, Tianjin, China
[c] Engineering Training Center, Hebei University of Technology, Tianjin, China

Original scientific paper
https://doi.org/10.2298/TSCI220905189L

Flameproof enclosures are widely installed as safety equipment at dangerous industrial sites to reduce ignition risks. However, electrical components typically installed in such flameproof enclosures for the production process can cause ignition and compromise the safety of the enclosures. Thus, in such cases, the explosive characteristics of the flameproof enclosures is severely affected. Accidental gas explosions in industrial sites rarely occur under standard operating conditions. Premixed gas explosions in flameproof shells are complex processes. A 560 mm × 400 mm × 280 mm flameproof enclosure commonly used in industrial sites was used to investigate the phenomenon. The explosion characteristics of ethylene-air premixed gas in the flameproof enclosure was simulated using FLUENT software to investigate the influences of ignition source location, ignition source energy, ambient temperature, and obstacles on the maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index of the flameproof enclosure. The results revealed that the surface area of heat exchange considerably influences the maximum explosion pressure of the flameproof enclosure. The larger the ignition energy is, the larger the maximum explosion pressure value, the maximum rate of explosion pressure rise, and the maximum explosion index of the flameproof enclosure are. With the increase in the ambient temperature, the maximum explosion pressure decreased, whereas the maximum rate of explosion pressure rise and the maximum explosion index exhibited limited change. The results of this study provide theoretical guidance for the design and suppression of flameproof enclosures.

Key words*: flameproof enclosure, ignition source, temperature, obstacle*

Introduction

Explosion-proof electrical equipment is widely used in hazardous places with explosive gas environments. Electrical equipment used in industrial sites with explosive gas environments that generate high temperature or sparks during operation is usually designed as flameproof type, and its explosion-proof performance is achieved through flameproof enclosures. Flameproof enclosures are designed to withstand explosive mixtures entering the interior of the enclosures through any joint surface or structural gaps. The ignition of the external explosive gas environment formed by one or more gases or vapors can severely damage equipment and

* Corresponding author, e-mail: lidong@pcec.com.cn

cause catastrophic fires [1]. Flameproof enclosures should have sufficient mechanical strength to withstand the explosive pressure generated by the explosion inside the enclosure. The maximum explosion pressure, maximum pressure rate, and maximum explosion index are critical indexes for evaluating the performance of flameproof enclosures [2], Flameproof shells should be designed according to the aforementioned indicators in a cost-effective manner.

Studies on the explosive characteristics of premixed fuels have focused on pipe-lines for investigating the influence of ignition source location, ignition source energy, initial temperature, and obstacles on the explosive characteristics of premixed fuels. Kindracki *et al*. [3] investigated the ignition source location on the explosive characteristics of combustible materials by using a pipe of diameter and length of 128.5 and 1325 mm, respectively, The results revealed that the maximum explosion pressure and maximum explosion pressure rise rate of the middle ignition were higher than those of the end ignition when the pipe was horizontally or vertically. Bi *et al*. [4] investigated a pipe of diameter 128 mm and AN L/D of 6-10.35, the ignition and detonation characteristics of premixed methane-air in a closed pipe with a large L/D ratio were numerically simulated using FLUENT software, the results revealed that the ignition position considerably influenced the ignition and detonation characteristics of the closed pipe, and the maximum explosion pressure at the center ignition was higher than that at the end ignition. In the research of ignition source energy on the explosive characteristics of combustibles, Li *et al*. [5] investigated combustible explosion characteristics and ignition sources on semi-open pipes under five ignition powers (133 W, 155 W, 211 W, 248 W, and 275 W). The experimental results revealed that when the ignition power was 275 W, the pressure increased the fastest and temperature peak was the highest. The peak explosion pressure increased with the increase in the ignition power, thus exhibiting a positive correlation. Ajrash *et al*. [6] investigated the influence of three electric fire energy conditions (1 kJ, 5 kJ, and 10 kJ) on the explosion parameters of the methane-coal dust mixture. The experimental results revealed that the higher the ignition energy is, the higher the explosion pressure is. Zhou *et al*. [7] experimentally investigated a 12 m long seamless stainless steel straight pipe and revealed that the higher the ignition energy is, the greater the maximum explosion peak pressure of propane-air premixed gas is. In the research of temperature on the explosion characteristics of combustibles, Pekalski *et al*. [8] evaluated the effect of the temperature on the explosive characteristics of combustible materials. Studies on the explosion of a 20 L sphere under a constant initial pressure revealed that the maximum explosion pressure was a linear function of the reciprocal of the initial temperature. Gieras *et al*. [9] investigated the explosion characteristics of a 40 dm^3 container and detailed that when the initial ambient pressure remained unchanged, the maximum explosion pressure of the methane-air mixture decreased with the increase in the initial temperature, whereas the increase rate in the maximum explosion pressure increased slightly. Mitu *et al*. [10] discovered that the maximum explosion pressure of ethanol and air mixture decreased with the increase in the initial temperature, and the initial pressure was more influential than the initial temperature on the increase rate of the maximum explosion pressure. Grabarczyk *et al*. [11] investigated the effect of the initial temperature on the explosion pressure of isooctane, toluene, methanol and obtained the same conclusion for three mixtures. The maximum pressure increased with the decrease in the initial temperature. Li *et al*. [12] investigated the methane-hydrogen-air mixture as the experimental gas and concluded that with the increase in the initial temperature, the maximum explosion pressure decreased, whereas the increase rate of the explosion pressure increased. In the research of the explosive characteristics of the obstacles to the combustibles, Zhao *et al*. [13] experimentally and numerically studied the influence of the initial temperature on the explosion process of premixed hydrogen gas with air. The results revealed that when the initial temperature increased by 20%, the total amount of matter in the container decreased and the maximum explosion pressure decreased by 15%. Yu *et al*. [14] investigated the influence of obstacles on the explosion characteristics of hydromethane under various number of obstacles in the pipe-line. The results revealed that the maximum explosion pressure increased with the increase in the number of obstacles in the same hydrogen content. Ding *et al*. [15] performed experiments for five obstacles (slab, cuboid, triangular prism, four-prism and cylinder with blocking ratios of 20%, 40% and 60%, respectively) in flame propagation in a premixed methane pipe-line. The experimental results revealed that the maximum overpressure in the pipe-line without obstacles was 9.3×10^4 Pa, and the maximum overpressure in obstructed pipe-lines was $1.5\text{-}2.1 \cdot 10^5$. At the same blocking ratio, plate and prism can increase the flame propagation velocity and overpressure considerably. With the cuboid in center, cylindrical and quadrilateral prisms exhibit limited influence. Andrews *et al*. [16] studied the influence of barrier separation distance on the acceleration of explosive flame in pipe-line and revealed that the barrier separation distance considerably influenced the maximum pressure and pressure development curve. For dust explosion research, the focus of the research is mainly on the suppression of dust explosion [17, 18].

