Numerical Simulation and Experimental Study on the Anti-explosion Characteristics of Cavity Structure

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Abstract. In order to study the anti-explosion effect of 500*500*200mm (length*width*height) cavity, the corresponding numerical simulation was carried out. It was found that the explosion suppression cavity has a good inhibitory effect on the explosion flame. The simulation results were verified by a field comparison test between the cavity and the straight pipe. It was found that the P1-P2 shock wave peak overpressure suppression rate was -8.11% in the straight pipe, and the F1-F2 flame suppression rate was -25.87%. After the cavity is coupled, the peak overpressure suppression rate of the shock wave becomes 17.12%, and the flame suppression rate becomes 40.85%. Compared with the straight pipe, the shock wave overpressure suppression rate of the cavity is increased by 25.23%, and the flame suppression rate is increased by 66.72%. Through numerical simulation and corresponding experiments, it is found that the cavity of 500*500*200mm (length*width*height) has better suppression effect on gas explosion. And the cavity wave elimination is a structural explosion suppression method, which can effectively suppress the gas explosion and its secondary explosion disaster.

1. Introduction
Gas explosion is one of the main obstacles restricting the safe production of coal mines in China. The prevention and control of gas explosion is the top priority of coal mine safety work. The anti-explosion technology can effectively control the power of gas explosion and reduce the destructive power of the explosion[1-3].

2. Test system and process
The test system is shown in Figure 1. It consists of a test pipeline, an explosion suppression chamber, a high-speed data collector, and an auxiliary test system (gas distribution, mixing, ignition).
2.1. Test system

The explosion pipeline is a seamless steel pipe with a wall thickness of 10mm, an inner diameter of 200mm and a total length of 34 m. The length of the detonator is 11m, the connecting pipe is 2.5m, and the propagation pipe is 20m. The explosion-proof cavity is a steel cavity with a wall thickness of 10mm and a length of 500mm. When straight pipe test is carried out, the cavity is replaced by a straight pipe of the same length, and the pipe is connected between the pipe and the pipe through the flange, so that it is easy to disassemble. Rubber gaskets are placed between adjacent flanges to ensure their airtightness.

The flame sensor and the pressure sensor are numbered P1, F1, P2, and F2 from the near to the farthest according to the position of the ignition electrode. The distance parameters are as shown in Table 1, and the ignition system is used as the measuring point position.

A set of comparative experiments of straight pipe and straight pipe coupling cavity were set up, and the experimental results were compared with the results of numerical simulation.

| Flame sensor | F1 | F2 |
|--------------|----|----|
| Distance measurement point position (m) | 13.3 | 14.3 |
| Pressure sensor number | P1 | P2 |
| Distance measurement point position (m) | 13.2 | 14.2 |

2.2. Selection of anti-explosion chamber

In this paper, the cavity of 500*500*200mm (length*width*height) is selected as the experimental explosion-proof structure. The physical picture of the cavity is shown in Figure 2. The main reason is that the actual width of the coal mine roadway often does not exceed 5 meters. Considering the feasibility of underground construction and support, and referring to the research of vacuum chamber by the research team of Jiang Shuguang of China University of Mining and Technology [4], it is concluded that the choice of cavity size should not exceed 4 times the width of the roadway. Finally, a 500*500*200mm (length*width*height) cavity structure with relatively convenient support was selected. In order to verify the feasibility of the experiment, a numerical simulation was first carried out.
3. Numerical simulation of cavity suppression

3.1. Physical model
The numerical simulation in this paper is based on CFD software. The gas explosion test pipe has an inner diameter of 200mm and a detonation pipe length of 100mm. It combines a cavity of 500*500*200mm (length*width*height) and a propagation pipe of 100mm.

3.2. Geometric model and meshing
The calculation is performed using a three-dimensional physical model. The geometric model and mesh division are shown in Figure 3. The lengths of the X, Y, and Z directions in the calculation area are 0.5m, 2.525m, and 0.2m, and the number of grids in the corresponding direction is 25, 126, and 10, respectively. During the simulation, the number of grids that were more precise than the mesh division was tested, and the simulation results did not change, which proved the grid independence.

3.3. Initial and boundary conditions
The initial conditions are: the initial normal pressure on the wall of the pipe, the initial temperature and the initial density gradient are both zero.

The boundary conditions are: the pipe and the cavity wall are insulated and no slippage occurs.

3.4. Mathematical models and numerical methods
The gas explosion in the pipeline is an ideal gas expansion process, which satisfies the mass conservation equation, the energy conservation equation, the momentum conservation equation, the turbulent flow energy dissipation rate equation, the turbulent flow energy equation, the fuel composition equation and the mixture composition equation. These can be uniformly expressed as the following forms [5]:

$$\begin{align*}
\frac{\partial}{\partial t}(\rho \phi) + \nabla \cdot (\rho u \phi) &= \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) + S_\phi, \\
\Gamma_\phi &= \frac{\mu_{\text{eff}}}{\sigma_\phi}.
\end{align*}$$

Where: \( \rho \) indicates density; \( t \) indicates time, \( x \) is the space coordinate; \( j \) (\( j = 1, 2, 3... \)) is the velocity component in the \( x \) direction; \( \Gamma_\phi \) is the exchange coefficient of the flux \( \Gamma_\phi \); \( S_\phi \) is the energy source term; \( \mu_{\text{eff}} \) is effective viscosity; \( \sigma_\phi \) is the Prandtl number ; \( \phi \) is a general variable; \( \frac{\partial}{\partial t}(\rho \phi) \) is an unsteady term, \( \frac{\partial}{\partial x_j} (\rho u_i \phi) \) is a convection term, \( \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) \) is a diffusion term, \( S_\phi \) and is a source term.

