Research Article

Numerical Studies on the Heat Effect of Explosion Suppression by a Heat Pipe

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A composite structure with a heat pipe and foamed iron-nickel composite fire suppression is proposed on the basis of the phase-change heat transfer of the heat pipe, which simultaneously attenuates the metal foam explosion energy. A numerical simulation is conducted to evaluate the feasibility of the designed construction for suppressing explosions under various thicknesses and pore diameters of the metal foam. The results demonstrate that when the foam iron-nickel metal is installed in the pipeline, the temperature reduction rate in the pipeline can reach 8.9%. The new heat pipe foam composite structure can reduce the flame temperature to 1600 K within 0.095 s. It is concluded that the heat pipe composite metal foam structure pipeline has a strong effect on suppressing combustion and explosion overpressure. Due to the combined effect of the heat pipe vacuum chamber suction energy and the foamed iron-nickel, the flame temperature decay rate increases. The maximum attenuation rate of the foamed iron-nickel for the gas explosion shock wave reaches 41.76%, and the maximum flame temperature attenuation rate reaches 64.7%. The composite heat pipe structure can quickly disperse and transfer heat, thereby effectively destroying the heat storage environment as soon as possible to prevent a secondary explosion from occurring.

1. Introduction

The explosion of combustible gas in the pipeline will release a large amount of heat instantaneously, which is accompanied by a continuous explosion or multiple explosions. The coupling effect of explosive energy and a pressure wave often leads to increase in the degree of disaster and in the range of action [1]. Therefore, blocking of the detonation wave that is generated by the secondary explosion and the propagation of the flame and timely diffusion of the explosive energy are crucial for suppressing the thermal hazard of the explosion.

The explosion suppression and explosion-proof measures that are adopted include explosion-proof water tanks, water bags, and rock powder sheds [2]. The main mechanism of action of these measures is heat transfer from the combustion zone to realize cooling to terminate the combustion chemical reaction, thereby quenching the flame wave. The current explosion suppression measures do not inhibit the turbulent flow field of the explosive energy, and they ignore

the coupling effect of the explosion flame and the shock wave [3]. A pipe that is embedded with a porous wall weakens the explosive transverse wave. The maximum overpressure attenuation of the foamed ceramic can reach 51% [4]; the special three-dimensional network structure of the foamed ceramic can effectively destroy the free radicals of the gas explosion reaction, thereby blocking chain reaction and inhibiting gas explosion [5].

Metal mesh and corrugated flame arresters, which are widely used in the petrochemical and coal mining industries, have received increasing attention due to their quenching effect on flames and their suppression of pressure waves [6]. Scholars at home and abroad have studied the antiexplosion effects of porous materials [7] and have found that multilayer mesh materials have the advantages of small volume, lightweight, and satisfactory quenching performance [8]. Wei et al. [9, 10] studied the antiexplosion characteristics of wire mesh materials, foamed ceramics, and metal foam and established a comprehensive quantitative evaluation model of the

explosion barrier effect of the porous materials. Zhou and Li [11] found that parameters such as the narrow diameter and the flame velocity affect the flame quenching process. Klemens et al. [12, 13] studied the method of optimizing the suppression performance of the suppression system. The microchannels filled with the ceramic fibers with high porosity (0.94) and low thermal conductivity (0.3 W/(m·K)) have been studied, which can effectively broaden the speed range of the flame waves. Metal mesh, foamed ceramics, and porous foamed iron-nickel have a satisfactory attenuation effect on the gas explosion flame. The porous material attenuates the explosive energy via multiple frictions [14]; based on the quenching effect of porous material on the flame propagation of flammable gas explosion and the suppression of pressure waves, a three-layer composite structure of steel mesh-foamed ceramic-steel mesh is proposed [15]. The propagation and impact properties of pressure waves in porous lightweight materials such as rigid foam plastics and porous aluminum are studied [16]. In addition, the vacuum-cavity-suppressing explosion technology has superior effects on the coupling effect of the explosion flame and the shock wave [17] and the temperature field decay degree. However, whether the weak surface material is broken in time remains unclear. These issues should be urgently resolved to enable the extensive application of suppression explosion devices.

