Application of Nanoporous Super Thermal Insulation Material in the Prevention and Control of Thermal Hazards in Deep Mining of Metal Mines

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As an important energy material, mineral resources have an important role in the rapid growth of the national economy. In recent years, with the enhancement of mining strength and the improvement of mechanized production level, the depth of mining has also increased year by year. Therefore, the number of heat hazards in deep mine mining has increased year by year, and the problem of heat loss in deep mines has become increasingly prominent, which has seriously affected the safe and efficient production of mines. In this paper, the application of nanoporous super insulation materials in the prevention of thermal damage in deep mining of metal mines is studied, and the related theories of nanoporous super insulation materials and the prevention of thermal damage in deep mining of metal mines are understood on the basis of literature data. Nanoporous thermal insulation materials refer to thermal insulation materials with pore diameters in the nanometer range. This material can effectively prevent the collision of gas molecules and prevent the heat conduction of the gas. Then, the application experiment of nanoporous super thermal insulation materials in the prevention and control of heat damage in deep mining of metal mines is carried out. Through experiments, it is concluded that the room temperature thermal conductivity of the experimental material decreases with the increase of the addition of SiO2 aerogel, and the downward trend is linear, and when the coating surface temperature of the aerogel thermal insulation coating is only 60°C, the thermal insulation temperature difference is 140°C. From these data, it can be seen that the thermal insulation performance of nanoporous super thermal insulation materials is better, which verifies the feasibility of its application in the prevention of heat damage in metal mine mining.

1. Inductions

Mineral resources, as one of the main energy consumed by the current social development, have played a vital role in the progress of social development. The mines in the central and eastern mining areas have introduced deep mining before, and the current mining depth of deep mines is still expanding [1, 2]. However, due to the expansion of mining depth, the temperature of deep mine shafts continues to rise, which seriously affects normal safe production [3, 4]. Thermal damage in deep mine development is an objective reality, and creating a cool working environment is also an issue that needs to be improved in China’s domestic mine development [5, 6]. Since China is the world’s largest mineral resources producer, 95% of its mineral resources come from wells. In-depth study of mine utilization methods in order to obtain more mineral resources to support national construction and many mines in China have been developed at depths of more than 900-1300 meters, so high temperature heat loss in mines is an urgent need to solve the problem [7, 8].
In order to meet the high demand for mineral resources in the rapid development of society, it is necessary to increase the exploitation of mineral resources in the deep part of the earth. Solving the problems of ventilation difficulties and high temperature heat damage encountered in the process of deep well mining will greatly reduce the difficulty of mining mineral resources deep in the earth, improve the availability of underground energy, and promote the rapid development of society [9].

Regarding the investigation of thermal damage in mines, some scientific researchers pointed out that ventilation and refrigeration is the most common nonfreezing cooling method at present, which can be used to cool, dehumidify, and increase air concentration on the surface of hot mines. Mine ventilation can bring enough air to underground workers, and it can also reduce the content of harmful gases, thereby reducing the high temperature in the basement, but by increasing the ventilation, the pressure increases linearly, and the output of the fan is increased by three times, so mine ventilation alone cannot effectively alleviate the thermal hazards of high temperature mines. Therefore, the conventional coal mine ventilation principle cannot completely alleviate the thermal damage of high temperature coal mines [10]. Relevant researchers believe that the temperature of the original rock rises with the expansion of the mining depth, and the heat release of the original rock is also one of the main heat sources in the deep mine. In the tunnel under the hot mine, because the temperature of the cold air rises, the cold air inevitably conducts countercurrent heat exchange with the hot tunnel wall. If heat insulation materials are used to isolate the heated road wall from the cooling flowing air, the high temperature of the hot mine can be significantly reduced, similar to the thermal insulation of the building facade, which can prevent the facade from interacting with each other in summer and winter. The air between the inner walls performs countercurrent heat exchange, which has a cooling effect in summer, and a heat preservation effect in winter [11]. In the research of nanoporous insulating materials, some scholars have pointed out that SiO₂ and its composite aerogel have the characteristics of extremely low density, large specific surface area, and high porosity. They are suitable for many fields, and many unknown fields have great applications. Especially in the field of private thermal insulation, with the progress of economic growth, the world pays more and more attention to energy issues, and daily energy saving is particularly important. Due to the special pore structure characteristics of aerogel, it has an excellent thermal insulation effect. Compared with other insulation materials such as cotton insulation and polyurethane insulation, it has the advantage of better insulation performance and makes up for the disadvantage of poor thermal stability, so it has good potential application value [12]. To sum up, the research on the prevention and control of heat damage in mines has attracted much attention, but most of the studies have focused on artificial cooling measures, and few scholars have studied the use of heat insulation materials to control the generation of heat sources.