Studies on the explosion characteristics of premixed combustibles have focused on the experimental and numerical simulation of pipe-lines. However, studies on flameproof shells have revealed that flameproof shells exhibit the *gap flameproof principle*. Furthermore, the flameproof joint surface of the flameproof shell is a crevice, which differs from the shape of pipes. Electrical components are typically installed inside flameproof enclosures. Therefore, the influence of electrical components on flame propagation should be studied.

The explosion-proof enclosure is designed to install various types of electrical equipment and components inside, and the enclosure pressure test is carried out according to standard conditions during design and testing. However, when it is installed in an industrial site, it is different from the standard conditions from the analysis of internal and external factors. Electrical equipment and components are installed in the flameproof enclosure, which becomes the ignition source during operation, and the location and energy of the ignition source are non-standard. The ambient temperature has changed, and the temperature has a gradient. The effects of ignition source location, ignition source energy, ambient temperature, and obstacles on the explosion characteristics of premixed gas in flameproof enclosure require further study.

The explosion of combustible gas in flameproof enclosures is a complex process. It is difficult to get the whole process of explosion by experimental means. Numerous boundary conditions increase the cost of the experiments. Therefore, numerical simulation should be conducted to overcome these drawbacks. In this study, FLUENT software was used to numerically investigate the influence of ignition source location, ignition source energy, temperature, and electrical components on the maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index of the flameproof enclosure to provide theoretical guidance for the design and explosion suppression of flameproof enclosures.

Experimental system

The experimental device consisted of a gas distribution system, an electric control system, an explosion tank, and a pressure acquisition system. The gas distribution system was used to complete the concentration ratio of combustible gas, which is composed of air compressor – 1, gas storage tank – 2, combustible gas cylinder – 3, and supporting devices – 4, 6, 7. The explosion tank – 8 was used to arrange experimental sample – 9, which is used to avoid the danger caused by the unqualified sample. The electric control system was used to control gas distribution and ignition. The ignition system consists of spark plug and control system – 10. The pressure acquisition system was composed of the pressure sensors, charge amplifiers and data acquisition system to measure the pressure – 5, 11, 12. The schematic of the experimental device is displayed in fig. 1. Standard ambient conditions of 1 bar pressure and 40% humidity were used. The flameproof shell was filled with 8 ±0.5% ethylene by volume to air at a standard atmospheric pressure, and the premixed gas was ignited [1].

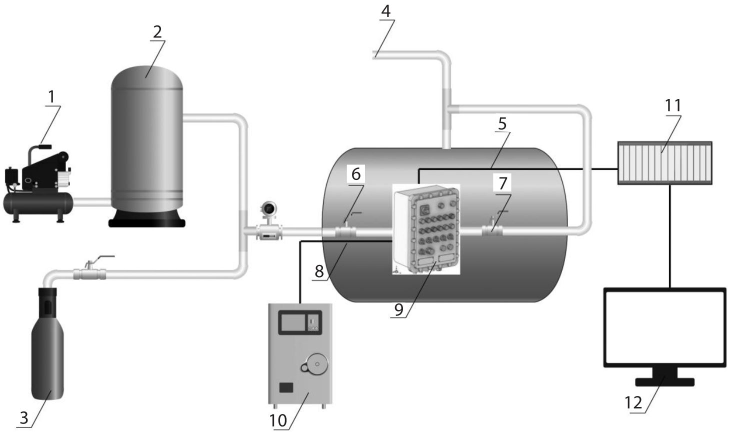

Figure 1. Schematic of the experimental system: *1 – air compressor, 2 – air tank, 3 – C_2H_4, 4 – evacuation tube, 5 – pressure measurement, 6 – intake valve, 7 – outlet valve, 8 – explosion tank, 9 – flameproof shell, 10 – electronic control system, 11 – pressure acquisition system, and 12 – display unit*

Numerical simulation method and validation

Physical model

The flameproof shell with an external size of 560 mm × 400 mm × 280 mm was used to study internal premixed gas explosion characteristics. Electrical components, such as