The research group used a preliminary heat pipe to extract the spontaneous combustion heat from the coal pile and confirmed the efficient thermal conductivity of the heat pipe [18]. The study found that the metal foam can effectively reduce the thickness of the laminar bottom layer and enhance the heat transfer performance [19]. The instantaneous heat of the explosion is significantly improved. If the internal energy does not dissipate in a short time, the combustibles on the other side of the flame arrester will pose a fire hazard. Based on this, combining the heat pipe with the porous foam structure to realize flame retardance and explosion prevention is proposed, which is expected to realize dual suppression of flame and pressure waves, along with weakening of the coupling effect via the negative pressure suction of a vacuum chamber.

2. Heat Pipe Foam Composite Structure

In view of the unsuitability of suppression and isolation apparatuses for gas explosion, a closed heat pipe chamber structure that is composed of metal foam for explosion suppression was designed on the basis of the phase-change heat transfer and vacuum chamber suction energy of the heat pipe. The heat pipe foam composite structure is a composite structure that is composed of metal foam on the basis of an ordinary heat pipe. This structure is shown in Figure 1, and a composite heat pipe conceptual model is presented in Figure 2. A porous metal foam wick has the advantages of large capillary limit, low fluid flow resistance, and high heat transfer rate. Compared with sintered metal powder, the higher porosity of metal foam increases the

- 1, connector;
- 2, foamed iron-nickel plate;
- 3, ribs;
- 4, heat pipe;
- 5, shell;

FIGURE 1: Composite structure for explosion suppression.

- 1, liquid;
- 2, foamed iron-nickel wick;
- 3, heat;
- 4, liquid;
- 5, fin;
- 6, steam;
- 7, tube wall;
- 8, heat pipe;

FIGURE 2: Model of the composite structure.

working fluid flow rate, which substantially increases the maximum heat transfer rate. The higher permeability can reduce the reflux pressure and increase the capillary limit; the foamed iron-nickel core has a large capillary force and a high effective thermal conductivity, and its capillary limit and boiling limit are higher than those of the wire mesh core; in addition, no heat transfer limitation is prone to arise.

In case of fire, high-temperature and high-pressure gas will enter the heat pipe quickly due to the vacuum chamber suction of the heat pipe, and the thermal energy will be transferred using the phase change of the heat pipe simultaneously; the metal foam can absorb energy through the effect of multiple porosity, which will reduce the harmfulness of the flame and the overpressure that is induced by the explosion. The porous metal mesh has a prominent capacity to weaken gas explosion shock waves and the flame energy, and it has low sintering thermal resistance. Due to its special pore structure, low density, high porosity, and large specific surface area, the metal foam has strong effects on flame wave and pressure wave attenuation. It has been investigated in a filling tube and embedded in a tube and a flat plate, and its excellent heat transfer characteristics have been proven. In

particular, porous-foamed iron-nickel shows excellent heat transfer performance and permeability. It is found that 0.3 g/cm³ foamed iron-nickel metal has a decay rate of 7.1%–70.7% in the explosion flame and an explosion overpressure rate of 55.1%–73.8% [20], and the pressure decay rate is 12.9%–73.8% [21]. Therefore, the foamed iron-nickel metal is selected as the wick of the composite heat pipe structure.

3. Analysis of the Explosion Suppression

The current research in China on the forced suppression of detonation in pipelines by mesh absorption materials focuses mainly on the variation characteristics of the flame velocity and the temperature during the propagation process [22]. After studying the thickness variation and duration of the flame in the pipeline [23], for the first time, an empirical formula for the relationship between the geometric parameters of the metal mesh and the critical quenching speed, critical quenching pressure difference, quenching amount, and maximum overpressure value reduction ratio is established [24]. The effect of porous compressible materials on the propagation of explosions was studied [25], and the feasibility of using porous materials to attenuate explosive energy waves was demonstrated.