The innovations of this paper are as follows: (1) The application of nanoporous super insulation materials in the prevention and control of heat damage in deep mining of metal mines is studied. (2) The thermal damage in deep mining of metal mines and the thermal insulation principle of nanoporous super insulation materials are analyzed. (3) The feasibility of applying nanoporous super insulating materials in the prevention and control of heat damage in deep mining of metal mines is analyzed. (4) The application test of nanoporous super insulating material in the prevention and control of heat damage in deep mining of metal mines was carried out, and the feasibility of the method was verified by experiments.

2. The Prevention and Control of Thermal Damage in Deep Mines in Metal Mines and Nanoporous Super Thermal Insulation Materials

2.1. Analysis of Thermal Hazards in Deep Mine Mining in Metal Mines. The mining depth is more than 800 m, which is a deep well mining. Rocks with type II deformation characteristics at this depth will experience frequent rockbursts, which will affect the safety of the operation. The factors that cause thermal damage to deep wells include geothermal heat (mainly hot water produced by surrounding rocks and wells) and air compression heat entering the well (mainly air intake wells, inclined wells, etc.), ore oxidation, and thermal diffusion of underground electromechanical equipment, heat dissipation, explosive heat, and underground heat [13]. The mining methods of deep well mines are basically the same as those of shallow well mining, including three categories: open field method, filling method, and caving method. However, its structural parameters, mining sequence, and mining process should be adjusted according to the characteristics of deep mines, and due to the particularity of deep mines, the backfill mining method will become the mainstream mining method. Among them, the problems faced in deep well mining include deep well heat damage, ventilation and cooling problems, high ground pressure, and deep well water inflow. As the mining depth and lifting height increase, the weight of the lifting wire rope increases, and the ineffective energy consumption caused by the dead weight of the wire rope in the lifting operation becomes more and more prominent.

The heat of blasting is released instantaneously and plays a major role in the instantaneous rise of the temperature in the well, but the heat in the mine does not rise because of the short duration. Especially the underground DC ventilation can effectively prevent the accumulation of shock waves and quickly dissipate heat. Generally speaking, iron ore requires staff to clean up the site before organizing ore mining and blasting. After blasting, ventilation is required for a period of time before personnel can enter. Therefore, it is not necessary to consider the super position of blast heat as a cooling system to improve the working environment of underground workers [14]. Among them, deep well mining has the following main characteristics: high ground pressure, high ground temperature, and large mine gas.

2.1.1. Geothermal (Wall Stone). For deep iron ore, the initial rock temperature is very high, which is usually the main...
reason for the high temperature of the mine. The heat transfer between hot wall rock and airflow is a complex and unstable heat transfer process. The airflow is very active in the mine. The walls and roads of the mine are convex. The thermal energy on its surface releases heat to the wind flow, thereby transferring the heat from the original rock to the cold mine wall and driveway. At the same time, the deep rocks are also cooled to form a cooling zone, and the temperature rises after heating. With the extension of the aeration time (generally one year later), the expansion of the cooling zone begins to weaken after the surrounding rock and the airflow have fully heat exchanged [15].

2.1.2. Thermal Oxidation. Sulfur and iron in iron ore may undergo an exothermic oxidation reaction when they encounter oxygen in the air, leading to an increase in soil temperature. The heat released by oxidation is generated by the ore exposed to wind currents. After the connecting strips of the iron ore vein road, all the walls of the road surface are fixed with concrete mortar, so the oxidation heat release is mainly carried out in the vein tunnel and mining [16].

2.1.3. Heat Dissipation of Electromechanical Equipment. With the increase in the degree of mechanization of production links such as underground mining, tunnel boring, and iron ore transportation, the installed capacity of electromechanical equipment has grown rapidly. The installed power of tunnel surface is above 1000 kW. The electrical energy consumed by underground electromechanical equipment is either used to increase the kinetic energy of materials or liquids (the kinetic energy changes very little, usually negligible), or it is converted into heat energy, and almost all of the heat energy generated is diffused into the air [17].