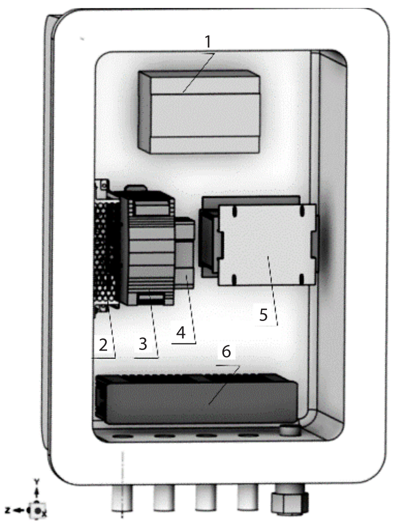

Figure 2. Schematic of the arrangement of electrical components inside the flameproof enclosure: *1 – programmable logic controller (length = 238 mm, width = 90 mm, height = 80 mm), 2 – charger (length = 32 mm, width = 152.4 mm, height = 76.2 mm), 3 – uninterruptible power supply (length = 55.5 mm, width = 125.2 mm, height = 100 mm), 4 – relay (length = 6.1 mm, width = 80 mm, height = 86 mm), 5 – transformer (length = 114 mm, width = 115 mm, height = 120 mm), and 6 – battery (length = 221 mm, width = 44 mm, height = 99 mm)*

programmable logic controller, transformer, uninterruptible power supply, relay, transformer and battery were installed inside the flameproof shell. The schematic of the internal lay-out is displayed in fig 2.

Grid division

The FLUENT software was used to solve numerical simulation, and the explosion process of the flameproof shell premixed ethylene-air was reproduced. In this study, the physical model of the tetrahedral unstructured grid division was adopted. To ensure grid independence and the convergence of the calculation results, the grid independence was evaluated by repeating the simulation with different grid numbers, the number of grids divided were 807538, 14939461, and 2689103, as shown in fig. 3, the differences of the maximum explosion pressure were only marginal, therefore, the number of grids used in this study was 2689103. The surface mesh division is displayed in fig 4, and the volume mesh division is displayed in fig. 5. In the numerical calculation, the time step was set to be 0.0001 seconds, and each time step was set to be 20 iterations. The calculation residual of each time step was less than 0.001, which ensured the convergence of the calculation results. Because of numerous 3-D calculations, considering that the maximum explosion pressure value in the design of flameproof shell is a critical parameter in the calculation of the wall thickness, the calculation is not performed when the explosion pressure peaks, which satisfies the requirements of this study.

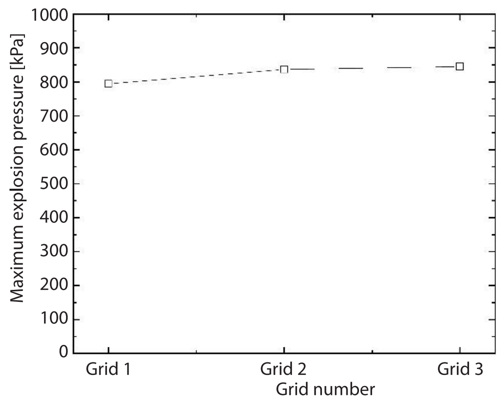

Figure 3. Grid independence analysis using 807538, 14939461, and 2689103 grid number

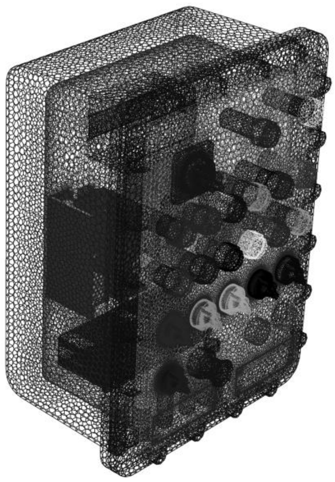

Figure 4. Model surface mesh generation

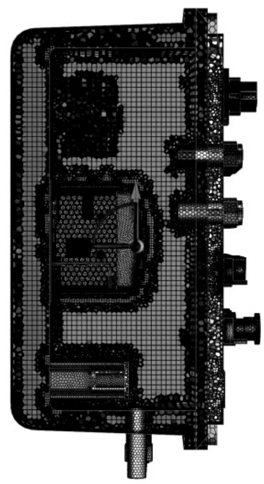

Figure 5. Model volume mesh generation

Mathematical model

According to the explosive reaction, the governing equations are mass conservation equation (continuity equation), momentum conservation equation, energy conservation equation, and component transport and reaction model equation (explosion) [19].

The explosive reaction has high velocity so the influence of turbulence on energy equation, momentum equation, energy equation, and explosive reaction should be considered. In engineering applications, the k-ε turbulence equation is widely used, and the calculation process is stable and accurate. These results include the compressibility of the fluid, buoyancy, and the effect of explosion on the flow. The k-ε turbulence equation is categorized into three models, namely standard k-ε model, RNG k-ε model, and realizable k-ε model, according to the viscosity calculation method, the Prandtl number controlling the turbulent diffusion, and the dissipation term. Among the three models, the realizable k-ε model exhibits the broadest adaptability [20, 21].This calculation is the most accurate. The realizable k-ε model was adopted for the turbulence equation, and the governing equation is:

$$\frac{\partial(\rho k)}{\partial t}+\nabla(\rho k\vec{\mathrm{v}})=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right]+G_k-\rho\varepsilon-Y_M \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\nabla(\rho\varepsilon\vec{\mathrm{v}})=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon^2}{k}C_{3\varepsilon}G_b \tag{2}$$

where ρ is the fluid density, t – the time, k – the turbulent kinetic energy, $\vec{\mathrm{v}}$ – the velocity vector, ε – the turbulence dissipation rate, σk and σ_ε are turbulence Prandtl number of K and σ, respectively, C_2, $C_{l\varepsilon}$ and $C_{3\varepsilon}$ are calculation constants of turbulence model, $C_2 = 1.9$, $C_{l\varepsilon} = 1.44$, $C_{3\varepsilon} = 1.92$, μ_t – the turbulence viscosity, $\mu_t = \rho C_\mu(k^2/\varepsilon)$, C_μ – the turbulence viscosity constant, G_k – the turbulence kinetic energy generated because of the average velocity gradient, and Y_M – the effect of fluctuation expansion in compressible turbulence on the total dissipation rate.

