Numerical simulation on methane explosion propagation in a one-dimensional straight duct with porous metal materials

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Abstract

Based on the theoretical and experimental results of methane explosion propagation in porous metal materials, methane explosion propagation in a one-dimensional straight duct with different layers of porous metal materials is simulated by *Fluent* software. The layers and length of porous metal materials have influence on the flame propagation velocity and explosion shockwave overpressure. Only the propagation distance of methane explosion is beyond 5 times the diameter of the duct, the flame and explosion wave can be attenuated by the porous metal materials. Moreover, the more the layers are, the better the attenuation effect is. The numerical simulation results show that, during methane explosion propagation in porous metal materials, the attenuations of explosion wave overpressure and flame propagation velocity takes on synchronization and correspondence. Consequently, the porous metal materials can suppress methane explosion propagation. The process of methane explosion in the duct well reappears with numerical simulation, thus the model is established correctly and the numerical simulation is a good supplementary means of experiment.

Keywords: Methane Explosion, Porous Metal Materials, Flame Propagation Velocity, Explosion Shockwave Overpressure, Fluent Software

1 Introduction

Methane explosion is a serious disaster in mines, thus how to prevent and control methane explosion has always been a hot research and the focus of everyone's attention. Nevertheless, methane explosion prevention is mainly manifested in two aspects: how to attenuate explosion wave and how to extinguish flame. At present, during methane explosion propagation in porous metal materials, the theory on flame quenching mainly includes the thermal effect, the wall effect and the flame expansion principle [1, 2]. Moreover, when explosion shockwave and porous metal materials interact, the porous metal materials can attenuate explosion shockwave [3, 4].

Gvozdeva, Dupe, Vasil'ev, Teodoreczyk, Reddy et al. found that porous compressible materials can significantly attenuate the pressure wave intensity, and the absorption material installed on the pipe wall can effectively suppress the detonation wave [5-9]. Yu Jianliang et al. experimentally studied the relationship among three parameters (i.e. critical quenching velocity, critical quenching pressure and quenching parameter) and geometry parameter of the multi-layer wire mesh suppressive structure and obtained the empirical formula of the relationship [10]. Wang Zhencheng and Terushige Ogawa experimentally studied the suitable wire gauze parameter, and obtained the equation among the bound flame speed, wire gauze shape coefficient (d/W) and the number of the layer of wire gauze [2]. Fedorov and Fedorchenko studied the problem of shockwave interaction with a layer of a porous material on a solid surface [11]. In addition, many scholars numerically simulated the explosion shockwave overpressure and flame propagation velocity during methane explosion in porous metal materials, obtained that porous metal materials have the actions of flame quenching and shockwave attenuation on methane explosion, and found that porous metal materials can suppress methane explosion propagation [12, 13].

According to the above literatures, the porous metal materials have suppression effects on methane explosion, but the influence of porous metal material parameters on methane explosion suppression cannot be determined. Based on methane explosion propagation characteristics in porous metal materials and *Computational Fluid Dynamics* theory, the mathematical model is established, the appropriate algorithm is selected, and the attenuation law of methane explosion propagation in a one-dimensional straight duct with different layers of porous metal materials (the number of layers is equal to 0, 1, 2, 3, 4, 5, respectively) is numerically simulated by *Fluent* software.

2 Geometric modelling and mesh generation

In the process of numerical simulation, the duct was simplified as a two-dimensional geometric modelling Figure 1. The length of the duct was 8.5 m, the diameter of duct section was 15 cm, the porous metal material was installed on the duct wall in the range of 4.5-7.5 m from

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the left end, the ignition system was located on the left of the helical accelerating ring, the left end was close and the right end was open.

The computational grid was generated by *GAMBIT* with quadrilateral cells. In the axial direction, the mesh was uniform, and it size was about 8 mm. In the cross section, the mesh near the wall was fine and its size was about 1 mm. And mesh size was about 5 mm in the centred zone. The mesh contains 48482 nodes, 46288 quadrilateral cells and 94769 faces.

