Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 1529490, 12 pages
https://doi.org/10.1155/2018/1529490

Research Article

Heat Treatment and Ventilation Optimization in a Deep Mine

Xingxin Nie, Xiaobin Wei, Xiaochen Li, and Caiwu Lu

School of Management, Xi'an University of Architecture and Technology, Xi'an, Shaanxi 710055, China

Correspondence should be addressed to Xingxin Nie; 670127529@qq.com and Xiaobin Wei; 1462658088@qq.com

Received 19 March 2018; Accepted 14 June 2018; Published 1 August 2018

Academic Editor: Hugo Rodrigues

Copyright © 2018 Xingxin Nie et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In order to address the issue of high temperatures and thermal damages in deep mines, the factors causing downhole heat damage at high temperatures were analyzed, the mine ventilation system was optimized and rebuilt, and a cooling system was established. The proposed cooling system uses mine water as the cooling source, and its features are based on the analysis of traditional cooling systems. The current ventilation system in the 1118 m deep pit of the Jinqu Gold Mine was evaluated, and the ventilation network, ventilation equipment, and ventilation structures near the underground working face were optimized. The low-temperature mine water stored in the middle section of the mine at 640 m depth was used as the cooling source, and a cooling system was established near the 440 m deep middle return well to alleviate the high-temperature and high-humidity conditions of the 280 m deep middle-western area. The results show that the effective air volume in the west wing at 280 m was 3.0 m^3/s, the operating ambient temperature was 27.6°C, the relative humidity was reduced to 76%, and the temperature was reduced by 5-6°C after the optimization of the system.

1. Introduction

In an era of rapid development of the global economy, the energy dependence is increasing rapidly [1–4]. As the shallow mineral resources on Earth's surface have been depleted [5], countries worldwide have successively begun to mine deep resources. As the mining depth increases, the temperature of the rock increases, and the heat damage caused by the ground temperatures and other factors is amplified [6–11]. For example, at a depth of 900 m in a mine in Germany, the average temperature is 41°C and at the mining depth of 1712 m, the maximum temperature is 50°C. In gold mines in India, at a depth of 3000 m, the geothermal temperature is more than 60°C. The world's deepest underground mine is South Africa's Carletonville gold deposit: the mining depth is 4000 m and the ground temperatures is 70°C. At present, China is also encountering the problem of high temperatures in deep mines, as in the Shandong Sun Cun mine [12], the Tongling Shizishan copper mine [13], and the Fushun Hongtoushan copper mine [14] where the mining depth is more than 1000 m and the geothermal temperature is 45°C. The general distribution of high temperatures and heat damage in deep mines in China is shown in Figure 1. The hot and humid working environment has seriously endangered the miners' health [15–18]; according to China's Technical Specification for Ventilation System of Metallic and Non-Metallic Underground Mine, the air temperature in downhole operation sites shall not exceed 28°C [19]; therefore, it is very important and of practical significance to minimize the heat damage in underground high-temperature and heat damage-prone working environments. The high-temperature, high-humidity, and low-velocity work environment on the working surface in deep mines will cause the central nervous system to be inhibited by workers working underground for a long period of time. The symptoms include mental retardation, lack of concentration, and decreased ability to work. At the same time, the environment is hot and humid. Working for a long time will also make the workers feel uncomfortable, irritated, and have eczema and other diseases that will seriously affect the safety production efficiency of the mine. Solving the problem of ventilation difficulties and high-temperature heat damage in deep mines can not only protect the physical and mental health of underground miners, but also help improve the