Setting of the numerical simulation condition

Numerical simulations were conducted on the explosion characteristics of ethylene-air premixed gas in the flameproof shell by using FLUENT software. The working conditions are presented in tab. 1. The ethylene-air volume ratio was (8 ±0.5)%, which was consistent with the experimental requirements. Eight working conditions were numerically simulated. Working conditions 1-3 were set to study the influence of the ignition position on the explosive char-

Table 1. Simulated working conditions

Working conditions	T	Ignition source location	E_j	Obstacle
1	298.15	Top	300	Absence
2	298.15	Center	300	Absence
3	298.15	Bottom	300	Absence
4	298.15	Center	200	Absence
5	298.15	Center	600	Absence
6	Operation	Center	300	Absence
7	328.15	Center	300	Absence
8	328.15	Center	300	Presence

acteristics of the flameproof enclosure. In working Conditions 4 and 5, the influence of the ignition energy on the explosive characteristics of flameproof enclosure was studied. Working Conditions 6 and 7 revealed the influence of the ambient temperature on the explosion characteristics of the flameproof enclosure. Working Conditions 7 simulate the influence of the internal temperature gradient on the explosion characteristics of the flameproof enclosure when the ambient temperature was 328.15 K. In working Conditions 8, the influence of the empty flameproof shell on explosion characteristics was studied. A monitoring point was set at the center of the symmetry plane of the flameproof enclosure in all working conditions.

Comparison between numerical simulation results and experimental data

To verify the reliability of the premixed gas explosion of the flameproof shell by FLUENT software and provide a basis for the analysis and discussion of the numerical simulation results under multiple conditions in the next step, the ambient temperature was 298.15 K, the ignition energy was 300 W, and the upper ignition was the boundary conditions for the experiment [1]. Figure 6 displays a comparison between the maximum pressure values of five experimental explosions and the numerical simulation results. According to the analysis results, the deviation between the numerical simulation results and the experimental mean was 6.29%, which is acceptable.

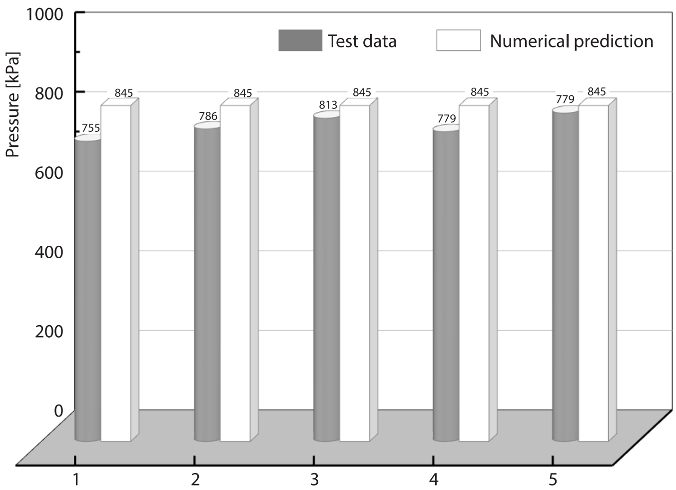

Figure 6. Comparison of maximum explosion pressures for the numerical simulation and experiments

Results and discussion

Influence of the ignition position on the explosion characteristics of the premixed gas of flameproof enclosure

The upper ignition source is 160 mm away from the center of the flameproof enclosure, the middle ignition source is at the center of the flameproof enclosure, and the lower ignition source is 160 mm away from the center of the flameproof enclosure. Figure 7 displays the explosion pressure curve of the flameproof enclosure at various ignition positions. The analysis of the the maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index at various ignition positions are presented in tab. 2. As displayed in fig. 7 and tab. 2, in terms of the maximum explosion pressure, the ignition in the middle is

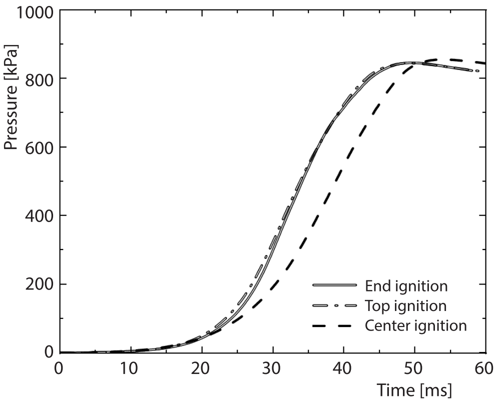

Figure 7. Explosive pressure curve at various ignition positions

slightly higher than that in the upper and lower parts, and the ignition in the upper part is lower than that in the lower part because during the explosion process, the less heat loss caused by the combustion reaction, the greater the explosion pressure is. The heat loss depends on the surface area of the flame front in contact with the wall. Figure 8 displays the temperature field distribution in the flameproof enclosure at various ignition positions when t = 0.016 seconds. At this stage, the flame surface does not contact with the solid wall during intermediate ignition, and heat exchange occurs between the upper and lower ignition surfaces and the solid surface during intermediate ignition. Furthermore, compared with the lower ignition, the surface area of the heat exchange between the upper ignition and the solid wall is larger than that of the lower ignition, as shown in figs. 2 and 8. Therefore, the maximum explosion pressure of the upper ignition is lower than that of the lower ignition. This phenomenon is in contrast to the maximum pressure rise speed and maximum explosion index. Ignition occurred when the upper and lower ignition parameters were almost identical because the ignition flame reached the middle wall on both ends of the ignition. This ignitions is longer than axisymmetric structures at both ends of the ignition position because this result occurs at almost the same time of arrival in the wall.

