

Preparation of CO₂/N₂ cryogenic slurry and its pipeline flow characteristics

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Abstract: It was proposed to use CO₂/N₂ to effectively prevent and control Class A solid spontaneous fires such as coal. The preparation process of CO₂/N₂ cryogenic slurry pipeline and its pipeline flow characteristics were studied. The temperature field, pressure field and phase change characteristic changed during the transportation of the CO₂/N₂ mixture in the pipeline are analyzed by numerical simulation. The results showed that: the fluid in the pipeline exchanged heat and started to contact at a position of 0.1m in the pipeline. The temperature first rapidly dropped to the lowest temperature of 103K, and then the fluids in the range of 0.1m to 0.3m were fully mixed, and the temperature rised to 164K. The temperature was consistent with the equilibrium state in the pipe, and the temperature was gentle and stable; the pressure in the pipe was on the whole downward trend, and each position along the main pipe produced a positive pressure difference relative to the end of the pipe. The closer to the mixing place, the greater the corresponding pressure difference; During the mixing process, LN₂ was acted as a cold source to sublime CO₂ to form dry ice particles. And through the cryogenic fluid mixing experiment, the temperature distribution in the pipeline, range of the dry ice particle generation position, and the dry ice particle generation phenomenon was measured. The results showed that the mixing was completed within 0.8 m of the pipeline, and the temperature in the tube rised to 168K and remain stable. The data were basically consistent. And dry ice particles generated at the temperature of 194.5K, and a diffuse gas cloud formed at the outlet with the momentum of the jet.

1 Introduction

China is rich in coal resources, but due to the influence of coal seam geological conditions, mining technology, ventilation management and coal's own characteristics, the annual direct burning loss due to spontaneous combustion reaches 10~13.6Mt[1-2]. Coal spontaneous combustion disasters have caused serious waste of resources and even casualties. Its governance has always been a hot issue of research [3-5].

Countries around the world have done a lot of work in the treatment of underground coal fires, and successively proposed technologies such as yellow mud grouting, coal seam water injection, pressure equalization, inhibitors, high-expansion foam, and inert gas injection in the goaf [6-8]. Among them, the inert gas anti-extinguishing cooling rate is slow, and the cooling effect is relatively poor. Based on this, in order to make up for the shortcomings of traditional fire-fighting technology, many experts and scholars have done a lot of research work on CO₂ fire-fighting and its application technology, which has good cooling performance, oxygen reduction, strong inertia, and convenient transportation. Gao Yukun and others used Fluent to simulate the dry ice in the goaf to release low-temperature CO₂ to prevent fire and extinguishing technology, and found that low-temperature CO₂ quickly spreads over the goaf, which has a good fire-fighting effect [9]. Ann G. Kim et al. used a cryogenic

slurry made by mixing liquid nitrogen and liquid CO₂ on site to extinguish the fire on the abandoned coal gangue hills in Ohio, and achieved good results [10]. Chaiken invented a patent for low-temperature slurry of liquid nitrogen and granular CO₂ used to extinguish mine fires [11]. Zhang Xinhai and others invented a method and device for preventing and extinguishing snow from cryogenic inert gas. The solid carbon dioxide particles formed by sublimation are dispersed in liquid nitrogen to form a slurry that is easy to transport, covering the surface and cracks of spontaneous combustion coal. Quickly cool down and isolate oxygen to achieve efficient fire fighting [12, 13]. The dry ice particles in the cryogenic slurry are formed by the condensation of low-temperature carbon dioxide gas. Yoshiyuki uses a vertical dry ice crystallizer made of Pyrex to visually observe the CO₂ sublimation process. Under the action of low temperature, CO₂ directly undergoes sublimation to produce dry ice particles [14]. Li Juan et al. introduced CO₂ into saturated liquid nitrogen through different types of pipelines to form fine and dispersed dry ice particles and a uniform solid-liquid mixture in the pipeline. They studied the particle size and pipe blockage during the mixing process and found that capillary tubes were used. Tube blockage does not occur sometimes [15]. Yuan Lingcheng studied the CO₂ sublimation mechanism in the N₂/CO₂ binary mixture system, and analyzed the CO₂ sublimation under different flow characteristics and cooling conditions [16, 17]. Jiang

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Xiaobo studied the CO₂ sublimation process and the crystal crystallization during the sublimation process, and obtained crystal pictures through optical instruments, and summarized the nucleation probability and the size of the nucleation [18]. Liu Yao analyzed the influencing factors of CO₂ sublimation heat transfer under different boundary conditions and found that the lower the N₂ temperature at the inlet, the higher the CO₂ sublimation temperature [19, 20]. Fan Yafang used numerical simulation to study the sublimation heat transfer process of UF₆ gas in an 8L condensing vessel [21]. Wang Yaning proposed a one-dimensional dynamic model for simulating the sublimation process of CO₂ in a low-temperature surface mixed gas, and revealed the change law of parameters such as temperature distribution and sublimation time during the sublimation process [22].