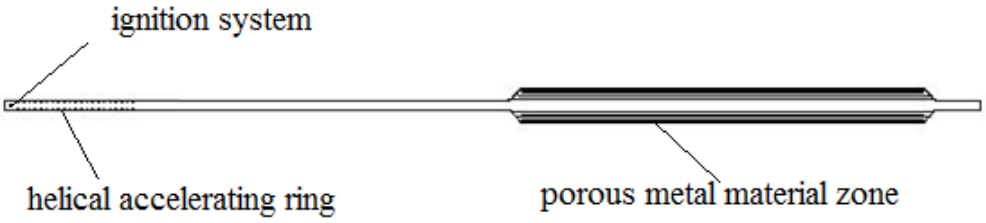


FIGURE 1 Geometric modelling

3 Numerical modelling

Before the numerical modelling was built, we hypothesized that: (1) the premixed methane-air mixture is considered as ideal methane, (2) the methane concentration in pre-mixed methane-air mixture is 9.5% (Concentration percentage value refers to percent by volume), (3) heat radiation and volume force can be ignored.

3.1 GOVERNING EQUATIONS

Methane explosion propagation in the duct is governed by the conservation laws for mass, momentum and energy. In the methane explosion process, if the combustion and supersonic flow need to be calculated, the density fluctuation cannot be ignored. Therefore, the differential control equations are obtained by the density weighted average concept proposed by Faver. They can be described in the following equations [14].

The continuity equation can be written as:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0. \tag{1}$$

The conservation equation for momentum can be written as:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\rho u_i\right)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial P}{\partial x_i}\\&+\frac{\partial}{\partial x_j}\left[u_e\left(\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+u_e\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}\right].\end{aligned} \tag{2}$$

The conservation equation for energy can be written as:

$$\frac{\partial\left(\rho h\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j h-\frac{u_e}{\sigma_k}\frac{\partial h}{\partial x_j}\right)=\frac{dP}{dt}+S_h. \tag{3}$$

Composition equation can be written as:

$$\begin{aligned}&\frac{\partial \rho Y_{fu}}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j Y_{fu}-\frac{u_e}{\sigma_{fu}}\frac{\partial Y_{fu}}{\partial x_j}\right)=R_{fu}\\&\delta_{ij}=\begin{cases}1\left(i=j\right)\\0\left(i\neq j\right)\end{cases};u_e=u+u_t\end{aligned}, \tag{4}$$

where, t is time, ρ is the density of a material, P is pressure, h is total enthalpy, σ_k is effective Prandtl Number of turbulent kinetic energy diffusion, σ_ε is the Prandtl Number of Pulsation kinetic energy dissipation rate ε. The subscript i, j, k are summation conventions, u_i is velocity component in the i direction, k is turbulent kinetic energy, Y_{fu} is fuel mass fraction, δ_{ij} is Kronecker-δ function, u viscosity coefficient of laminar flow, u_i is viscosity coefficient of turbulent flow, R_{fu} is chemical reaction rate, namely, combustion rate.

3.2 TURBULENCE MODEL

In the simulation, the RNG k-ε model was used to be the turbulence model. The RNG k ε model was derived using a statistical technique called renormalization group theory. It is similar in form to the standard k-ε model, but the RNG k-ε model more accurate and reliable for a wider class of flows.

3.3 COMBUSTION MODEL

In the simulation, the EDC (eddy-dissipation-concept) model was used to be the combustion model. The EDC model is an extension of the eddy-dissipation model to include detailed chemical mechanisms in turbulent flows. It assumes that reaction occurs in small turbulent structures, called the fine scales. The length fraction of the fine scales is modelled as Equation (5):

$$\xi^*=C\xi\left|\frac{v\varepsilon}{K^2}\right|^{1/4}, \tag{5}$$

where * denotes fine-scale quantities, ξ is micro-scale number, C_ξ is a volume fraction constant equal to 2.1377, v is kinematic viscosity.

Species are assumed to react in the fine structures over a time scale as equation (6) [15, 16]

$$\tau^* = C_\tau \left(\frac{v}{\varepsilon}\right)^{1/2}, \tag{6}$$

where C_τ is a time scale constant equal to 0.4082.