The implication of this finding is that manufacturers should design flameproof enclosures such that electrical components are placed as far as possible, and the lay-out should be centralized for heat dissipation.

Table 2. Parameters of explosion characteristics at various ignition positions

Working conditions	Ignition source location	E_j	P_m	$(dp/dt)_{max}$	K_{max}
1	Top	300	845	45	261.91
2	Center	300	856	38	224.87
3	Bottom	300	846	46	266.45

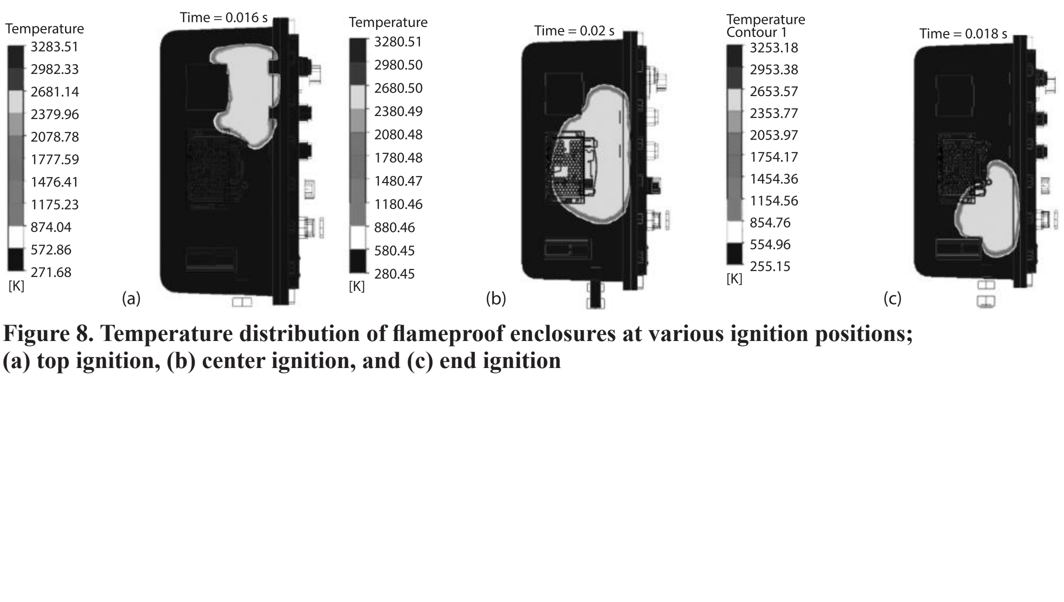

Figure 8. Temperature distribution of flameproof enclosures at various ignition positions; (a) top ignition, (b) center ignition, and (c) end ignition

Influence of ignition energy on the explosion characteristics of premixed gas in flameproof enclosures

Figure 9 displays the explosive pressure curves of flameproof enclosures during intermediate ignition when the ignition energy is 200 W, 300 W, and 600 W. The maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index of the flameproof enclosure under various ignition energies were analyzed, as presented in tab. 3. The analysis revealed that with the increase in the ignition energy, the maximum explosion pressure value, the maximum explosion pressure rise rate, and the maximum explosion index of the flameproof enclosure increased. This phenomenon could be attributed to the mechanism of the ethylene reaction [22, 23]. The higher the ignition energy is, the higher the energy molecules can obtain per unit time; the greater the probability of fuel molecule collision; the higher the generation rate of H, O, and OH. The faster the explosive reaction and explosion pressure are [24]. The pressure rise rate and maximum explosion index increased.

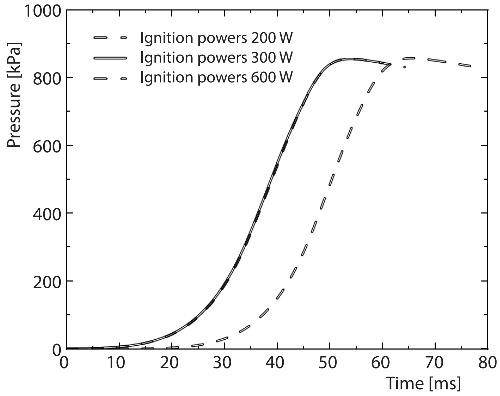

Figure 9. Explosive pressure curve at various ignition energies

Thus, the influence of the ignition source power on the explosion pressure should be considered when testing the pressure of flameproof enclosures.