2.1.4. The Surface Atmosphere Brings Heat. Air flows from the surface to the wellhead, and the temperature and humidity of the surface atmosphere inevitably affect the temperature and humidity of the air in the well. The moisture content of the surface atmosphere changes very little every day, showing a pattern of high at noon and low at night. Although the daily temperature fluctuates greatly, when it flows into the well, due to the heat exchange with the rocks in the surrounding tunnel, the fluctuation of the air temperature in the well gradually becomes smaller, and this change is basically not felt in operation. The main influence of downhole air temperature by climate is the seasonal variation of surface temperature, especially water content. This is because the latent heat of water vaporization is much greater than the specific heat of air. In summer, the surface temperature and humidity are relatively high, which is one of the factors that affect the increase in temperature and humidity of downhole air flow [18].

2.2. Thermal Insulation Principle of Nanopore Super Thermal Insulation Material

2.2.1. Principle of Heat Conduction. The essence of heat conduction is the process of transferring energy from the high temperature part of the object to the low temperature part, or from the high temperature object to the low temperature object, by the collision of a large number of molecular thermal motions in the material. A porous material is a material with a network structure composed of interconnected or closed pores [19]. For porous materials, the gas thermal conductivity measured experimentally is often greater than the sum of the gas thermal conductivity and the gas thermal conductivity. The gassolid combined thermal conductivity is the increase in thermal conductivity caused by the gas-solid interaction. In the process of transferring heat to the porous material, some gas molecules are placed in the small holes, which can be used as a shortcut for heat transfer to create new heat transfer channels. Compared with continuous medium materials, porous materials generally have the advantages of low relative density, high specific strength, high specific surface area, light weight, sound insulation, heat insulation, and good permeability. If the material contains many channels, it can conduct gaseous heat, which will make the gaseous heat have a more obvious effect (as shown in Figure 1). This heat transfer process is carried out with gas molecules as the carrier, so it is related to the number of gas molecules (gas pressure). The greater the difference between the thermal conductivity of solid and the thermal conductivity of gas, the more obvious the bonding effect, and the greater the thermal conductivity of gas-solid bonding. If the pore size is very small, the gas molecules transfer heat in a manner similar to the lattice vibration, which can produce a very obvious gas-solid bonding thermal conductivity [20]. In the industry, there are many heat transfer processes dominated by heat conduction, such as heating and vulcanization of rubber products and heat treatment of steel forgings. The law of heat conduction plays an important role in the design and calculation of kilns, heat transfer equipment, and thermal insulation and in the analysis of temperature distribution of catalyst particles [21].

2.2.2. Characteristics of Nanoporous Thermal Insulation Materials. Nanoporous thermal insulation materials refer to thermal insulation with pore diameters in the nanometer range. This material can effectively prevent the collision of gas molecules and prevent the heat conduction of gas. The thermal conductivity of the nanoporous thermal insulation material under normal temperature and pressure can be lower than that of static air. Therefore, nanoporous thermal insulation materials and vacuum thermal insulation materials are also called super thermal insulation materials. At present, nanoporous insulating materials are mainly composed of aerosol and nanopowder insulating composite materials. Table 1 shows the density and thermal conductivity of many nanoporous insulating materials. It can be seen that the thermal conductivity of nanoporous insulating materials is relatively low. Nano-microporous thermal insulation materials mainly include thermal insulation materials such as nanoinsulation boards and nanoaeroel felts, and Jinshi nano-microporous thermal insulation materials. According to the particularity of thermal motion, it uses the unique thermal conductivity of nanoporous materials and the heat reflection function given by functional
materials and is suitable for binders and various inorganic elements. A low thermal conductivity thermal insulation material is produced by a synthetic process, which is actually smaller than the thermal conductivity of still air.

2.2.3. Reasons for Heat Insulation

(1) The pore size of the nanoaerogel is below 100 nm, which effectively increases the reflective interface. If the particle size of the material is in the same order of magnitude as the incident wavelength, the incident electromagnetic wave will be affected by the scattering effect, and the transmittance of the incident electromagnetic wave will decrease. The ability of the material to absorb heat radiation significantly achieves the purpose of heat insulation.

