Current Science
CS 5 (2), 1781-1786 (2025)
Received 25 Jan 2025 | **Revised 21 Feb** 2025 | **Accepted 15 March**. 2025 | **Online Available 11 April** 2025
https://doi.org/ 10.52845/CS/2025-5-2-41

Current Science

Current Science

OPEN ACCESS

ISSN(O)2795-8639

ORIGINAL ARTICLE

Simulation Study on the Impact of Obstacles on Fire Explosion Characteristics in Stadium

Xiao Gang Hao[1], Wen Bing Wu[2], Wen Si Chen[2], Xiao Rong Wang[2*]

[1]The School of Physical Education, Jiangsu University of Science and Technology, Zhenjiang, 212100, China

[2] The School of Mechanical Engineering Jiangsu University of Science and Technology Zhen Jiang, China

[*]Corresponding Author: Xiao Rong Wang

Abstract

As large-scale public buildings,sports stadiums are extremely dangerous in case of fire due to their special structural layout and high density of people. This paper focuses on the influence of obstacles within sports stadiums on the deflagration characteristics of fire, aiming to provide a theoretical basis for fire prevention and control and safety design. Through establishing the geometric model of sports stadiums and combining with numerical simulation, the influence of the existence of obstacles on flame propagation is analyzed. The research results indicate that obstacles can aggravate the deflagration characteristics of fire to a certain extent, especially when obstacles are dense or the space is limited, the flame propagation path is obstructed, leading to a sharp increase in pressure. The research in this paper has significant reference value for optimizing the fire protection design of sports stadiums. It is recommended that the arrangement of obstacles and their potential influence on fire risks be considered at the architectural design stage.

Keywords: Sports venues, obstacles, fire deflagrations, numerical simulations

Introduction

SPORTS venues, as large enclosed spaces with complex interior designs and dense crowds, may have their architectural structures and obstacles (such as seats, stands, billboards, etc.) significantly impact the spread of flames during a fire. Under special circumstances, the high-temperature gasification of plastic products, fiber products, and metal materials in sports venues can break the chain and form various combustible gases, such as ethanol vapor, methane, and hydrogen. After these gases are mixed with air, they are highly prone to cause intense combustion or explosion when encountering a fire source.Both domestic and international scholars have conducted extensive research on the impact of obstacles on gas deflagration characteristics. Foreign studies started earlier, with Chapman et al. pioneered the study of flame propagation in pipelines with obstacles[1]. Johansen et al studied the effect of blockage ratios in square ducts on flame acceleration, finding that obstacles with high blockage ratios significantly enhanced flame acceleration[2]. Domestic research has primarily focused on the deflagration characteristics of common combustible gases in urban environments, such as natural gas, hydrogen, and methane. Wang Y. et al conducted an in-depth analysis of the influence of the gradient of obstacles on the flame propagation characteristics of hydrogen/air premixed gas in a closed chamber[3]. The research found that the gradient of obstacles did indeed increase the flame propagation speed, and the obstacle wake vortex was the main factor causing the flame evolution and flow field changes in the closed cavity.

Obstacles in stadiums, such as seats, structural columns, and billboards, may influence the speed, direction, and intensity of flame propagation.

These obstacles can create turbulence, further accelerating the combustion of the gas mixture and intensifying the deflagration. During the deflagration process, obstacles may also cause the reflection and overlap of pressure waves, leading to increased pressure buildup inside the stadium. This, in turn, can trigger stronger shockwaves, raising the risk of casualties and structural damage. Through numerical simulations, it is possible to recreate complex combustion and deflagration scenarios within stadiums in a virtual environment. These simulations can analyze the combustion behavior of ethanol, hydrogen, and methane under different conditions, as well as the influence of obstacles on deflagration. Numerical simulations not only help optimize fire protection designs but also provide theoretical support for reducing casualties and property damage in fires. By simulating the deflagration process in stadiums filled with combustible gases and complex obstacles, critical data can be provided to support disaster prevention designs under the most severe conditions.

Materials and Methods

Geometric Model Building and Mesh Division

The main content of this study involves simulating the explosion of premixed gas in a confined space. Simulations were conducted both with and without the presence of obstacles to explore their impact on the flame propagation structure and peak pressure of the premixed gas. Considering that the focus of this study is the impact of the presence or absence of obstacles on the explosion behavior of premixed gas in a confined space, and to facilitate solving the transport equations, it was assumed during the numerical simulation that before ignition, the premixed hydrogen/methane/ethanol gas is evenly distributed in the confined space, and the flow of the explosive gas is compressible, following the ideal gas law. According to previous research, the lower the ethanol content, the higher the explosion intensity. Therefore, this section selects premixed gas with 20% ethanol for simulation. Moreover, relevant studies indicate that a two-dimensional model can successfully simulate the explosion process of premixed gas in a confined space when the properties of the burned and unburned products are known. Hence, to more concisely study the explosion process of premixed gas in a confined space, a two-dimensional model was chosen to simplify the internal structure, and the schematic of the computational domain is shown in Figure 1. In this study, Fluent was used to perform CFD simulations of explosions in confined spaces based on the K-epsilon model. First, a two-dimensional model was built in ANSYS SpaceClaim, then imported into ANSYS Mesh for meshing. A two-dimensional enclosed region was established, with tetrahedral meshes, and the number of mesh nodes was approximately 25,000.