Table 3. Parameters of explosion characteristics at various ignition energies

Working conditions	E_j	P_m	$(dp/dt)_{max}$	K_{max}
4	200	854	39	227.40
2	300	856	38	224.87
5	600	858	40	232.70

Influence of the ambient temperature on the explosion characteristics of the premixed gas of the flameproof enclosure

Figure 10 displays the explosion pressure curves when the ambient temperature inside the flameproof enclosure is 298.15 K and 328.15 K, respectively, and normal operation of equipment. When equipment is in normal operation, the operating conditions are: ambient temperature is 328.15 K, south China Sea, 12-13 hours in summer, and no wind. Considering solar radiation, fig. 11 displays the temperature distribution cloud diagram inside the flameproof shell. The maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index under various ambient temperatures were analyzed, as presented in tab. 4. Figure 10 reveals that the maximum explosion pressure decreases with the increase in the ambient temperature, which can be explained by eq. (3). The pressure after explosion is inversely related to the temperature of unignited gas. The higher the temperature of unignited gas is, the lower the explosion pressure is.

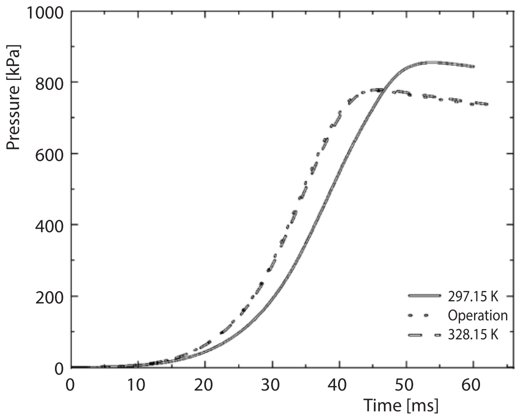

Figure 10. Explosive pressure curve at various environmental temperatures

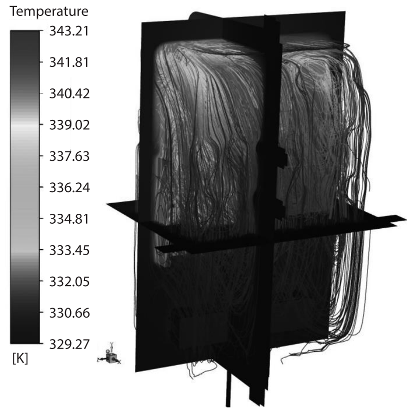

Figure 11. Internal temperature distribution diagram of the flameproof enclosure during operation

Table 4. Related parameters of explosion characteristics at various environmental temperatures

Working conditions	T	P_m	$(dp/dt)_{max}$	K_{max}
2	298.15	856	38	224.87
6	Operation	779	42	245.73
7	328.15	776	41	244.04

In this study, the results from the experiment verification, premixed gas combustion process inside the explosion-proof enclosure, explosion-proof enclosure internal pressure changed constantly under the action of pressure difference. The enclosure was not flammable, and the temperature changed constantly because the combustion reaction time is short. To qualitatively analyze the influence of temperature on explosion parameters, the ignition and detonation process in the flameproof enclosure was assumed to be a adiabatic process, in which heat loss is ignored [25], and the maximum explosion pressure under the adiabatic model can be expressed:

$$p = p_0 \frac{T}{T_0} \frac{m}{n} \tag{3}$$

where p is the pressure after explosion, p_0 – the initial pressure, T – the temperature after combustion of combustible gas, T_0 – the temperature of unignited gas, and m and n is the total number of molecules of unignited and ignited substances.

According to the analysis of tab. 4, the change in ambient temperature did not influence the maximum explosion pressure rise rate. With the increase in the ambient temperature, the maximum explosion pressure rise rate exhibited a non-linear characteristic. According to eq. (4), the maximum explosion pressure rise rate was proportional to the laminar flame velocity, whereas the ambient temperature exhibited limited influence on the laminar flame velocity.

The expression of the maximum explosion pressure rise rate is expressed:

$$\left(\frac{dp}{dt}\right)_{max} = \alpha \frac{\pi}{L} S_L \left(p - p_0\right)\left(\frac{p}{p_0}\right)^{1/\gamma} \tag{4}$$

where, α is the turbulence factor, L – the length, S_L – the laminar flame velocity, an γ – the eadiabatic index.

Figure 10 reveals that the time to reach the maximum explosion pressure decreases with the increase in the ambient temperature. The time to reach the maximum explosion pressure under the three conditions was 54 ms, 46.4 ms, and 45 ms. The chemical reaction rate is a scalar measuring the speed of the chemical reaction. According to molecular dynamics model theory and collision theory of the chemical reaction, the coefficient of the chemical reaction rate is related to the temperature and not related to the concentration of reactants or products. Arrhenius proposed the empirical formula for reaction rates:

$$k = A\mathrm{e}^{-E/\mathrm{R}T} \tag{5}$$

where k is the frequency factor, E – the activation energy, and R – the molar gas constant.

According to collision theory and Arrhenius law, an increase in the ambient temperature increases the probability of intermolecular collision and the reaction rate coefficient, which shortens the maximum explosion pressure time.

Thus, manufacturers should consider the actual operating environment of the product when designing flameproof enclosures.

Influence of obstacles on explosion characteristics of the premixed gas of the flameproof enclosure

Figure 12 displays the explosion pressure curves of flameproof enclosures with and without obstacles when the ignition energy is 300 W. The maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index were analyzed, tab. 5. The electrical parts are placed in the flameproof shell, which results in obstacles for flame propagation, the programmable logic controller, chargers, uninterruptible power supply, relays, transformers and battery installed in the flameproof enclosure of the research object are all obstacles. The maximum explosion pressure of the flameproof shell without electrical parts was 888 kPa, and the maximum explosion of the flameproof shell with electrical parts was 856 kPa. The maximum boost velocity and maximum explosion index were higher without electrical components than with electrical components. Numerical simulation results are consistent with the experimental results of Vishwakarma *et al.* [26], because in the shell with the same volume, the smaller the internal surface area is, the less heat loss and the greater the explosion pressure are. The pressure field distribution in the flameproof shell under the two working conditions is displayed in fig. 13.