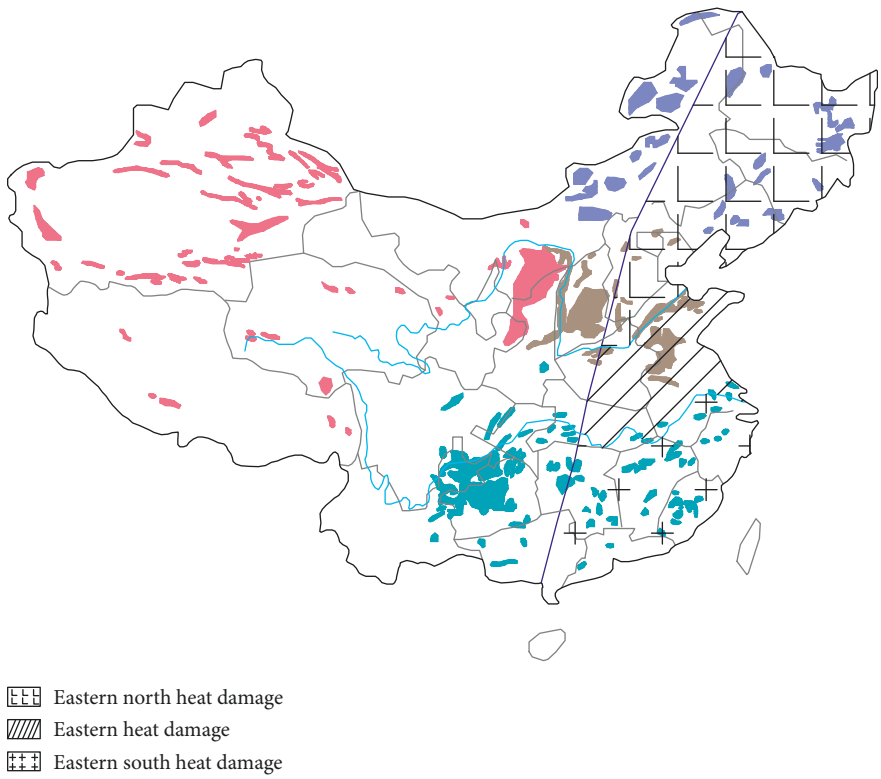


Figure 1: Distribution map of high-temperature mine in deep mining in China.

production efficiency of deep mine operating surfaces and contribute to the exploitation of mineral resources rich in the depth of the Earth.

High-temperature thermal damage in underground mines can be minimized by nonartificial refrigeration cooling and artificial refrigeration cooling. Common nonartificial refrigeration cooling methods include ventilation cooling, heat insulation, and personal protection. Common artificial cooling methods include water cooling, ice cooling, and thermoelectric cooling combined with cogeneration. However, nonartificial refrigeration cooling methods cannot be applied in deep mines to minimize high temperatures due to the limitations in the cooling capacity. Yuan et al. [20] proposed a new coupled cooling method of Latent Heat Thermal Energy Storage (LHTES) combined with Precooling of Envelope (PE). Guo and Chen [21] used the deep well return air as the cold source of the cooling system to achieve cooling and dehumidification on the working surface. Shi et al. [22] used liquid nitrogen to inject into the working face to achieve cooling effect. Guo et al. [23] used the heat of the bathing water on the surface and created a refrigeration unit to achieve a heat exchange between the chilled water and the high-temperature air on the working surface; the heat created by the condensation of the refrigeration unit was recovered and the thermal hazard of the high temperatures in the mine was converted into heat energy, thereby improving the energy efficiency. Wang et al. [24] optimized a ventilation system and increased the ventilation of a mine and the distribution of the air volume to accelerate the downhole airflow to achieve cooling. Zou et al. [25] used the theories of fluid mechanics and heat transfer to develop heat insulation materials in the mine main ventilation tunnel to achieve heat insulation, heat removal, and cooling. Zhang [26] used combined heat and power cogeneration technology using steam lithium bromide chillers and centrifugal chillers for heating, power generation, and refrigeration to improve the energy utilization. In this study, we propose a downhole centralized cooling system using mine water as the cooling source with a focus on underground mines with inflow water or water seepage. The method is based on the principle of heat exchange between the cold mine water and the high air temperatures of the working area and minimizes the heat damage in the working area. The cooling system assisted by mine water source cooling is to reduce the output of refrigeration unit cooling capacity by using the cold energy hidden by the groundwater source to save the running cost of cooling and cooling system. In addition, the condensing heat discharged by the cooling and cooling system can be absorbed by the cold energy contained in the mine water source itself, reducing the emission of condensation heat and reducing the secondary thermal hazards generated underground.

2. Thermal Damage Analysis of High-Temperature Mine

The related research shows that the fundamental cause of the high-temperature heat damage near the working face of the mine is the concentration of the heat on the working surface

because the heat cannot be discharged from the well in time. This results in an increase in the ambient temperature of the working surface. Therefore, the main reasons for the high-temperature heat damage in deep wells are the heat release from underground heat sources and the poor air circulation.

2.1. High-Temperature Heat Release

2.1.1. Heat Radiating from the Well Rock. The original rock temperature shows a nonlinear increase with the increase in the depth of the stratum. The thermal physical properties of the stratum rock in deep mining have a great influence on the high-temperature thermal damage [5]. High-temperature underground rock releases heat through heat conduction and convection due to heat exchange with the air, resulting in increased enthalpy in the air, and in high air temperatures in the roadways. In engineering practice, the formula for calculating the heat transfer between a high-temperature wall rock and the air in the roadway is

$$Q_r = K_\tau UL\left(t_{rm} - t\right), \tag{1}$$

$$K_\tau = \frac{1.163}{\left(1/9.6v_B\right) + 0.0441}, \tag{2}$$

where Q_r is the heat transfer of the surrounding rock in the tunnel, kW; K_τ is the unstable heat transfer coefficient between the surrounding rock and the airflow, kW/(m^2·°C); U is the perimeter of the mine roadway, m; L is the length of well, m; t_{rm} is the average primary rock temperature, °C; t is the average temperature of the air in the mine shaft, °C; v_B is the average velocity of the airflow in the mine shaft, m/s.