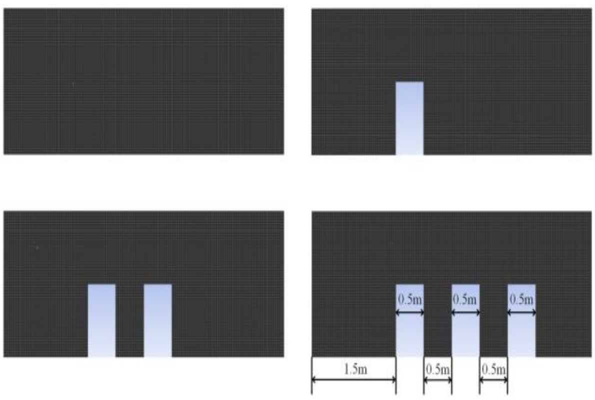


Figure 1. Schematic diagram of confined space meshing

Turbulence Model

In terms of turbulence model selection, the RNG k-ε model was chosen. Compared to other RANS models (such as the standard k-ε model), the RNG k-ε turbulence model can effectively simulate transient laminar and turbulent flows [4]. Therefore, the RNG k-ε turbulence model is more accurate.

RNG k-ε Model Equations:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M \quad (2\text{-}1)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R \quad (2\text{-}2)$$

$$\mu_{eff}=\mu+\mu_t \quad (2\text{-}3)$$

$$\mu_t=\frac{\rho C_\mu k^2}{\varepsilon} \quad (2\text{-}4)$$

where G_k and G_b represent the production terms of turbulent kinetic energy due to velocity gradients and buoyancy effects, respectively; Y_M accounts for the effect of compressible turbulence fluctuations on the total dissipation rate; μ_{eff} is the effective viscosity; and μ_t is the turbulent viscosity, $C_\mu = 0.084$, $C_{1\varepsilon} = 1.44$、$C_{2\varepsilon} = 1.92$、$C_{3\varepsilon} = 0.09$；$\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$。

Model Verification and Grid Independence Verification

To validate the accuracy of the numerical simulation conducted by Fluent software, it is necessary to carry out model accuracy verification. In this study, the chemical mechanism employed for the hydrogen/methane/ethanol premixed gas is obtained by integrating the ethanol oxidation reaction mechanisms of GRI-Mech 3.0 [5] and Marinov [6]. The detailed Chemkin mechanism is incorporated into the Fluent software to simulate the explosion process of this premixed gas, and the simulation results are compared with the experimental results in the literature to verify the accuracy of the model.