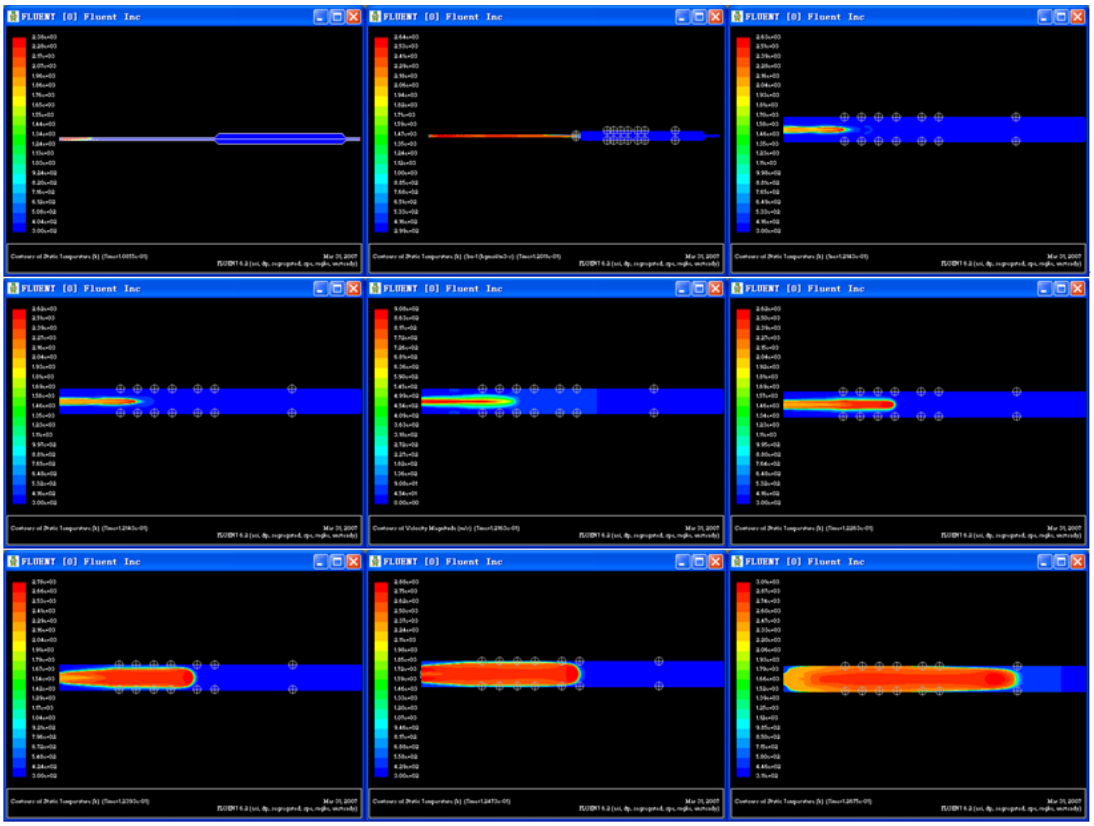
4 Boundary conditions

The duct wall-surface is considered as the outer boundary, and the open end of the duct is considered as the outflow boundary. There is no quality through the duct wall-surface. The whole calculated field is filled with 9.5% premixed methane-air mixture. At the initial moment, the premixed mixture is quiescent, and the premixed mixture temperature and pressure are 300 K and 1.0135×10^5 Pa, respectively. The velocity inlet, pressure outlet, and the porous jump boundary conditions are adopted [17].