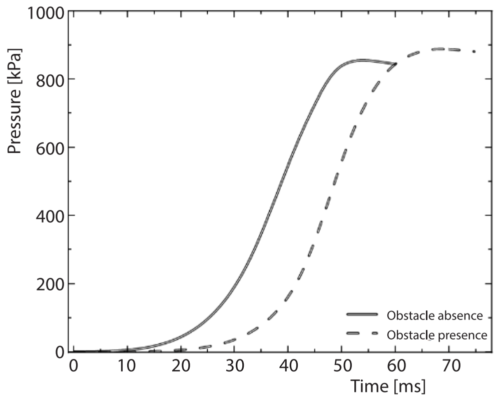

Figure 12. Explosive pressure curve at obstacle presence/absence

Thus, manufacturers should use the influence of electrical components as obstacles in the design of flameproof enclosures on explosive characteristics.

Table 5. Related parameters of explosion characteristics at obstacle presence/absence

Working conditions	Obstacle	P_m	$(\mathrm{d}p/\mathrm{d}t)_{max}$	K_{max}
2	Presence	856	38	224.87
8	Absence	888	41	262.01

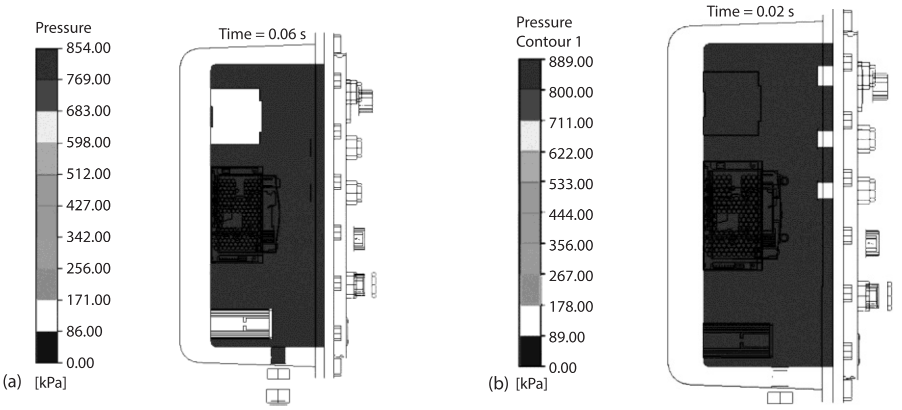

Figure 13. Pressure distribution of the flameproof enclosure at obstacle presence/absence; (a) obstacle presence and (b) obstacle absence

Conclusions

In this study, the flameproof enclosure was studied. The effects of ignition source location, ignition source energy, operating environment temperature, and obstacles on the maximum explosion pressure, maximum explosion pressure rise rate and maximum explosion index of the flameproof enclosure were studied using the 3-D numerical simulation method. The main conclusions of the study are as follows.

- The ignition position affects the maximum explosion pressure, maximum explosion pressure rise rate, and maximum explosion index of the flameproof enclosure.
- With the increase in the ignition energy, the maximum explosion pressure value, the maximum explosion pressure rise rate, and the maximum explosion index of the flameproof enclosure increase considerably.
- With the increase in the ambient temperature, the maximum explosion pressure decreases, whereas the maximum explosion pressure rise rate and the maximum explosion index did not have any effect.
- The maximum explosion pressure depends on the heat generated by the combustion explosion and the heat loss of the internal surface of the flameproof enclosure. The less the heat loss is, the greater the explosion pressure is.
- Designers should consider the influence of the arrangement of the obstacles in the flameproof enclosure on the explosion characteristics. The electrical components can be centrally arranged in the inner end of the flameproof enclosure during the design, which is conducive to the reduction of the explosion pressure.

Acknowledgment

This research was funded by CNOOC Energy Technology and Services Limited, grant number TJY-2021-FB-01.

The authors would like to thank all the reviewers who participated in the review and MJEditor (www.mjeditor.com) for its linguistic assistance during the preparation of this manuscript.

Nomenclature

$(\mathrm{d}p/\mathrm{d}t)_{max}$ – maximum rate of explosion pressure rise in [kPam^{-1}s^{-}1]
E – activation energy, [Jmol^{-1}]
E_J – ignition source energy, [W]
k – frequency factor
K_{max} – explosion pressure index = $(\mathrm{d}p/\mathrm{d}t)_{max} \times v^{1/3}$, [kPamm^{-1}s]
L – length, [m]
p – pressure after explosion, [kPa]
p_0 – initial pressure, [kPa]
P_m – maximum pressure [kPa]
R – molar gas constant
S_L – laminar flame velocity
T – ambient temperature, [K]
T_0 – initial temperature, [K]