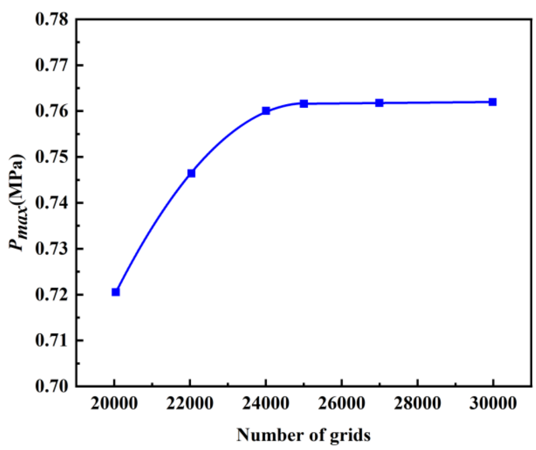


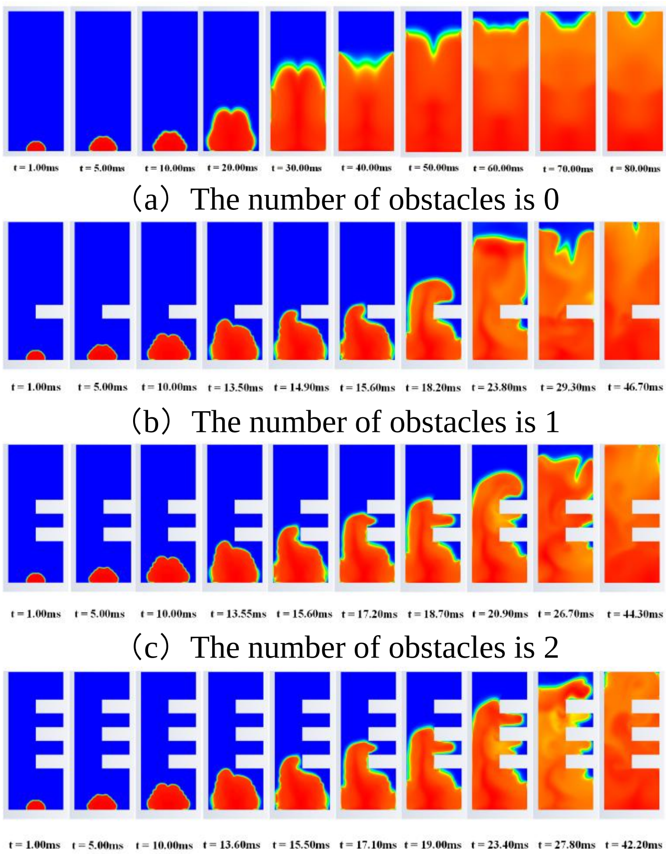
Figure 2 Mesh irrelevance verification

Results and Discussion

The Influence of the Number of Obstacles on the Flame Propagation Structure of Premixed Gases

In a confined space, the repetitive placement of obstacles can enhance the disturbance to the flame, resulting in an increase in the flame surface area and combustion rate [7]. In the numerical simulation, we initiated the placement of obstacles at a distance of 1.5 m from the front end of the confined space to investigate the acceleration condition of the flame after it crossed different quantities of obstacles. The number of obstacles was set as 1, 2, and 3 respectively, with an equal spacing of 0.5 m between each obstacle and a blockage ratio of 50%. Figure3 presents the simulation results of the flame propagation structure of the premixed gas under various numbers of obstacles. From the figure, it can be observed that the flame is not influenced by the obstacles before reaching them (t < 10 ms). In the case of multiple obstacles, the first obstacle is only 1.5 m away from the ignition source (2.5m for a single obstacle), thus the flame front is affected earlier, with deformation occurring at t = 13.50 ms (compared to t = 18.80 ms for the previous single-obstacle case). When the flame front approaches and passes through the obstacles, it is affected by the flow compression induced by the obstacles, the burning gas is ejected through the cross-sectional area above the obstacles, and due to wall reflection and pressure waves, the flame propagation structure undergoes unstable deformation, transitioning from laminar flame to turbulent flame [8,9].

When the flame collides with the second obstacle, it splits into two parts. The first part (the flame side) propagates towards the vortex region between obstacles 1 and 2; the second part (the flame front) continues to propagate along the axial direction. Subsequently, when the flame reaches and passes through the third obstacle, the flame structure undergoes similar changes as those observed with two obstacles, but the changes are more pronounced. Furthermore, as the number of obstacles increases, the time taken for the flame front to reach the end wall of the confined space decreases. This is mainly due to the turbulent combustion of the flame in the vortex region between the obstacles, which promotes the flame propagation speed. In conclusion, under the influence of obstacles, the flame speed increases. However, the flame acceleration mechanisms differ under different obstacle conditions. When there is a single obstacle, the flame acceleration is due to the influence of the turbulent flame. When there are two or three obstacles, the flame acceleration is primarily caused by the combined effects of the flow compression resulting from the changes in the cross-sectional area of the obstacles and the turbulent combustion in the vortex region.



（a） The number of obstacles is 0

（b） The number of obstacles is 1

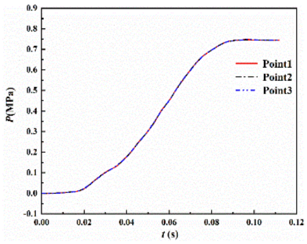
（c） The number of obstacles is 2

（d） The number of obstacles is 3

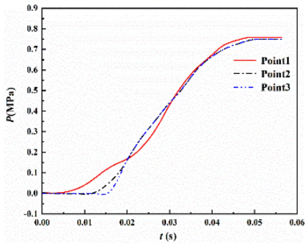
Figure 3. Flame propagation structure of premixed gas with different number of obstacles