(2) Since the air is mainly composed of nitrogen and oxygen, its mean free path of thermal motion is about seventy nanometers. The pore size of nanoininsulating materials is basically no more than fifty nanometers, which is much lower than the mean free path of thermal motion between molecules in the air, so it is in a condition similar to that of a vacuum. Gas molecules cannot enter the nanopores at will. When the gas adheres to the pore wall, the pores no longer conduct heat energy, thereby effectively reducing the thermal conductivity of the material. There are many performance indicators of insulating materials, and the characteristics of various insulating materials are also different. The main performance indicators of commonly used insulating materials include breakdown strength, heat resistance, insulation resistance, and mechanical strength.

(3) Due to the low bulk density of nanogels and a large amount of air inside, the thermal conductivity of air at room temperature is the lowest, which effectively improves the thermal insulation performance of the material.

Nanoaerogel thermal insulation coating is a kind of composite thermal insulation coating, which combines the characteristics of thermal insulation coating and radiation thermal insulation coating. The thermal insulation principle of the two works together [22].

2.3. The Application of Nanoporous Super Thermal Insulation Materials in the Prevention and Control of Thermal Hazards in Deep Mining of Metal Mines

2.3.1. Preventive and Management Measures against High Temperature Hazards. Nonartificial cooling measures mainly include optimizing the development system and road layout during mine development and development, optimizing extraction and filling methods, strengthening ventilation, adopting controllable circulation, and taking personal protective measures by workers [23].

(1) The development system and road layout are optimized. The mining development system should consider separate development methods as much as possible, and try to use a hybrid or lateral ventilation system with a short air inlet path to reduce heat absorption.

(2) Optimize the fixing method and filling method, and adopt the post-fixing sequence. Under the same conditions, the air volume and wind speed of the work surface is higher than that of the front support, which helps to reduce the temperature, which can improve the air circulation and heat dissipation conditions of the mine. Compared with the cavitation method, the filling method increases the effective air volume of the mine and solves the basic problems of hot water leakage, residual combustible ore and surrounding rock in the hole, roof heat, and floor heat diffusion. Lower filling materials will also absorb a lot of heat.

2.3.2. Application of Nanoporous Thermal Insulation Materials. According to the above analysis, the nanoporous super insulating material has excellent thermal insulation performance, so this feature can be used to control the heat dissipation of the deep well heat source. The following are the nanoporous thermal insulation measures.

(1) Laminated Insulation. The method of laminated insulation is relatively simple. Insulating laminate materials are usually filled with materials with low thermal conductivity and rolled onto the surface where insulation is required. There are three types of laminated insulation: foam type, powder type, and fiber type [24]. In addition to the average temperature of the insulating layer, the thermal conductivity of the foam insulation material also depends on the material and density of the foam gas. Therefore, the insulation laminate should be made of as dense material as possible, because the low density will reduce the heat in the solid. The main disadvantage of dust and fiber insulation is the penetration of water vapor and air through the insulating layer to the cold surface. This problem can be solved by installing a moisture-proof layer. In order to prevent the condensation and solidification of the gas in the insulation material space and ensure good insulation performance, it is necessary to fill and accumulate gas with low thermal conductivity, and the condensation temperature of this gas should be lower than that of the cold surface. Generally, cold
surface temperatures above 77 K are filled with nitrogen, and cold surface temperatures below 77 K are filled with argon.

(2) Vacuum (or Fiber) Heat Insulation. Vacuum heat preservation is to fill the insulating intermediate layer with porous insulating material and at the same time evacuate the space of the insulating intermediate layer to a specific vacuum. The heat conduction of gas is the main way of heat transfer between porous media. Filling the vacuum interlayer with dust can reduce the distance between the radiation surfaces and reduce the thermal conductivity of the gas. Dust particles can reflect and scatter radiation and reduce the heat transfer of radiation. At the same time, the contact area between the dust particles is small, the thermal resistance is high, and the thermal conductivity of the solid is low.

2.4. Preparation of Nanoporous Super Insulation Material. The silicon aerogel manufacturing process includes three basic steps: sol-gel process, aging process, and drying process. The possible uses of silica aerogels depend to a large extent on the microstructural properties of the 3D framework and the nanostructured surfactant group. These special surface structures can generally be obtained by adjusting the sol-gel process parameters and modified silica aerogels, and the process parameters can be used to obtain bubbles with different characteristics. Therefore, it is very important to select a suitable composition and processing method to prepare silica aerogel to meet the performance required by bubbles in various applications. Figure 2 summarizes the existing aerogel manufacturing process and some synthesis parameters. These parameters affect the formation of the gel network, which in turn affects the performance and application of aerogels. Almost all aerogels can be prepared by liquid chemistry (sol-gel method). During the preparation process, changes in several parameters such as the type and quantity and type and concentration of precursors will affect the evolution of the microstructure of the aerogel network. The chemical reaction process of the aerogel composition used to prepare the aerogel material, such as the type of solvent, reaction temperature, and pH value, should be designed according to the desired yield.