Greek symbols

α – turbulence factor
γ – turbulence factor factor

References

[1] ***, Explosive Atmospheres – Part 1: Equipment Protection by Flameproof Enclosures "d", International Electrotechnical Commision, Geneva, Switzerland, 2018
[2] Cammarota, A, F., *et al*., Experimental Analysis of Gas Explosions at Non-Atmospheric Initial Conditions in Cylindrical Vessel, *Process Safety and Environmental Protection*, *88* (2010), 5, pp. 341-349
[3] Kindracki, J., *et al*., Influence of Ignition Position and Obstacles on Explosion Development in Methane-Air Mixture in Closed Vessels, *Journal of Loss Prevention in the Process Industries*, *20* (2007), 4-6, pp. 551-561
[4] Bi, M., *et al*., Numerical Simulation of Premixed Methane-Air Deflagration in Large L/D Closed Pipes, *Applied Thermal Engineering*, *40* (2012), July, pp. 337-342
[5] Li, C., *et al*., Effect of Ignition Energy on Environmental Parameters of Gas Explosion in Semiclosed Pipe-line, *ACS Omega*, *7* (2022), 12, pp. 10394-1045
[6] Ajrash, M. J., *et al*., Effects of Ignition Energy on Fire and Explosion Characteristics of Dilute Hybrid Fuel in Ventilation Air Methane, *Journal of Loss Prevention in the Process Industries*, *40* (2016), Mar., pp. 10394-1045
[7] Zhou, N., *et al*., Effect of Ignition Energy on the Explosion Process and the Dynamic Response of Propane-Air Premixed Gas, *Explosion And Shock Waves*, *38* (2018), 5, pp. 1031-1038
[8] Pekalski, A. A., *et al*., Determination of the Explosion Behavior of Methane Andpropene in Air or Oxygen at Standard and Elevated Conditions, *Process Safety and Environmental Protection*, *83* (2005), 5, pp. 421-429
[9] Gieras, M., *et al*., Determination of Explosion Parameters of Methane-Air Mixtures in the Chamber of 40 dm^3 at Normal and Elevated Temperature, *Journal of Loss Prevention in the Process Industries*, *19* (2006), 2-3, pp. 263-270
[10] Mitu, M., Brandes, E., Influence of Pressure, Temperature and Vessel Volume on Explosion Characteristics of Ethanol/Air Mixtures in Closed Spherical Vessels, *Fuel*, *203* (2017), Sept., pp.460-468
[11] Grabarczyk, M., *et al*., Effect of Initial Temperature on the Explosion Pressure of Various Liquid Fuels and Their Blends, *Journal of Loss Prevention in the Process Industries*, *44* (2016), Nov., pp. 775-779
[12] Li, R., *et al.*, Effect of Initial Temperature and H_2 Addition on Explosion Characteristics of H_2-Poor/CH_4/Air Mixtures, *Energy*, *213* (2020), 118979
[13] Zhao, Y., *et al.*, Effects of External Space and Initial Temperature on Explosion Process of Hydrogen/Air Mixture, *Explosive Materials*, *51* (2022), 2, pp. 35-41
[14] Yu, M., *et al*., Effects of Hydrogen Addition on Explosion Characterisitics of Gas under Condition of Obstacles, *CIESC Journal*, *67* (2016), 12, pp. 5311-5312
[15] Ding, Y., *et al*., Experimental Study on the Effects of Five Different Shaped Obstacles on Flame Propagation, *China Safety Science Journal*, *21* (2011), 2, pp. 5311-5312
[16] Andrews, G., E, *et al*., Explosion Flame Acceleration over Obstacles: Effects of Separation Distance for a Range of Scales, *Transactions of The Institution of Chemical Engineers*, *Process Safety and Environmental Protection, 107* (2017), Part B, pp. 309-316
[17] Liu, T., *et al*., Experimental Research on the Suppression Effect of Different Typesof Inert Dust on Micron-Sized Lignite Dust Explosion Pressure in a Confined Space, *ACS Omega*, *7* (2022), 39, pp. 35069-35076
[18] Liu, T., *et al*., Suppression Effect of $CaCO_3$, NaCl, and $NH_4H_2PO_4$ on Gas-Fat Coal Dust Explosion Pressure and Flame Characteristics, *Thermal Scienc*e, *27* (2023), 2B, pp. 1553-1562
[19] Zhang, Y., *et al*., Experimental and Numerical Studies on the Closed and Vented Explosion Behaviors of Premixed Methane-Hydrogen/Air Mixtures, *Applied Thermal Engineering*, *159* (2019), 113907

[20] Wang, M., *et al*., Numerical Simulation of Semi-Confined Slot Turbulent Impinging Jet Using Different Turbulence Models, *Journal of China University of Petrolem*, *34* (2010), 4, pp. 75-78
[21] Yi, Z., *et al*., Numerical Simulation of Blast Furnace and Coke Oven Gas Combustion under Different Oxygen Enrichment Conditions, *Journal of Energineering For Theraml Energy And Power*, *37* (2022), 2, pp. 75-78
[22] Gong, C., *et al*., Combustion Mechanism Modelling of Ethylene and Its Application in Numerical Study of High Speed Turbulent Comubustion, *Journal of Propulsion Technology*, *41* (2020), 3, pp. 583-594
[23] Ding, Y., *et al*., Reduction of Ethylence Combustion Kinetic Mechanism, *Journal of Propulsion Technology*, *36* (2015), 1, pp. 142-148
[24] Hu, S., *et al*., Study on the Influence Mechanism of Propane on Methane-Air Premixed Gas Explosion, *Journal of Safety and Environment*, On-line first, https://doi.org/10.13637/j.issn.1009-6094.2021.2354, 2022
[25] Wang, L., Experimental and Numerical Simulation Reaearch on Gas Deflagration Propagation Laws in Large Road ways and Small Pipe-lines, Harbin Engineering University, Harbin, China, 2021, pp. 41-49
[26] Vishwakarma, R. K., *et al*., Comparison of Explosion Parameters for Methane-Air Mixture in Different Cylindrical Flameproof Enclosures, *Journal of Loss Prevention in the Process Industries*, *31* (2014), Sept., pp. 82-87

Paper submitted: September 5, 2022
Paper revised: October 17, 2022
Paper accepted: October 18, 2022