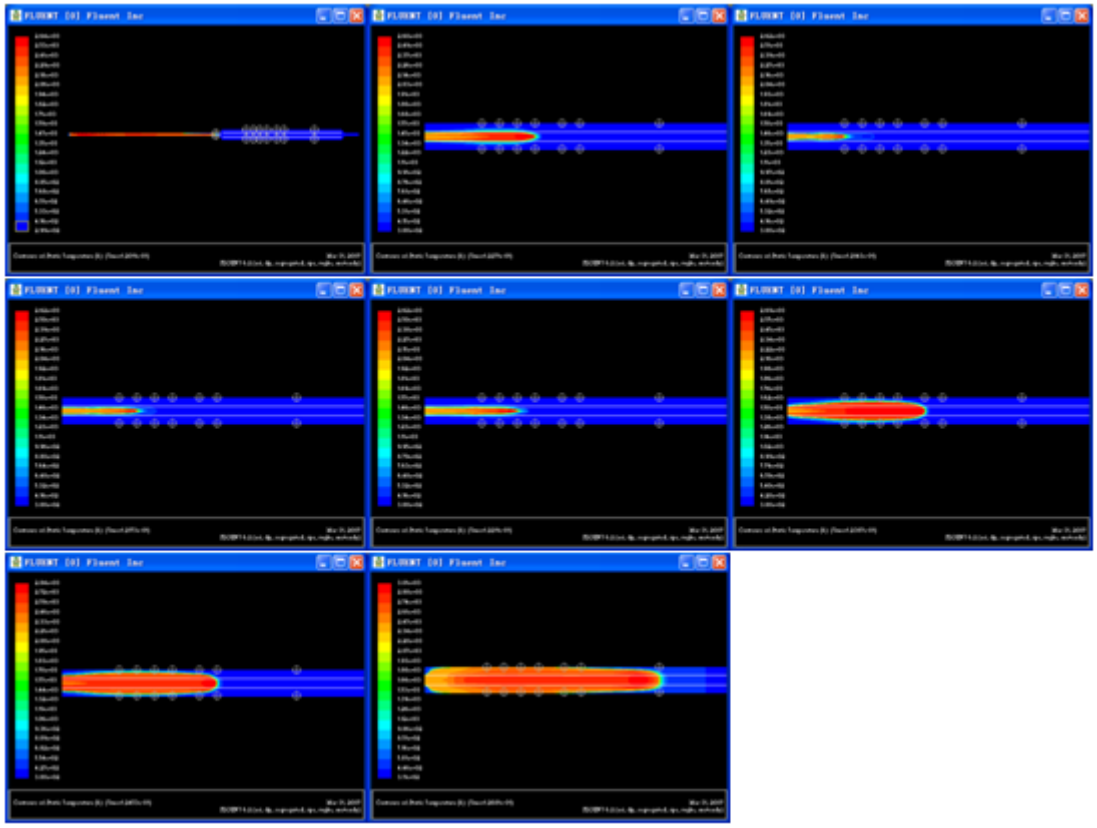
5 Results and Analysis on Numerical Simulation

5.1 NUMERICAL SIMULATION RESULTS

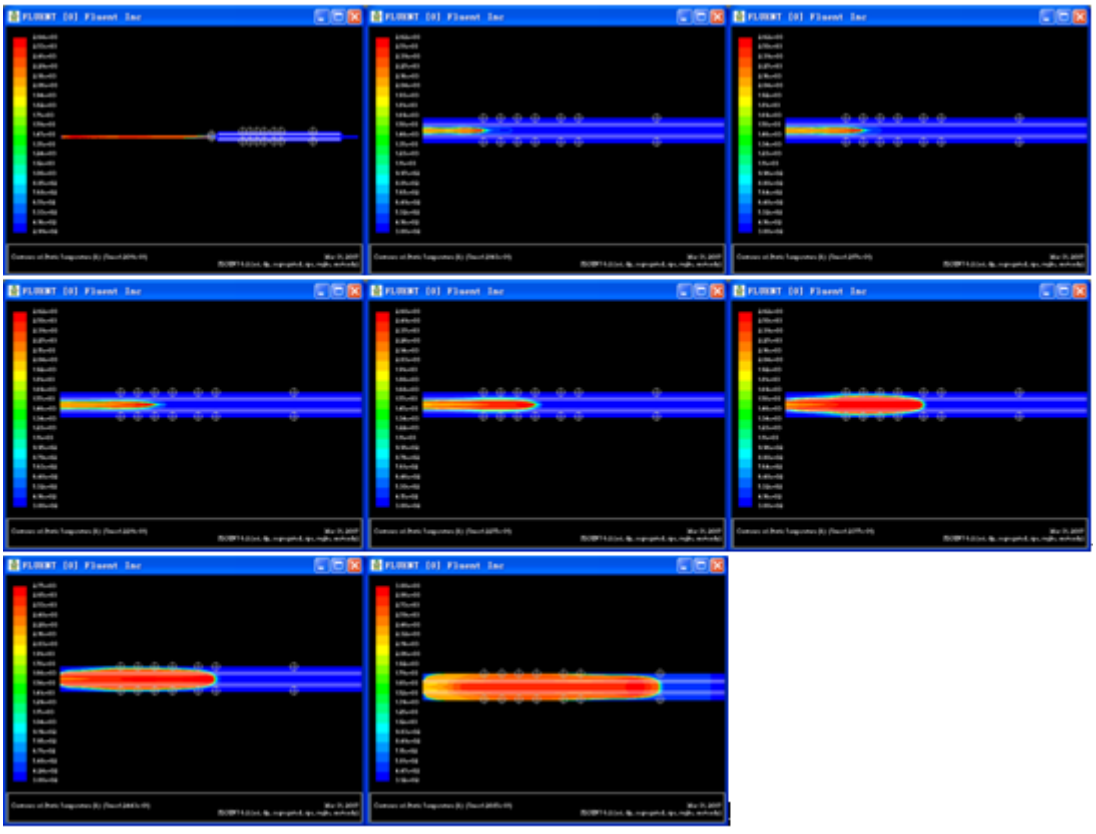
The theoretical and experimental results indicate that the methane concentration has great influence on the methane explosion intensity. When the methane concentration is 9.5%, methane explosion is most intense, and the flame propagation velocity, explosion shockwave pressure and temperature are biggest. Therefore, in the numerical simulation, the methane concentration in the premixed methane-air mixture was assumed to be 9.5%. The porous metal materials were installed in the range of 4.5-7.5 m away from the closed end of the duct, where the methane explosion intensity is greater. In order to facilitate the results analysis, eight pairs of measurement points are selected along the pipeline, the distances between them and the closed end of the duct are 4.3 m, 5.2 m, 5.4 m, 5.6 m, 5.8 m, 6.1m, 6.3 m, 7.2 m, respectively. In the process of numerical simulation, the explosion shockwave overpressure field, temperature field and flame motion field were calculated. The simulation results are shown in Figure 2 and Figure 3.