In the process of silicon aerogel forming colloidal gel with lattice structure, the alkoxide-forming aerogel can ionize the precursor through hydrolysis or acid-catalyzed reaction and then alkali-catalyzed dehydration and condensation. In the reaction, the two -OH remove a H2O molecule to form a siloxane bond. During the aerogel preparation process, the condensation polymerization reaction and hydrolysis reaction of the silane precursor and the alkoxide solvent proceed simultaneously, continue to exist in the entire colloidal gel process, and eventually lead to gel after the reaction.

The sol-gel reaction process has many parameters that affect its structure. The three-dimensional structure of the gel can be adjusted by adjusting the basic parameters of the reaction, and ultimately determine the nanostructure of the network and the properties of the final material, which is controlled. These parameters usually include precursor concentration, relative precursor and solvent concentration, solvent type, relative water and precursor concentration, temperature, and pH. In addition, organic molecular groups or nanoscale organic groups can be added during the sol-gel reaction process to give the gel network a specific function. Generally speaking, suitable alkoxide derivatives containing organic functional groups can be added by chemical reactions, or additives can be used in the porous network by natural methods. For example, it can be used in liquid gels to obtain hydrophobic aerogels, and the surface of the network structure is introduced by chemical reaction to introduce methyl functional groups to obtain a hydrophobic structure. It can also increase the mechanical strength of polymer mixtures and gels. In addition, catalysts, nanoparticles, magnetic, or titanium oxide nanoparticles can be added to the gel network structure to obtain new aerogel properties such as catalytic properties, optical properties, mechanical strength, and magnetic properties.

### Table 1: Density and thermal conductivity of nanoporous insulating materials.

| Materials | Composition | Density (g/cm³) | Thermal conductivity (W/(m·K)) | Maximum service temperature (°C) |
|-----------|-------------|----------------|-------------------------------|-------------------------------|
| Cellulose |             | 0.056-0.098    | 0.031-0.034                   | -270                          |
| Polyimide |             | 0.11           | 0.031                         | 350                           |
| Aerogel   | Phenolic aldehyde | 0.19 | 0.011                         | -250                          |
|           | SiO₂        | 0.16           | 0.013                         | 800                           |
| Carbon    |             | 0.052-0.183    | 0.020-0.037                   | ≥2000                         |

3. Application Experiment of Nanoporous Super Thermal Insulation Materials in the Prevention and Control of Heat Damage in Deep Mining of Metal Mines

3.1. Preparation of Experimental Materials

3.1.1. Experimental Materials. The materials used in the experiment are 45% concentration silica solution, solidified magnesium oxide, Portland P. C 32.5R initial strength silicate composite cement, White Soot 2000 mesh, foaming agent, pore former, and other additives.

3.1.2. Additives. The additives used were pore-forming agent and foaming agent obtained from Chengdu Kelong Chemical Reagent Factory.

3.1.3. Reinforced Materials. Glass fiber was obtained from Chengdu Kelong Chemical Reagent Factory. The chemical composition is shown in Table 2.
3.1.4. Formation Mechanism of Stomata Structure. Weigh cement-based materials, fillers, pore formers, etc. According to a certain mixing ratio, pour into a container and mix into a liquid slurry. After the blowing agent is injected, gas is generated and formed during the continuous expansion of the gas-wet interface. When gas passes through the liquid, the surface of the liquid shrinks automatically due to the action of surface tension, and the gas is wrapped by a layer of liquid film to form bubbles. At the same time, the added surfactant contains a large number of anionic groups, these anion groups are compressed into a gas absorption layer, and some of the remaining groups diffuse around the colloid or silicate beam particles, thereby producing surface micelles. The gas acts as a "coating" that sticks the bubbles to the system. The solid particles adhere to the vicinity of the bubble under the action of the initiator, thereby effectively preventing the precipitation of solid particles, and a uniform and stable three-phase power source "solid-liquid-gas" coexistence system is established near the bubble. When the solid phase is condensed, the liquid phase separates, and the solid phase closely surrounds the bubbles, thereby producing a porous silica-based porous insulator with closed pores.