The inner diameter of the pipe is 159 mm, the external temperature of the pipeline is 26°C, and the thickness of the foamed iron-nickel is 60 mm. This calculation involves the relationship in the original empty pipe between the peak temperature t of the pipe and the length x of the pipe [26]:

$$t = -3.0295x^3 + 48.811x^2 - 266.57x + 1058.7, \quad (1)$$

where t is the peak temperature of the pipe and x is the length of the pipe.

As illustrated in Figure 3, the foamed iron-nickel is positioned at a distance of 1 m from the right port of the explosion tank. Substituting (1), the initial temperature of the starting end of the foamed iron-nickel at the left end is $t_0 = 837.91^\circ\text{C}$; the heat pipe is arranged at 1.2 m, the original temperature at the heat pipe is $t_1 = 803.88^\circ\text{C}$, and the rear foamed iron-nickel is arranged at 1.4 m. The study found that the temperature peak arrival time of a gas explosion will decrease with the increase in the gas explosion concentration; thus, 8% methane-air mixture gas is used for research [26]. Mixed gas enters the foamed iron-nickel at high temperature. The heat transfer of the fluid in the pore, the heat conduction within the fluid foam skeleton, the radiative heat transfer on the foam skeleton surface, the convective heat transfer between the fluid and the skeleton, and the effective heat conduction coefficient of the foam material is as follows:

$$\lambda = \varepsilon \cdot \lambda_g + (1 - \varepsilon)\lambda_s, \quad (2)$$

where the porosity of the foam [27] is $\varepsilon = 0.3$, the thermal conductivity of the methane-air mixture gas is $\lambda_g = 0.06028 \text{ W}/(\text{m}\cdot\text{K})$, and the thermal conductivity of the foamed iron-nickel is $\lambda_s = 91.7 \text{ W}/(\text{m}\cdot\text{K})$; hence, $\lambda = 64.21 \text{ W}/(\text{m}\cdot\text{K})$.

1, explosion tank;
2, heat pipe;
3, foamed iron-nickel;
4, pipe;

FIGURE 3: Illustration of an example.

The heat conduction of the foamed iron-nickel material is simplified to flat-wall steady-state heat conduction, and the wall temperature is

$$t_{w2} = t_{w1} - q \frac{\delta}{\lambda}, \quad (3)$$

where t_w is the wall surface temperature, 1 and 2 denote the beginning and the end of the flat wall, q is the heat flux density (W/m^2), δ is the thickness of the flat wall (m), and λ is the thermal conductivity in $\text{W}/(\text{m}\cdot\text{K})$. The value of q is set to $8.02 \times 10^5 \text{ W}/\text{m}^2$ and substituted into the above formula. Then, $t_{w2} = 762.96^\circ\text{C}$, and the temperature reduction rate is

$$\eta = \frac{t_{w1} - t_{w2}}{t_{w1}} = 8.9\%. \quad (4)$$

Via analysis of the heat pipe section, the relationship between the heat pipe diameter d and the heat pipe inclination angle and the heat absorption Q of the evaporation section is established as follows:

$$Q = \rho \cdot l \cdot r = \frac{\rho^2 g d^4 (\theta - \sin \theta) (1 - (\sin \theta / \theta)) i}{256 \mu} r, \quad (5)$$

where Q is the heat exchange volume of the heat pipe evaporation section in J, ρ is the density of the working fluid in kg/m^3 , l is the evaporation section length in m, r is the latent heat of vaporization of the working water in the heat pipe in KJ/kg , g is the local gravitational acceleration in N/kg , d is the heat pipe diameter in m, μ is the working dynamic viscosity in $\text{N}\cdot\text{s}/\text{m}^2$, θ is the inclination of the heat pipe in degrees, and i is the slope value of the heat pipe installation in degrees.