In summary, the current CO₂ sublimation prevention and control of coal spontaneous combustion at room temperature mainly focuses on the microscopic mechanism of the sublimation process, such as the formation and growth of CO₂ solid crystal nuclei. There are few researches in the field of coal mine fire prevention and extinguishing. Research on the formation and flow characteristics of inert gas slurry in pipelines lays a theoretical foundation for fire-fighting technology. In this paper, CO₂ gas is converted into small solid particles by low-temperature liquid nitrogen (LN₂) and dispersed in LN₂ to form inert gas slurry. Fluent numerical simulation and experimental verification are used to study the temperature, pressure and phase of N₂ and CO₂ in the pipeline during the mixed transportation. The characteristics of state change provide relevant basis and reference for the cryogenic slurry anti-extinguishing technology to realize the solid-liquid two-phase transport into the coal spontaneous combustion high temperature area, so that the CO₂ is attached to the surface of the spontaneous combustion coal body in the form of small solid particles and cracks to cool down Oxygen barrier.

2 Numerical simulation

2.1 Geometric model and mesh

The gas mixing pipeline used in the simulation in this paper adopts a three-way pipe with a diameter of 20mm and a length of 1200mm. The geometric model is shown in Figure 1: CO₂ enters from inlet 1 of the pipeline, and LN₂ enters from inlet 2. Figure 2 shows the results of meshing the pipeline using the Mesh module. After mesh inspection, the geometric model mesh quality is greater than 0.4, accounting for 99.24, which meets the solution requirements.



Fig.1 Schematic diagram of the pipeline model

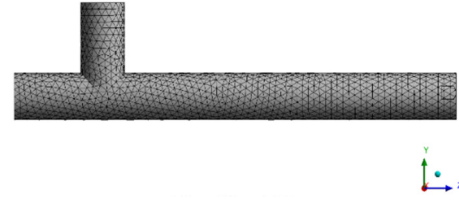


Fig.2 Mesh of the geometric model

2.2 Mathematical model

The simulation of incompressible viscous fluid uses the standard k-ε model to calculate the flow state in the pipeline [23]. In the process of fluid pipeline flow, the law of conservation of mass, the law of conservation of momentum and the equation of conservation of energy are observed. The specific differential equation is as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \quad (1)$$

The steady-state momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial \rho}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \overline{\rho u_i u_j} \right] \quad (2)$$

Energy conservation equation:

$$\frac{\partial(\rho T)}{\partial t} + \text{div}(\rho u T) = \text{div} \left(\frac{K}{c_p} \text{grad } T \right) + S_T \quad (3)$$

Mass transfer differential equation:

$$\frac{\partial \rho_A}{\partial t} + u_x \frac{\partial \rho_A}{\partial x} + u_y \frac{\partial \rho_A}{\partial y} + u_z \frac{\partial \rho_A}{\partial z} = D_{AB} \left(\frac{\partial^2 \rho_A}{\partial x^2} + \frac{\partial^2 \rho_A}{\partial y^2} + \frac{\partial^2 \rho_A}{\partial z^2} \right) \quad (4)$$

$$\frac{\partial \rho_B}{\partial t} + u_x \frac{\partial \rho_B}{\partial x} + u_y \frac{\partial \rho_B}{\partial y} + u_z \frac{\partial \rho_B}{\partial z} = D_{AB} \left(\frac{\partial^2 \rho_B}{\partial x^2} + \frac{\partial^2 \rho_B}{\partial y^2} + \frac{\partial^2 \rho_B}{\partial z^2} \right) \quad (5)$$

$$D_{AB} = \frac{0.0101 T^{1.75} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}}{P \left[\sum V_A^{1/3} + \sum V_B^{1/3} \right]^2} \quad (6)$$

2.3 Boundary conditions and solution settings

The turbulence model is a standard k-ε model, the inlet boundary condition is set as the velocity inlet, and the outlet boundary condition is the outflow. The physical parameters of the selected materials for the numerical

simulation are shown in Table 1, and the boundary conditions are set as shown in Table 2. The Mixture in the Multiphase Model module is selected for calculation, and the Euler phase number is selected as 2.