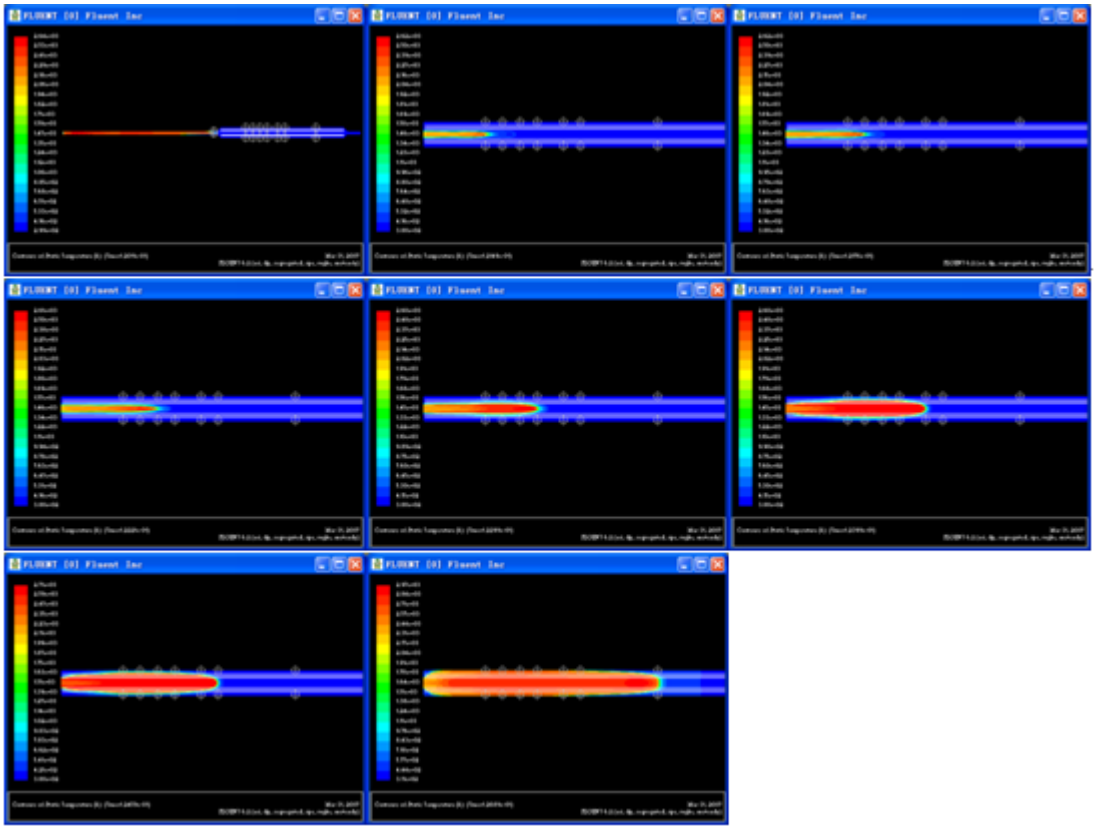
a. Duct without porous metal materials



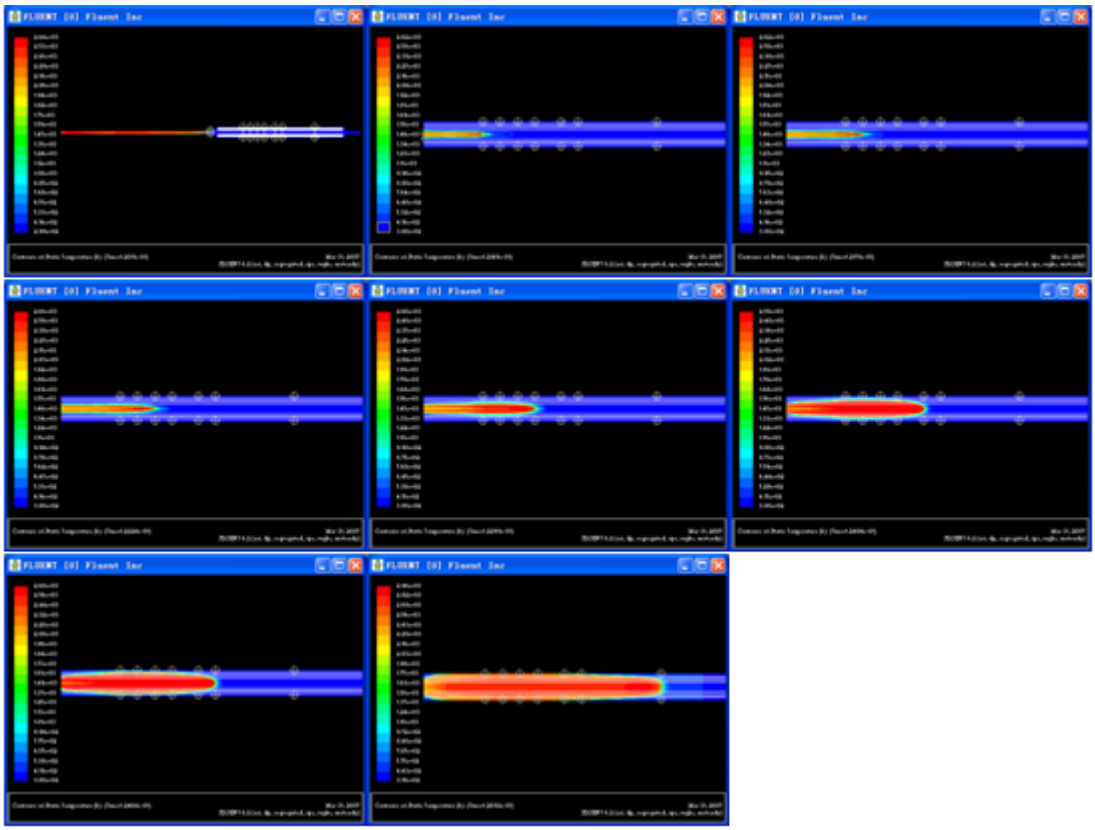
b. Duct with a layer of porous metal materials