The heat pipe is composed of stainless steel-water heat pipes. The length ratio of the condensation section to the evaporation section is 6:1, the diameter d of the heat pipe is 20 mm, the length is 1500 mm, the wall thickness is 3 mm, and the heat pipe inclination angle is 60° . The heat transfer quantity of the evaporation section can reach $1.71 \times 10^{12} \text{ J}$. It is found that the heat pipe foam composite structure can efficiently and quickly transfer the heat that is accumulated inside the pipe to the outside, and by destroying the heat storage environment inside the pipe, it was found that the heat pipe metal foam composite structure can effectively reduce the temperature of the pipe explosion pressure wave and effectively suppress the explosion. It effectively prevents the thermal damage of the wave from occurring.

4. Simulation Analysis

In this paper, heat pipes and foamed iron-nickel are arranged 1.5 m and 3.5 m, respectively, from the ignition point. The size of the foamed iron-nickel is $0.3 \times 0.3 \times 0.6$ m, the mixture is composed of 9.5% methane mixed gas, and the pressure outlet is on the right side. The following boundary conditions are set: (1) At the axisymmetric boundary, a two-dimensional asymmetrical pipe model is established. (2) At the wall surface, the fluid and solid regions are defined by wall boundary conditions, and a nonslip wall boundary condition is adopted to set the wall temperature to 300 K. (3) At the pressure outlet, the initial pressure is set to 1.01×10^5 Pa, and the static pressure at the pressure outlet boundary is set. (4) In the porous area, a porosity ratio of 0.90, a specific heat capacity of 0.42×10^3 J/(kg·K), and a density of 0.8 g/cm³ are set, and the viscous drag coefficient and the inertial drag coefficient are calculated with consideration for the chemical reaction of the combustion process. In this paper, the flame temperature at 3.6 m from the ignition point is used to reflect the cooling and quenching performances of various types of tubes in the gas combustion explosion process.

4.1. Comparative Analysis of the Flame Temperature.

According to Figure 4, the flame temperature variation with time is significantly reduced at 3.6 m from the ignition point for the empty tube, the foamed iron-nickel tube, and the heat-tube foam composite structure tube; the maximum temperature reduction rate of the foamed iron-nickel tube is 7.5%; and the temperature attenuation rate reaches 23.08%. The maximum temperature reduction rate of the heat pipe foam composite structure tube is 40%, and the temperature decay rate is 11.11%, which indicates that the heat pipe foam composite structure realizes superior cooling and quenching performance. When the flame propagates through the heat pipe foam composite structure pipe to the outlet end of the pipe, according to Figure 4, the temperature is attenuated to approximately 1210 K at 0.095 s, which is much lower than the minimum ignition temperature of 1202 K. In Figure 4, the flame energy attenuation effect in the foam-composite-structure-type heat pipe is readily observed. Since the combination of the composite heat pipe and the porous foam structure can quickly reduce the thermal energy, the energy that is necessary for the explosion cannot be supplied in time, and the next explosion will be suppressed.

4.2. Model Verification. In this paper, the k - ϵ turbulence model, the EBU-Arrhenius combustion model, the porous media model, and the nonequilibrium wall function method are used to examine the changes in various parameters in the pipeline. The length of the experimental system pipeline is 6.5 m, and the foamed iron-nickel is positioned at 3.5 m in the pipeline. Compared with the experimental result [12], Figures 5 and 6 present the foamed iron-nickel metal pore size and thickness and the flame temperature and overpressure, respectively, at each measuring point in the pipeline. The maximum relative error of the flame

FIGURE 4: Flame temperature changes with time.

FIGURE 5: Temperature comparison.

temperature is 14.3%, and the maximum relative error of the overpressure is 8%.