3.1.5. Process Flow. Figure 3 shows the manufacturing process flow of a porous insulating material based on silicon dioxide. Cement-based materials, fillers, air trapping agents, surfactants, and fibers are weighed in a certain proportion, mixed with the cement-based materials, and then the fillers, fibers, and surfactants are added to the container and stirred for about 40 seconds to form a uniform slurry. Then, add the air-entraining agent and stir evenly, and then quickly pour the slurry into the mold. The porous material is formed by on-site self-assembly technology and dried under natural conditions, and then, the experimental sample is cast.

3.2. Experimental Method

3.2.1. Thermal Conductivity Test. There are different thermal conductivity methods for measuring thermal conductivity according to measuring different types of materials, working temperature, and thermal conductivity materials. The method of measuring thermal conductivity can be classified according to the mechanism of thermal conductivity, the shape of the sample, and the direction of heat flow. According to the macroscopic mechanism of thermal conductivity, it is divided into steady method and unsteady method. According to the shape of the sample, it is divided into plane method, rod method, cylindrical method, and ball method. According to the direction of heat flow, it can be divided into longitudinal heat flux method and radial heat flux method. Usually laser method, hot cable method, heat flow method, protective hot plate method, etc. are used.

In this paper, the thermal conductivity of the insulating protective layer is measured by the protective plate method. The protective plate method is measured according to the basic principle of the steady-state differential equation of thermal conductivity. By installing the same two samples between the two cooling plates and the concentrated heating plate of the thermal conductivity meter, a laminated structure of cooling plate, sample, hot plate, sample, and intercooling plate can be produced. In order to ensure the same direction of heat flow through the two specimens, the structure is equipped with a heat preservation structure around the specimen and the heating plate to avoid radial heat transfer and conform to the characteristics of axial one-dimensional heat conduction. After waiting for the temperature distribution of the test sample to balance, a constant temperature $\delta T (\Delta T = T_2 - T_1)$ is formed on the top and bottom of the sample. By measuring the direction of the temperature flow of the sample and the temperature step.

### Table 2: Chemical composition of glass fiber.

|       | %  |     |     |     |     |     |
|-------|----|-----|-----|-----|-----|-----|
| SiO₂  | 51-59 | 24.5-26.5 | 11-20 | 0-0.9 | 0.6-1.5 | 1-4 | 0.6-0.8 |

3.1.4. Formation Mechanism of Stomata Structure. Weigh cement-based materials, fillers, pore formers, etc. According to a certain mixing ratio, pour into a container and mix into a liquid slurry. After the blowing agent is injected, gas is generated and formed during the continuous expansion of the gas-wet interface. When gas passes through the liquid, the surface of the liquid shrinks automatically due to the action of surface tension, and the gas is wrapped by a layer of liquid film to form bubbles. At the same time, the added surfactant contains a large number of anionic groups, these anion groups are compressed into a gas absorption layer, and some of the remaining groups diffuse around the colloid or silicate beam particles, thereby producing surface micelles. The gas acts as a "coating" that sticks the bubbles to the system. The solid particles adhere to the vicinity of the bubble under the action of the initiator, thereby effectively preventing the precipitation of solid particles, and a uniform and stable three-phase power source "solid-liquid-gas" coexistence system is established near the bubble. When the solid phase is condensed, the liquid phase separates, and the solid phase closely surrounds the bubbles, thereby producing a porous silica-based porous insulator with closed pores.
along it, the direction of the temperature flow and the thermal conductivity of the sample can be obtained using the following heat equation. The test principle of the protection board method is simple and the measurement accuracy is high.

\[ \Delta T(\tau) = \frac{P_0}{\pi^{3/2}kr} f(\tau). \]  

(1)

In the formula, \( p \) is the output power of the catheter, the unit is W, \( r \) is the radius of the catheter, the unit is m, and \( f(\tau) \) is a dimensionless transient function. Here, \( \tau = \sqrt{\alpha t / r^2} \).  

(2)

In the formula, \( \tau \) is the test time, the unit is s; \( \alpha \) is thermal diffusivity.