Table 1 Source phase parameters

material	N ₂	CO ₂
density (Kg/m ³)	1.138	1.7878
Specific heat capacity (J/Kg ^{-k})	1040.67	840.37
Viscosity (w/m ^{-s})	5 [·] 1.663×10 ⁻	5 [·] 1.37×10 ⁻

Table 2 Setting of boundary conditions

CO ₂	speed entry (m/s)	50
	Volume fraction	1
	T (K)	240
N ₂	V (m/s)	50
	Volume fraction	1
	T (K)	100
outlet	P (Pa)	101000
wall	Wall motion	Static wall
	Shear condition	No slip
	Wall roughness	0

3 Simulation results and analysis

Figure 3 is a cross-section of the symmetry plane to observe the temperature change cloud diagram of the two liquids after mixing. It can be seen from Figure 3 that during the mixing process of the two fluids, a temperature transition contact surface is formed at the contact position, and a stable temperature is gradually formed after the heat transfer of the two fluids.

Figure 4 shows the temperature-pressure change curve at the center of the pipeline. It analyzes the temperature and pressure changes at different positions of the main pipe and studies the flow characteristics in the pipe after mixing.

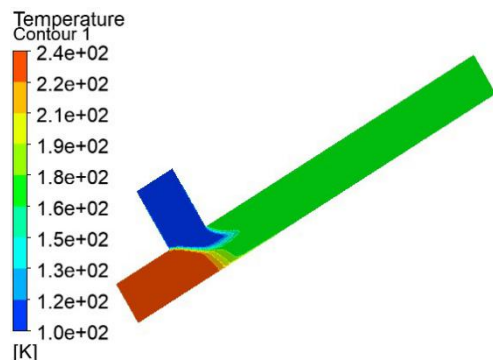


Fig.3 Cloud diagram of temperature distribution in the simulation tube

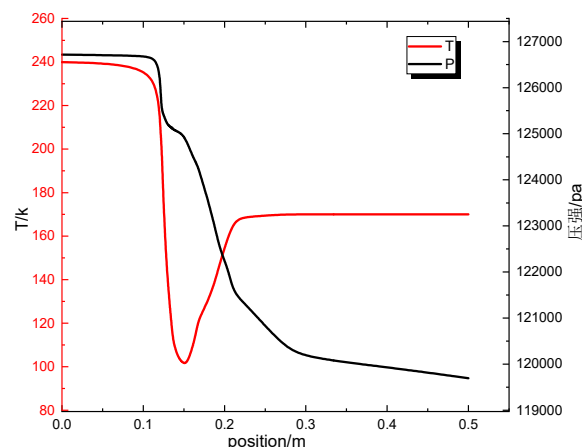


Fig.4 Temperature-pressure curve in simulated tube

It can be seen from Figure 4 that LN2 and CO₂ start to mix at 0.1, and the temperature limit is obvious. Initially, the temperature of LN₂ was 100K, and the temperature of CO₂ was 240K. After mixing, it quickly dropped to 103K, and then the temperature rose to 164K, which was consistent with the equilibrium state in the tube. A gentle and stable phenomenon; as the mixing progresses, the pressure in the pipe shows a downward trend as a whole, and each position along the main pipe produces a positive pressure difference relative to the end of the pipe. The closer to the mixing point, the greater the corresponding pressure difference. With the change of temperature and pressure, CO₂ presents three states: solid, liquid and gas. Under normal pressure, CO₂ has only two phases: gas and solid. At the freezing point, the temperature of atmospheric gas CO₂ can be directly condensed to form dry ice. The freezing point of liquid carbon dioxide is (196.5K, 0.1MPa). When the pressure is greater than the saturation pressure, gaseous CO₂ condenses into dry ice. In the range of 0.1 to 0.2m, the phase state of carbon dioxide changes, and solid particles of dry ice appear during the flow.

