Study on the Suppression Effect of Vacuum Cavity on Flame and Pressure Wave

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Abstract. The vacuum cavity was used to suppress gas explosion, and the explosion flame temperature and pressure in the pipeline were studied at different attachment positions of the vacuum cavity. The results showed that the different attachment positions of the vacuum cavity not only promoted but also inhibited the temperature and pressure of the explosion flame. The effect of the explosion suppression was better at 1.3m from the inlet; the influence of different length-width ratios of the vacuum cavity on the explosion flame and pressure was analyzed under the optimal distance and found that the effect was better when the aspect ratio was 3.

1. Introduction

Gas explosion accident seriously affects the safety of coal mine production. Regarding the research on gas explosion prevention technology, scholars have proposed methods including adding inert gas, powder or anti-explosive agent, setting fire arrester, fire barrier and venting device. These measures can reduce accident rates and reduce disaster loss. However, considering that some inhibitors are polluting the environment or have limited sources, they cannot be widely used.

The research has analyzed the anti-explosion effect and mechanism of foam ceramics[1]; the study found that porous material foam ceramics, wire mesh, and porous foam iron-nickel had a good effect on attenuating gas explosion flame temperature[2]. Klemens R studied the dust suppression device and explored ways to improve the explosion suppression performance of the explosion suppression system[3-4]. Baisheng Nie found that[5]: the heat loss of the explosive flame in the micropores of the porous medium caused the flame wave to be quenched, and the blast wave was reflected and scattered after entering the material, which greatly attenuated the shock wave[6]. Changming Guo[7] found that the porous steel plate absorbed the transverse wave while attenuating the detonation wave, but also strengthened the turbulent flow and accelerated the reaction process to promote the combustion reaction.

Hao Shao found that the relationship between the volume of the vacuum cavity and the critical volume had a great influence on the explosion suppression effect of the vacuum cavity[8]. The most influential factor in the explosion suppression effect was the location of the cavity. The smallest factor was the cavity size[9]; the vacuum cavity was reserved in the experimental pipeline, and the flame was suffocated and shocked under the action of suction and asphyxiation of the cavity. And the destructive power was reduced[10]. Zhongqing Li studied the explosion suppression effect of a single cavity and two cavities and different cavity sizes through experiments and numerical simulations and found that the influence of cavity size could not be ignored[11]. All of these provided new ideas for coal mine gas explosion prevention accidents. However, the influence of vacuum cavity materials and internal
structures on gas explosion suppression and the microscopic mechanism of foam metal suppression need further study.

In this paper, the numerical simulation method is used to study the inhibition effect of the vacuum cavity on the gas explosion, which is expected to achieve efficient and rapid control of gas explosion accidents, and lay a solid security foundation for petrochemical and other fields.

2. Model

A schematic diagram of the numerical simulation area is shown in Figure 1. The specific parameters of the gas explosion simulation pipeline are: inner diameter 300mm, length 5m, obstacles arranged at 0.4m, the length-width ratio of vacuum cavity is 1.5, 2.5, and 3.0 respectively.

Among them, the initial conditions are: methane concentration is 1, temperature is 300K, speed is 0.5m/s; oxygen concentration is 0.21, temperature is 300K, speed is 0.5m/s; between the two gas inlets patch a high temperature zone, the temperature is 2200K, pressure is 106325Pa, temperature in unburned zone is 300K, pressure is 101325Pa.

![Figure 1. Simulated Pipeline Diagram](image)

2.1 Mathematical model

In order to effectively perform numerical simulation studies, the following simplified assumptions are made on the model.

(1) The gas explosion is simplified to the ideal gas heating expansion process, and the flame propagation process is carried out in a two-dimensional pipeline.

(2) The inner walls of pipes and composite porous structures are regarded as adiabatic surfaces without heat exchange. The radiation and heat release of explosive shock wave in the propagation process are neglected, and the fluid-solid coupling effect between solid wall and impact flow is neglected.

Gas explosion follows the conservation of mass, momentum and energy in the process of pipeline system dynamics.

Energy conservation equation:

$$\frac{\partial}{\partial t} (\rho E) + \frac{\partial}{\partial x_i} (\rho u_i E) = - \frac{\partial}{\partial x_i} (\rho u_i u_j) + \frac{\partial}{\partial x_j} \left( \frac{\partial E}{\partial x_i} \right) + \tau_{ij} + \frac{\partial u_i}{\partial x_i}$$  \hspace{1cm} (1)

Conservation equation:

$$\frac{\partial}{\partial t} (\rho m_g) + \frac{\partial}{\partial x_i} (\rho u_i m_g) = \frac{\partial}{\partial x_i} \left( \frac{\partial m_g}{\partial x_i} \right) + R_g$$  \hspace{1cm} (2)

Due to turbulence caused by obstacles or pipe diameter changes during gas explosions, this paper chooses the RNG k-ε model for high Reynolds numbers. The expression of turbulent flow energy k is:

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_i} \left( \alpha_k \mu_e \frac{\partial k}{\partial x_i} \right) + \tau_{ij} \cdot S_{ij} - \rho \varepsilon$$  \hspace{1cm} (3)

In this paper, the gas explosion flame propagation is affected by turbulence. The laminar finite
rate/vortex dissipation model is used as the chemical reaction rate model.

2.2. Numerical methods
This paper chooses SIMPLEx algorithm.
Considering the fierceness of the gas explosion, this paper uses a non-equilibrium wall to treat the flow field near the wall.