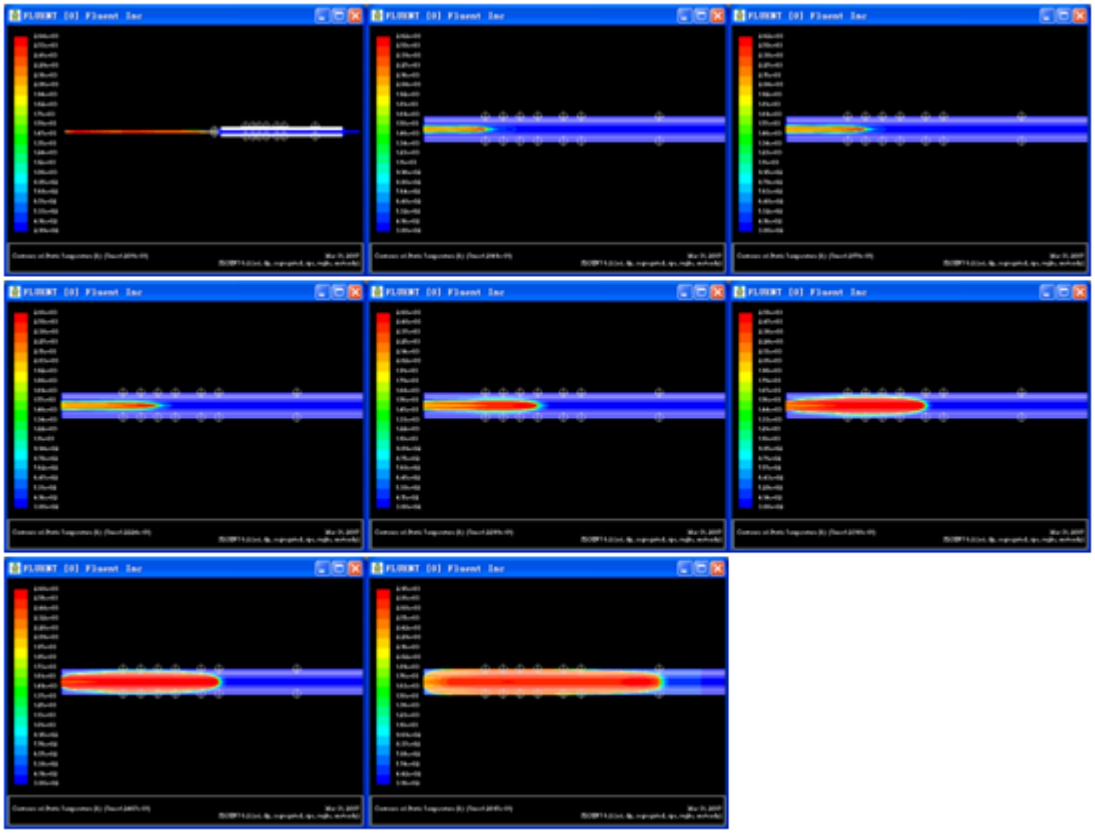
c. Duct with two layers of porous metal materials



d. Duct with three layers of porous metal materials



e. Duct with four layers of porous metal materials



f. Duct with five layers of porous metal materials

FIGURE 2 Flame propagation process of methane explosion in the duct with different layers of porous metal materials

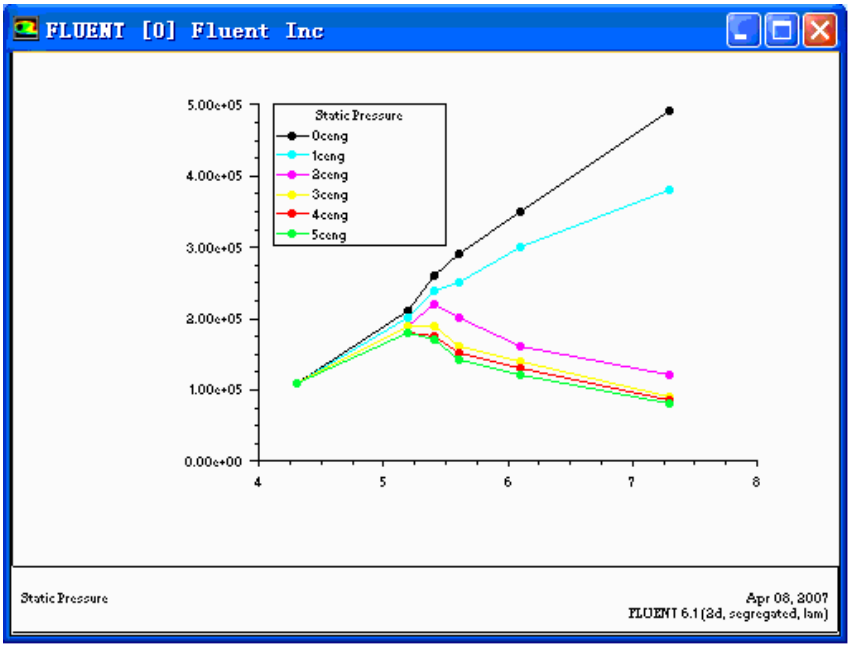


FIGURE 3 Overpressure-propagation distance scatter figure of methane explosion in duct with different layers of porous metal materials (the number of layers is equal to 0, 1, 2, 3, 4, 5, respectively)