4.3. Result Analysis and Discussion

4.3.1. Effect of the Pore Size and the Thickness of the Metal Foam. Figures 7–9 present the explosion pressure curves of the foamed iron-nickel at various measuring points with 10 ppi, 20 ppi, and 30 ppi metal foam, respectively. Under the conditions of the simulation, six monitoring points are selected, which are denoted as A, B, C, D, E, and F. The coordinates were A (0.6, 0.15), B (2.15, 0.15), C (3.1, 0.15), D (3.7, 0.15), E (4.65, 0.15), and F (6.2, 0.15), which were selected to reflect the pressure change of the whole pipeline during the gas combustion explosion process. The foamed iron-nickel is installed between measuring points C and D.

FIGURE 6: Overpressure comparison.

FIGURE 8: Pressure variations with various thicknesses at 20 ppi.

FIGURE 7: Pressure variations with various thicknesses at 10 ppi.

FIGURE 9: Pressure variations with various thicknesses at 30 ppi.

The attenuation of the gas explosion pressure by the porous foamed iron-nickel metal material is studied by using the percentages of the differences between the pressures at the measuring points *C* and *D* and the pressure at measuring point *C*. According to Figures 7–9, the shock wave pressure exhibits two rising and falling trends with the pipeline propagation, and it reaches an initial peak and a second peak, along with a first overpressure trough and a second trough. The first overpressure trough occurs after the explosion shock wave reaches the initial peak of overpressure between points *C* and *D*, and the metal foam decay attenuation overpressure effect is more significant under the thickness of 30 ppi. At the same pore diameter, the larger the thickness of the metal foam is, the stronger the vacuum absorption energy effect is. The metal foam with a pore size of 80 mm at 10 ppi shows a 15% increase in the attenuation rate compared to the 60 mm at 10 ppi metal foam, whereas

the metal foam with a pore size of 60 mm at 10 ppi has an attenuation rate of 26.76% compared to a 30 mm at 10 ppi metal foam material.

Due to the presence of the foamed iron-nickel porous skeleton, many recirculation zones are formed in front and behind the foamed iron-nickel. The tempering phenomenon causes the explosion pressure of the combustion gas to increase at 2.15 m and 4.65 m in the simulated pipeline, and as the gas continues to propagate backward, the pressure tends to decrease. The damping performance of the metal foam material on the explosion shock wave increases with the decrease in the pore size, and it increases with the increase in the thickness. The larger the thickness is, the smaller the pore size is. The shock wave encounters the pore-like structure and is impacted and folded back. Repeated impacts cause a part of the pressure wave to be absorbed, which causes the shock wave to attenuate; hence, the loss

FIGURE 10: Temperature variations with various thicknesses at 10 ppi.

FIGURE 12: Temperature variations with various thicknesses at 30 ppi.

FIGURE 11: Temperature variations with various thicknesses at 20 ppi.

energy is increased when the shock wave passes through the composite flame arrester, and the decay quenching effect is stronger.

4.3.2. Effects of the Pore Size and the Thickness of the Metal Foam. The metal foam is placed between measuring points C and D. Curves of the flame temperature as functions of the measuring point distance are plotted in Figures 10–12. The foamed iron-nickel metal pore sizes are 10 ppi, 20 ppi, and 30 ppi, respectively, and the flame temperature contrast curves are plotted for three thicknesses (30 mm, 60 mm, and 80 mm).

According to Figures 10–12, the flame temperature change trends of the empty tube and the foam composite metal structure heat pipe initially increase to the temperature peak and subsequently decrease and both show significant downward trends after 3.1 m. The flame temperature at a pore size of 10 ppi exhibits a slight upward trend at 3.75–4.65 m. Due to the small pore size of the metal foam, the turbulence after the flame passes significantly causing a small increase, which is due to the heat accumulation. The metal foam with a pore size of 60 mm in 20 ppi shows a 43.4% increase in the attenuation rate compared to 30 mm in 20 ppi, whereas the metal foam with a pore size of 60 mm in 30 ppi shows an attenuation rate of 40.2% compared to the 30 mm in 20 ppi metal foam material. The flame temperature reaches its maximum at 3.1 m. When the explosion flame passes through the tiny three-dimensional pore structure of the metal foam material, the flame is divided into several small flames, which cause the flame front to be discontinuous, and the heat of the reaction exchanges with the metal foam pore wall surface. The number of free radicals that are involved in the combustion is significantly reduced by the occurrence of the wall effects. The ability of the metal foam material to attenuate the temperature of the explosion flame increases as the pore size decreases, and the fire resistance increases with the increase in the thickness.