4 Experimental verification

4.1 Experimental setup

The experimental device adopts a self-designed and built cryogenic inert gas slurry preparation system, consisting of a low-temperature insulation gas cylinder with a volume of 170L, a digital display platform scale with a maximum load of 500kg, a stainless steel pipe with an inner diameter of 20mm, and a PT100 temperature sensor (temperature range -197°C 56°C, current 4 20mA), T=3 data acquisition instrument, notebook computer, etc. The experimental device is shown in Figure 5:

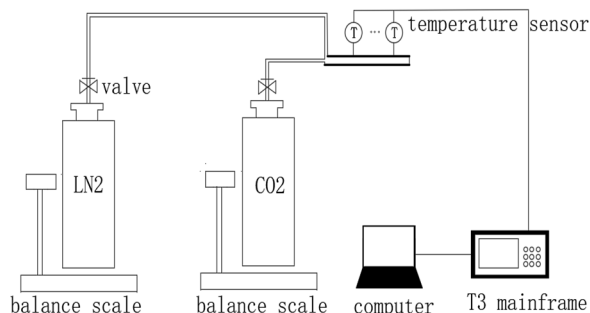


Fig.5 Experimental assembly drawing

4.2 Experimental procedure

Check the air-tightness of the device, open the liquid nitrogen valve and let the liquid nitrogen into the pipeline for pre-cooling for 35 minutes. When the temperature drops to 194.5K, open the CO₂ valve, the design flow rate is 50m/s, and the LN₂:1 ratio into. The temperature sensors are evenly arranged at a distance of 15cm in the cryogenic pipeline, and a total of 9 measuring points are arranged. After the injected fluid is stable, the temperature change in the pipeline is monitored in real time in a period of 10s.

4.3 Analysis of experimental results

By recording the temperature of the measuring point in the pipeline, the temperature change result is shown in Figure 6:

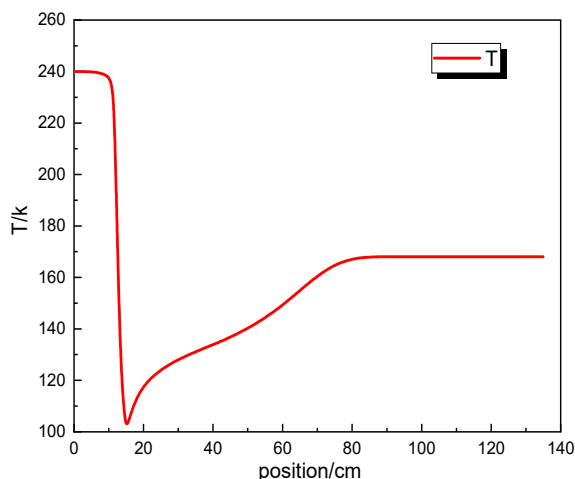


Fig.6 Temperature change curve in test tube

It can be seen from Figure 6 that liquid nitrogen and carbon dioxide mix rapidly in the pipeline, heat exchange occurs at the contact surface, and the temperature changes. Before 0.1m, it is a rapid cooling stage, and the temperature drops to 103K. At 0.1 ~ 0.8m Within the range, due to the latent heat of carbon dioxide phase change, in the subsequent heat exchange process, the temperature drop rate appears a concave function change trend, the temperature rises to 168K, and the mixing ends after 0.8m. The final mixing temperature of the cryogenic

inert gas slurry is 168K. Compared with the results of the numerical simulation, the temperature is higher than that of the numerical simulation. Due to the heat exchange between the cryogenic inert gas slurry and the outside temperature under the action of the pipeline, the temperature of the slurry increases.

5 Conclusion

1) Through fluent numerical simulation, the temperature field, pressure field and phase change characteristics in the cryogenic pipe during the mixing process are studied. The results show that the two rapidly mix at 0.1m in the cryogenic pipe, and the temperature limit is obvious. After mixing, the temperature is stable at 154K. The medium pressure decreases continuously as the mixing progresses, and when the sublimation conditions are met, sublimation occurs to produce dry ice particles.

2) According to the experimental visualization results, during the mixing process, due to the role of liquid nitrogen as a low-temperature cold source, heat exchange occurs, and carbon dioxide condenses at low temperature to form granular dry ice particles, which are driven by the jet momentum to form diffuse gas clouds.

3) By comparing with the experimentally measured data, the numerical simulation results are basically consistent with the experimental data, which verifies the reliability of the simulation.

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