Influence of the number of obstacles on the explosion pressure of premixed gas

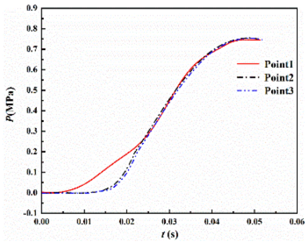
Figure 4 presents the variation curve of the explosion pressure of premixed gas with time under different quantities of obstacles. From this figure, it can be observed that the variation curve of explosion pressure and time in the simulation curve is similar to that in the previous section and can be classified into three stages: slow growth, rapid growth, and stable equilibrium. However, it can be noted that when the position of the first obstacle in the case of multiple obstacles is only 1.5 m away from the ignition source (2.5m for a single obstacle), the time when the explosion pressure reaches its peak is advanced from t = 72 ms to t = 47 ms. This indicates that the closer to the ignition source, the earlier the flame is influenced. With the increase in the number of obstacles, it can be seen that the peak explosion pressure is not sensitive to the variation in the number of obstacles. Nevertheless, the time to reach the peak explosion pressure decreases significantly as the number of obstacles increases. This suggests that the more obstacles there are, the shorter the time required for the flame to complete its propagation. The reason lies in that the vortices formed by the disturbance of obstacles intensify the component transport rate and the combustion rate, thereby accelerating the transition of the flame from laminar flow to turbulent flow [10]. The acceleration of flame propagation leads to an increase in the rate of pressure rise, which in turn results in an increase in explosion intensity.



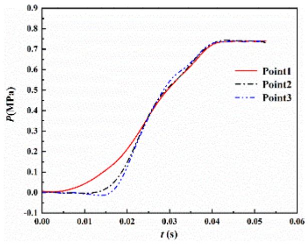
(a) The number of obstacles is 0



(b) The number of obstacles is 1



(c) The number of obstacles is 2



(d) The number of obstacles is 3

Figure 4. Explosive pressure curves for premixed gas with different number of obstacles

Conclusion

The influence of the number of obstacles on the flame propagation structure is mainly reflected in the effects of flow compression and the expansion of combustion products. Under multiple-obstacle conditions, the structure of the flame when passing through each obstacle is similar. When the flame passes through multiple obstacles, affected by the flame distortion after passing through the previous obstacle, the deformation of the flame becomes more severe after passing through each obstacle in sequence.

From ignition to the complete passage of the flame through the obstacles, the variation of explosion overpressure with time consists of three stages: slow growth, rapid growth, and stable equilibrium. Changes in the obstacles 's obstruction rate and the number of obstacles have essentially no impact on the final explosion pressure peak. The maximum explosion pressure rise rate increases with the increase of the obstacle blockage rate and number. Additionally, both the explosion pressure peak and the maximum pressure rise rate gradually increase with the increase in the initial pressure.

The closer the obstacles are to the ignition source, the earlier the flame is affected. The time to reach the explosion pressure peak significantly decreases with the increase in the number of obstacles. The eddy currents formed by the disturbance of the obstacles intensify the component transport rate and the combustion rate, thereby accelerating the transition of the flame from laminar flow to turbulent flow. The acceleration of flame propagation leads to an increase in the pressure rise rate, which in turn leads to an increase in the explosion intensity.

Conflict of Interest Statement: The authors declare no conflict of interest.

References

1. Chapman, W. R., Wheeler, R. V. The propagation of flame in mixtures of methane and air. Part IV: The effect of restrictions in the path of the flame[J]. J Chem Soc, 1926, **129**:2139-2147.
2. C. T. Johansen and G. Ciccarelli. Visualization of the unburned gas flow field ahead of an accelerating flame in an obstructed square channel[J].Combust Flame,2009,**156**(2):405-416.
3. Wang Y, Zhong S. Effect of Obstacle Gradient on the Deflagration Characteristics of Hydrogen/Air Premixed Flame in a Closed Chamber[J]. Processes,2024, **12**(5): 962.
4. Koutsourakis, N., Bartzis, J.G., Markatos, N.C. Evaluation of Reynolds stress, k-ε and RNG k-ε turbulence models in street canyon flows using various experimental datasets[J]. Environ. Fluid Mech., 2012, **12**(4): 379-403.
5. Smith G P, Golden D M, Frenklach M, et al. GRI-mech3.0[EB/OL]. (1999-07-30).http://www.me. berkeley.edu/gri_mech/.
6. Marinov, N. M. A detailed chemical kinetic model for high temperature ethanol oxidation [J]. Int J Chem Kinet, 1999, **31**(3): 183-220.
7. Masri, A. , AlHarbi, A. , Meares, S. , and Ibrahim, S. A Comparative Study of Turbulent Premixed Flames Propagating Past Repeated Obstacles [J]. Ind. Eng. Chem. Res., 2012, **51** (22): 7690-7703.
8. S. Lai, C. Xu, M. Davy, and X. Fang. Flame acceleration and transition to detonation in a pre-/main-chamber combustion system[J]. Phys. Fluids, 2022, **34**(11): 116105.
9. A.Y. Poludnenko. Pulsating instability and self-acceleration of fast turbulent flames[J]. Phys. Fluids, 2015, **27**(1): 014106.
10. Luan, Z.,Huang, Y.,Deiterding, R.,Peng, H.,You, Y.Flow characterization during the flame acceleration and transition-to-detonation process with solid obstacles and fluid jets[J].Shock Waves, 2022, **32**(7): 617-632.