3. Simulation results and discussion

3.1. The influence of the vacuum cavity position on the explosion flame and pressure of the pipeline
(1) Analysis of flame temperature distribution at different positions of the vacuum cavity

From Figure 2 (a) and (b), it can be seen that the temperature of the vacuum cavity is different, and the flame temperature inside the pipe is decreasing. When the attached position is 1.1m, 1.3m, 1.5m, 1.8m, 2.5m, 3.0m, 3.5m, the flame temperature in the pipe has a downward trend at the position of the cavity, that is, the cavity has a restraining effect on the flame under the four working conditions, and when the location is 1.3m, the flame temperature in the pipe decreases rapidly, and the temperature at the end of the pipe is as low as 850k; when the attached position is 1.5m, 2.5m, 3.0m, 3.5m, the flame temperature has an upward trend, that is, the position of the cavity is promoted to the flame under these three working conditions effects. When the attached position is 1.5m, 3.0m, and 3.5m, the temperature at the end of the pipe is still relatively high. When the attached position is 1.1m and 1.3m, the explosion flame is effectively attenuated by the action of the cavity. When other positions are attached, the flame is attenuated in the cavity, and a secondary flame appears. Overall, the flame temperature is greatly attenuated.

(2) Analysis of explosion pressure at different positions of the vacuum cavity

From Figure 3 (c) and (d), it can be seen that the pressure of the vacuum cavity is different, and the pressure inside the pipe is fluctuating. When the attached position is 1.1m, 1.3m, 1.5m, 1.8m, 2.5m, 3.0m, 3.5m, the pressure in the pipe has a downward trend at the position of the cavity, that is, the cavity has a restraining effect on the flame under the four working conditions, and when the location is 1.3m, the pressure in the pipe decreases rapidly, and the pressure at the end of the pipe is greatly attenuated. When the attached position is 1.5m, 3.0m, and 3.5m, the pressure at the end of the pipe is still relatively high. When the attached position is 1.1m and 1.3m, the explosion pressure is effectively attenuated by the action of the cavity. When other positions are attached, the pressure is attenuated in the cavity, and a secondary flame appears. Overall, the pressure is greatly attenuated.
It can be obtained from Figure 3 (c) and (d): when the vacuum cavity is placed at 1.1m, 1.5m, and 2.5m, there is still a large area of positive pressure in the pipe, that is, the attached cavity does not have a detonation effect or the anti-explosion effect is limited. The negative pressure exists in the rest of the pipe because of the suction of the cavity, the heat absorption of the reactant and the input of combustible gas. When the attached position is 1.5m and 1.8m, the negative pressure inside the pipe is large, which is likely to cause an explosion. When the attached position is 3.0m and 3.5m, the pressure in the pipe has no attenuation trend, that is, the cavity does not play a corresponding role; when the attachment position is 1.3m, the pressure in the pipe is effectively attenuated, which proves that the cavity can play a better role.

3.2. Effect of vacuum cavity aspect ratio on flame pressure

It is found that the explosion flame and pressure could be effectively controlled and attenuated when the attached location is 1.3m from the inlet. Therefore, this section controls the attachment position of the cavity to be 1.3m, changes the length-width ratio of the cavity, and studies the influence of three length-width ratios on the explosion flame and pressure in the pipe.

(1) Analysis of temperature distribution of explosion flames in the vacuum cavity with different aspect ratios

It can be obtained from Figure 4: under different aspect ratios, the overall trend of the flame temperature in the pipe decreases. When the aspect ratio is 2.5 and 3, the flame temperature develops slowly and then decreases, and the temperature decreases rapidly at 3.3m and 2m respectively. When the aspect ratio is 1.5, the flame temperature continues to decrease, and the temperature decreases rapidly at 2.4m from the inlet end; the temperature decreases rapidly in the three working conditions; the flame temperature decays faster in the three working conditions, and the position of the cavity is delayed. When the cavity aspect ratio is 3, the temperature in the pipe begins to decay earlier and the decay rate is faster.

(2) Analysis of explosion pressure law in the vacuum cavity with different aspect ratios

It can be obtained from Figure 5: under different aspect ratios of the vacuum cavity, the pressure in the pipe shows a downward trend at the cavity, and then the pressure increases and then decays. When the aspect ratio of the cavity is 1.5 and 2.5, the pressure change in the tube is more obvious. When the aspect ratio is 2.5, the maximum pressure can reach 2.07MPa; when the aspect ratio is 1.5, the maximum negative pressure can reach -12MPa; when it is 3, there is negative pressure in the pipe, but the change is relatively slow and the pressure in the pipe is relatively stable. Therefore, when the aspect ratio is 3, the pressure attenuation of the pipeline is more favorable, that is, when the aspect ratio is 3, the cavity suppresses the explosion pressure in the pipe better.

4. Conclusion

(1) It is found that the better the effect of temperature reduction and explosion suppression is when the
cavity is 1.3m from the pipeline, the lower the temperature at the end of the pipeline is to 850k, and the maximum attenuation of explosion over-pressure is 2.88mpa. The best location of the cavity attachment is determined as the distance 1.3m at the entrance end.

(2) At the optimal cavity layout position, a cavity structure is attached to the piping system. The cavity size is 300mm wide and the length is 1.5 times, 2.5 times, and 3 times the diameter of the pipe, that is, 450mm, 750mm, and 900mm. When the width ratio is 3, the flame temperature at the end of the pipe is 750K, the explosion pressure changes gently, and the explosion suppression effect is the best.

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