In this experiment, the Swedish thermal constant analyzer HotDisk TPS250 was used to determine the thermal conductivity of the coating. The sensor placed between the two materials acts as the heat source and temperature sensor of the device and generates specific output energy by introducing current pulses. Since the temperature rise of the catheter is proportional to the voltage, the thermal conductivity of the material can be calculated from the temperature data that changes over time, and the average value of each sample group is measured 3 times.

3.2.2. High Temperature Insulation Performance Test. Dry the 15 cm × 15 m × 3 cm sample to be tested, and then place it on a constant temperature hot stage with ceramic digital display to ensure that a stable and uniform air flow can be formed on the heated surface of the sample. Due to the temperature change on the back and the heat-resistant ceramic fiber insulation blanket around the thermocouple, the temperature error caused by the air flow moving on the back of the sample is reduced. Through the three detection points on the front and back of the sample, the temperature evaluation test is carried out within 30 minutes of data. For samples with good high temperature insulation, the lower the front and back temperature, the better the effect of the high temperature insulation system of the sample.

3.3. Establishment of Thermal Conductivity Model. According to Fourier’s law, the thermal conductivity of randomly distributed nanowires is

\[ k_{eff} = -\frac{Q_z}{\Pi VT}. \]  

(3)

In the equation, \( Q_z \) is the heat flow through the cross section, and \( VT \) is the temperature difference in the direction of the heat flow. This is because the pores of the fibrous porous material are very small, and the filling stage is air. Therefore, in the model, the contribution of air to the thermal conductivity of the fibrous porous material is negligible. Therefore, \( Q_z \) is the sum of the heat flux of each nanowire passing through the cross section, which can be written as

\[ Q_z = \sum_{a=1}^{n} Q_{a}. \]  

(4)

In the formula, \( Q_{a} \) is the average heat flow through a single nanofiber, the negative sign indicates that the direction of the heat flow is opposite to the z-axis direction, and \( Q_{a} \) is the areal density of the nanowire. Assuming that the contact points of all nanofibers have the same contact thermal resistance, and when the heat passes through the contact points, half of the heat flow flows into or out of a single nanofiber, so we get the heat flow of a single fiber as

\[ Q_{a} = k_0 A_0 \frac{N_c}{2} Bi \frac{\Delta T_{a\beta}}{L}. \]  

(5)

In the formula, \( k_0 \) represents the thermal conductivity of a single nanofiber, \( \Delta T_{a\beta} \) represents the temperature difference between contacting nanofibers, and \( Bi \) represents the biological number. The formula is

\[ Bi = \frac{HL}{k_0 A_0}. \]  

(6)

In the equation, \( H \) is the thermal conductivity of the
nanowire contact, which is the reciprocal of the contact thermal resistance.

Therefore, for randomly distributed nanowires, according to geometric parameters such as the volume fraction, size, and orientation distribution of the nanofibers, the effective thermal conductivity of the porous fiber material can be expressed as follows.

$$k_{eff} = \frac{\phi}{\sigma(4.55 + Bi_T)} k_0. \quad (7)$$

In the formula, $\varphi$ is the filling rate of fibers in the fibrous porous material, and $k_{eff}$ and $k_{eff}$ respectively, represent the effective thermal conductivity of the fibrous porous material and the thermal conductivity of the fibrous material.

4. Experimental Results

4.1. Thermal Conductivity Test Results. The thermal insulation coatings with different addition amounts of SiO$_2$ aerogel (as shown in Table 3) were prepared into 15 cm × 15 m × 3 cm samples, and the thermal conductivity of the coatings at room temperature was tested after drying. The results are shown in Figure 4.

It can be seen from Figure 4 that the room temperature thermal conductivity of the experimental material decreases with the increase of the SiO$_2$ aerogel addition, and the downward trend is linear.

4.2. High Temperature Insulation Performance Test. In order to investigate the influence of aerogel on the thermal insulation temperature difference, the test results of the thermal insulation temperature difference between the aerogel-free experimental material and the aerogel thermal insulation material were compared, and the results are shown in Figure 5.

It can be seen from Figure 5 that the surface temperature of the aerogel insulation material is generally lower than the surface temperature of the non-silica-based insulation material. This shows that SiO$_2$ aerogel can effectively enhance the thermal insulation effect of thermal insulation coatings. When the heat source temperature is 200°C, the surface temperature of the material of the thermal insulation layer (without aerogel) is 100°C, and the thermal insulation temperature difference is 100°C, but when the surface temperature of the aerosol thermal insulation material is 60°C, the insulation temperature difference is 140°C. Compared with the nonaerogel thermal insulation material, the temperature of the silica-based thermal insulation material is reduced by 42.3%, and the thermal insulation temperature difference is increased by 42.9%. In contrast, silica-based thermal insulation materials have excellent thermal insulation effects.