4.3.3. Analysis of the Flame Propagation. According to Figure 13, the radial velocity of the flame that is propagating in the pipe after the ignition of the mixed gas in the pipe exceeds the axial velocity. When the flame continues to propagate for 0.05 s, the flame passes through the porous material and propagates to the outlet end of the pipe. After 0.095 s, the temperature was attenuated to approximately 1700 K. Since the heat pipe has high-efficiency phase-change thermal performance, when the flame propagates to the vicinity of the heat pipe, the heat pipe conducts heat in a

FIGURE 13: Flame propagation: (a) blank pipe; (b) metal foam pipe; (c) composite metal foam heat pipe.

liquid-gas phase deformation form and exhibits excellent thermal conductivity. The flame energy suppression effect is stronger in the cloud map of 0.05 s-0.095 s, which is because the heat pipe and the porous-foamed iron-nickel cooperate to quickly export high thermal energy to the larger area.

5. Conclusions

The proposed explosion suppression equipment is designed based on the effect of the phase-change heat transfer for heat pipes, and metal foam can suppress initial explosion energy instantaneously before a large-scale explosion occurs, which showed a satisfactory suppression effect on the flame and pressure for combustible gas. Built-in foam iron-nickel metal pipes with three thicknesses (30 mm, 60 mm, and 80 mm) and three pore sizes (10 ppi, 20 ppi, and 30 ppi) are inserted at a specified position. The explosion suppression characteristics were numerically simulated and compared with those of an empty pipe. The main results of this study are as follows:

- (a) The heat pipe with the composite metal foam structure can quickly disperse and transfer heat. The results demonstrate that when the iron-nickel metal foam is installed in the pipeline, the temperature reduction rate in the pipeline can reach 8.9%. The composite heat pipe can transfer 1.71×10^{12} J of heat in phase-change form. The symmetrically distributed foamed iron-nickel metal can effectively weaken the

explosion pressure wave and effectively destroy the heat storage environment in the pipe.

- (b) The attenuation performance of the foamed iron-nickel metal material on gas explosion shock waves is enhanced with the decrease in the material pore diameter and thickness. The foamed iron-nickel with a pore size of 10 ppi and the thickness of 80 mm has the largest attenuation rate of the explosion over-pressure, which reaches 41.76%.
- (c) The temperature decay performance of the metal foam material on the gas explosion flame increases with the decrease in the material porosity and the thickness. The pore size of 30 ppi and the thickness of 80 mm of the foamed iron-nickel yield the largest attenuation rate for the explosion flame, which reaches 64.7%.

Nomenclature

- x : The length of the pipe, m
 Q : The heat exchange volume of the heat pipe evaporation section, J
 q : The heat flux density, W/m^2
 l : The evaporation section length, m
 r : The latent heat of vaporization of the working water in the heat pipe, KJ/kg
 g : The local gravity acceleration, N/kg
 d : The heat pipe diameter, m
 i : The slope value of the heat pipe installation

Greek symbols

- ε : The porosity of the foam
 ρ : The density of the working fluid, kg/m^3
 δ : The thickness of the flat wall, m
 θ : The inclination of the heat pipe

Subscript

- λ : The thermal conductivity, $\text{W/(m}\cdot\text{K)}$
 λ_g : The thermal conductivity of the methane-air mixture gas, $\text{W/(m}\cdot\text{K)}$
 λ_s : The thermal conductivity of the foamed iron-nickel, $\text{W/(m}\cdot\text{K)}$
 t_w : The wall surface temperature, $^{\circ}\text{C}$.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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