This numerical simulation uses the control volume integral method to derive the discrete expression of the convection-diffusion equation. The staggered grid technique and the SIMPLE algorithm are introduced to realize the separation of the coupled pressure field and velocity field. The
flow velocity of the fluid is derived. The numerical calculation formula of physical quantities such as pressure; using the backward difference method and the incremental method, the dispersion of the chemical reaction field, the material structure field, and the chemical flow field control equation is realized, and the reaction conversion rate, the average molecular relative molecular mass, and Numerical calculation of physical quantities such as fluid viscosity [6].

3.5 Cavity suppression mechanism simulation results
The simulation results of the cavity suppression gas explosion are shown in Figure 4(a) to (e). The simulation results of the contrast experiment between the cavity explosion and the straight pipe gas explosion are shown in Figure 4(f) to (j). The rightmost color card of Figures 4 represents the flame temperature. Fig. 4(a) to (e) show the propagation process of the flame of the gas explosion through the cavity, and Fig. 4(f) to (j) show the propagation process of the flame of the gas explosion in the straight pipe. It can be seen from Fig. 4 (f) to (j) that after the gas is ignited, a spherical flame is first formed, and the flame propagates in a hemispherical shape in the pipe. With the propagation of the flame, the flame front axis is axially affected by the wall of the flame and the flame is stretched. It can be seen from Fig. 4(b) that after the explosion flame reaches the cavity, due to the sudden increase of space, the binding force of the pipe wall to the flame disappears, and the flame propagates in a spherical shape. When the flame propagates to the cavity exit, the flame blocked by the inner wall of the cavity, part of the flame continues to propagate, and the flame energy passing through the cavity shows a decreasing trend. It can be seen from the propagation law of the gas explosion in the straight pipe and the cavity that the cavity has a good suppression effect on the explosion flame. According to the associated relationship between the flame and the shock wave, it can be inferred that the cavity has a good suppression effect on the shock wave. This simulation results verify the correctness of selecting a 500*500*200mm (length*width*height) cavity as the test cavity.

4. Experimental results and analysis
4.1. Explosion shock wave and flame propagation law in straight pipeline
The peak overpressure suppression rate of the shock wave is defined as \( \alpha = \frac{P1 - P2}{P1} \). It can be seen from Fig. 5(a) that the peak overpressure value of the pressure sensor P1 is 0.2848Mpa, the peak overpressure value of the pressure sensor P2 is 0.30792Mpa, and the peak overpressure suppression rate from the P1-P2 is - 8.11%; Flame suppression rate is defined as \( \beta = \frac{F1-F2}{F1} \). Figure 5 (b) is the flame front view captured by the F1 flame sensor and the F2 flame sensor. The area enclosed by the curve
and the abscissa represents the flame size, and the flame value at F1 is 0.0567. The flame value at F2 is 0.0714, so the flame suppression rate of F1-F2 is -25.87%.

4.2. Cavity suppresses explosion shock wave and flame law

Figure. 6(a) is the peak overpressure diagram of the front and rear pressure sensors P1 and P2. The peak overpressure value of P1 is 0.2946. After passing through the cavity, the P2 peak overpressure is 0.2775, and the peak overpressure suppression rate is 5.80%. Figure. 6(b) is a flame diagram of the front and rear flame sensors F1 and F2. The flame size of F1 is 0.1405, the flame size of F2 is 0.0831, and the flame suppression rate after passing through the cavity is 40.85%. Comparing the cavity with the straight pipe, the blast wave in the straight pipe passes through the P2 and F2, and the peak and overpressure of the flame and the shock wave show the reinforcing effect. However, after the cavity is installed, the explosion flame and the shock wave peak after the cavity are overpressured and the cavity front. Compared with the trend of declining, the results of mutual verification with the numerical simulation results show that the cavity has a good effect of suppressing the gas explosion flame and the peak overpressure of the shock wave.

5. In conclusion

Using CFD numerical simulation software to simulate, by comparing the law of gas explosion in the straight pipe and cavity flame, it is found that the cavity of 500*500*200 can effectively suppress the gas explosion flame.

Under the conditions of this study, the peak overpressure inhibition rate of P1-P2 shock wave in straight pipeline is -8.11%, the flame suppression rate of F1-F2 is -25.87%. After the coupling of the cavity, the peak overpressure suppression rate of the shock wave becomes 17.12%, and the flame
suppression rate becomes 40.85%.

Compared with the straight pipe, the peak overpressure suppression rate of the hollow pipe is increased by 25.23%, and the flame suppression rate is increased by 66.72%. It is verified that the 500*500*200mm (length*width*height) cavity has a good suppression effect on gas explosion.

The cavity of 500*500*200mm (length*width*height) is structurally explosion-proof, which can effectively suppress the gas explosion and its secondary explosion disaster.

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