5.2 ANALYSIS ON SIMULATION RESULTS

5.2.1 Analysis on flame propagation

From Figure 2, when methane explosion propagates in the duct with different layers of porous metal materials, the flame propagation times (the flame propagation time refer to the time that the flame front at the axial reaches a certain place) from the ignition system to the same place of the duct are different. Regardless of the layers of porous metal materials, the flame propagation times from the ignition system to the second measurement point are

0.12143 s. Behind the second measurement point, the flame propagation time from the ignition system to the same measurement point increases with the increase of layers. When the duct is without porous metal materials, the flame propagation time from the ignition system to the eighth measurement point is 0.12675 s. When one layer of porous metal materials is installed with the duct, the flame propagation time from the ignition system to the eighth measurement point is 0.12681 s. When two layers of porous metal materials are installed with the duct, the flame propagation time from the ignition system to the eighth measurement point is 0.12685 s. When three layers of porous metal materials are installed with the duct, the flame propagation time from the ignition system to the eighth measurement point is 0.12689 s. When four layers of porous metal materials are installed with the duct, the flame propagation time from the ignition system to the eighth measurement point is 0.12692 s. When five layers of porous metal materials are installed with the duct, the flame propagation time from the ignition system to the eighth measurement point is 0.12695 s. Hence more layers of porous metal materials can bring lower flame propagation velocity.

Regardless of layers of porous metal materials, during flame propagation in porous metal materials, the flame velocity increases within a certain distance, which is considered as the minimum attenuation distance of the flame propagation velocity. Only the flame propagation distance is beyond the minimum attenuation distance, the flame propagation velocity begins to decrease. The numerical simulation results shows that the minimum attenuation distance is about 5-6 times the diameter of the duct, and it increases with the decrease of layers. Moreover, layers of porous metal materials have greatly effect on the flame propagation velocity, the flame propagation velocity decreases with the increase of layers. Therefore, the porous metal materials have good suppression effect on flame propagation in the process of methane explosion.

5.2.2 Analysis on explosion shockwave overpressure

When methane explosion propagates in porous metal materials, the repeated oscillations of explosion shockwave make the overpressure take on several peaks at the same measurement point, so that the *Fluent* software simulation figure is difficult to directly display the change process of explosion shockwave overpressure. Thus the post-processing is carried out by *Fluent* software, a XY scatter figure of overpressure-propagation distance of methane explosion in the duct with different layers of porous metal materials (the layers is equal to 0, 1, 2, 3, 4, 5, respectively) is drawn. As shown in Figure 3, methane explosion shockwave overpressure is affected by the layers and the length of porous metal materials. Only when the number of layers is more than 1, the explosion shockwave overpressure decreases obviously. The explosion shockwave overpressure is increasing within a certain distance in porous metal materials, which is considered as the minimum attenuation distance of the explosion shockwave overpressure. Only the explosion shockwave propagation distance is beyond the minimum attenuation distance, the explosion shockwave overpressure decreases with the methane explosion propagation. The numerical simulation results shows that the minimum attenuation distance is about 5-6 times the diameter of the duct, and it decreases with the increase of layers. Moreover, layers have great influence on explosion shockwave overpressure. The more the layers are, the larger the decrease of the explosion shockwave overpressure is. Thus, the porous metal materials have good suppression effect on the explosion shockwave overpressure.

The numerical simulation results and their analysis show that, in the process of methane explosion propagation in a duct with porous metal materials, the attenuation of flame propagation velocity and explosion shockwave overpressure takes on synchronization and correspondence.

6 Conclusions

The methane explosion propagation in a one-dimensional straight duct with different layers of porous metal materials was numerically simulated, the conclusions are obtained as follows:

(1) The numerical simulation results can well reflect the process of methane explosion in porous metal materials, which show that the model is the correct and the numerical simulation is a good supplementary means of experiment.

(2) The porous metal material has good suppression effect on methane explosion propagation, the layers and the length of porous metal materials affect the flame propagation velocity and explosion shockwave overpressure. During methane explosion propagation in porous metallic materials, only the propagation distance is beyond the minimum attenuation distance, the flame propagation velocity and the explosion shockwave overpressure begin to decrease. The more the layers are, the better the attenuation effect is. Numerical simulation results are well consistent with the theoretical and experimental results. Hence porous metal materials can suppress methane explosion propagation.

(3) During methane explosion propagation in porous metal materials, the attenuation of explosion shockwave overpressure and flame propagation velocity takes on synchronization and correspondence.

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