Figure 6 is a graph showing the temperature change with time of a silica-based insulation material and a silica-based insulation material-free material.

![Figure 4: Thermal conductivity of paint at room temperature.](image)

It can be seen from Figure 6 that as time goes by, the temperature of the backside of the silica-based insulating material gradually increases. The heating rate is very fast in the first 20 minutes, and the temperature on the back of the sample rises linearly, rising by 7-8°C every minute. After 20 minutes, the growth rate began to slow down. This is mainly due to the fact that as the silica aerogel starts to function and decomposes at high temperatures, the reaction begins to absorb part of the heat. The addition of aerogel powder increases the porosity of the material, resulting in most pores with a diameter of less than 50 nm, which actually eliminates the transfer of heat in the material.

4.3. Fire Performance Analysis. In this part of the experiment, closed pores and air-entraining agents introduced by aerogel powder were used to form a complex insulation system. The aerosol content puts different volume fractions of closed pore gas into the slurry while maintaining its raw material ratio unchanged. Finally, it is possible to produce high-fire performance composite materials with closed porous aerogel material powders with different bulk densities. At the same time, considering the bursting of the foam during the adding or mixing process, the amount of foam added can be adjusted by adjusting the volume density of the mixture. The closed pores refer to the air bubbles sucked by chemicals from the air, except for cement concrete, excess water and other pores produced by cement hydration. In the test, a reference sample with the same composition and no insulation component is usually used as the reference

| Sample no. | The volume fraction of SiO$_2$ aerogel in the mixture (%) | The volume fraction of closed pores in the mixture (%) |
|------------|----------------------------------------------------------|------------------------------------------------------|
| QY-1       | 49                                                       | 4                                                    |
| QY-2       | 44                                                       | 4                                                    |
| QY-3       | 41                                                       | 4                                                    |
| QY-4       | 39                                                       | 4                                                    |
| QY-5       | 34                                                       | 4                                                    |

Table 3: Addition of SiO$_2$ aerogel.
material, and the relative density between the insulation component sample and the control sample is used to express the porosity. Table 4 shows the composition ratio of the closed-cell aerogel material and the powder composite coating. In the course of the experiment, the corresponding error is allowed according to the adjustment of the bulk density of the mixture.

The samples QY-1 to QY-5 that reached the 28th curing period were tested for thermal conductivity, fire resistance, and adhesive strength. The test result is shown in Figure 7.

It can be seen from Figure 7 that both the thermal conductivity of the composite coating and the thermal conductivity of the aerogel coating gradually decrease with the decrease of the volume density of the closed-cell gas.

### Table 4: Composition ratio of closed-cell aerogel powder composite coating.

| Sample no. | The volume fraction of aerogel in the mixture (%) | The volume fraction of closed pores in the mixture (%) |
|------------|-----------------------------------------------|----------------------------------------------------|
| QY-1       | 53                                            | 0                                                  |
| QY-2       | 53                                            | 4                                                  |
| QY-3       | 53                                            | 7                                                  |
| QY-4       | 53                                            | 10                                                 |
| QY-5       | 53                                            | 13                                                 |

### 5. Conclusions

This article focuses on the application of nanoporous super insulation materials in the prevention of heat damage in deep mining of metal mines. After understanding the relevant theories, the application experiments of nanoporous super insulation materials in the prevention of heat damage in deep mining of metal mines are carried out. According to the experimental results, in the heat insulation test experiment, the temperature of the back surface of the experimental material gradually increases with the increase of time. The temperature rises quickly in the first 20 minutes, and the temperature on the back of the sample rises linearly, rising by 7-8°C every minute. After 20 minutes, the growth rate begins to slow down. This is mainly due to the addition of aerogel powder and the increase in the porosity of the coating, which reduces the pore size inside the coating, most of which is less than 50 nanometers, which effectively eliminates the increase in heat transfer inside the coating. However, due to the limitation of time and technology, we have not carried out in-depth research on it, so we will further explore other aspects of nanoporous insulating materials in the follow-up.
Data Availability
No data were used to support this study.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this article.

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