However, in the real life, the wall surface of underground mine tunnel is not dry, and there is water seepage in the surrounding rock wall of the roadway. The evaporation of moisture will absorb part of the heat to generate heat and moisture exchange. Therefore, the latent heat exchange between the water and wind flow in the tunnel wall is calculated. It is required. The formula for calculating latent heat exchange between water and air is

$$Q_w = \beta F k_B\left(p_w - p_B\right), \tag{3}$$

$$\beta = 0.0846 + 0.0262v_B, \tag{4}$$

$$k_B = \frac{101.325}{B}, \tag{5}$$

where Q_w is the amount of latent heat exchange between water and winds, kW; β is latent heat exchange coefficient, J·s^{-1}·N^{-1}; F is the heat dissipation surface area of water, m^2; k_B is the pressure correction factor; p_w is the saturated steam pressure at the water surface temperature, kPa; p_B is the partial pressure of water vapor in the air, kPa; B is the downhole atmospheric pressure, kPa.

2.1.2. Electromechanical Equipment Is Exothermic. With the continuous improvement in the mechanization of mine mining, the exothermic heat of the electromechanical equipment in the downhole production process has become a major heat source for high-temperature thermal hazards downhole [27]. Mining equipment, wind turbines, transportation equipment, exploration equipment, and lighting are powered by electrical energy and release heat. The equation for heat generated by electromechanical equipment during the operation is

$$Q_d = \sum \varphi N_d, \tag{6}$$

where Q_d is the heating capacity of the electromechanical equipment to the downhole airflow, kW; φ is the heat dissipation coefficient of the electromechanical equipment; and N_d is the total power of the electromechanical equipment operating at the same time, kW.

The exothermic heat of electromechanical equipment is an important heat source for heat dissipation from the downhole heat source. The heat dissipation coefficient of the electromechanical equipment is an important factor affecting the heat dissipation of the equipment. The heat dissipation coefficient of the equipment is determined according to its own characteristics, so the heat dissipation coefficient of different equipment is different. In this paper, the heat dissipation coefficient of the downhole electromechanical equipment is determined according to the characteristics of the equipment itself and the on-site conditions.

2.1.3. Heat Released during Ore Transportation. The newly mined ore is exposed to the air, which increases the contact area with the downhole air and speeds up the cooling of the ore. The emitted heat is absorbed by the airflow in the transportation lane. The heat dissipation efficiency of the ore being mined is faster than that of unmined ore; therefore, the heat emitted by the ore during transport cannot be ignored. The equation of the exothermic reaction of the ore during transport is

$$Q_k = 0.0024L^{0.8}\left(t_r - t_{wm}\right)mC_m, \tag{7}$$

where Q_k is the heat release of ore during transportation, kW; L is the distance of ore transportation, m; t_r is the average temperature of ore in transit, °C; t_{wm} is the average temperature of the air in the transportation lane, °C; m is the ore transport capacity, kg/s; and C_m is the specific heat capacity of the ore, kJ/(kg·°C).

2.1.4. Heat Release from the Air due to Compression. When fresh air flows from the outside to the well bottom surface, the air pressure increases with the increase in the depth. According to the principles of air compression and heat release, the air will release a certain amount of heat during the compression process. Under adiabatic conditions, the airflow will flow about 102 m vertically and its temperature increases about 1°C [28]. Under normal circumstances, there is a heat and moisture exchange between the wellbore and the airflow in the air intake tunnel. The heat balance equation for these conditions is

$$G(i_2 - i_1) - \frac{Z_1 - Z_2}{427}G - G\frac{\omega_2^2 - \omega_1^2}{2 \times 427} = Q_x + Q_q + Q_j - Q_1, \tag{8}$$

where Q_x is the sensible heat in the heat transfer from the borehole wall to the air, J/s; Q_q is the latent heat in the heat transfer from the borehole wall to the air, J/s; Q_j is the local heat release, J/s; Q_1 is the heat that evaporates from the surface of a water droplet due to air absorption, J/s; G is the ventilation, kg/s; and 1/427 is the work heat equivalent, J/kgf·m.

Under normal circumstances, when there is little change in the wind speed, the wellbore can be defined as $\omega_2 = \omega_1$; then (8) can be changed to

$$G(i_2 - i_1) = \frac{\Delta Z}{427}G + Q_x + Q_q - Q_1. \tag{9}$$

In the adiabatic state, the following is considered: $Q_x + Q_q - Q_1 = 0$.

Therefore, only the adiabatic heat of compression is calculated here. The equation can be simplified as

$$Q_{\text{heating}} = \frac{\Delta Z}{427}G, \tag{10}$$

where ΔZ is the height difference between the ground and the mining working face.

However, for mines that are mined in reality, the mine roadway is not adiabatic, and the sensible heat and latent heat in the mine will occur during the flow of air. Therefore, in actual mining wells, the heat generated by self-compression for every 100 m drop in air is insufficient due to the presence of heat exchange and its own temperature is increased by 1°C. Through experiments, it can be concluded that the temperature rises for every 100 m of air drop 0.4-0.5°C.

2.2. Poor Ventilation of the Working Surface. Mine ventilation systems are important for the safe operation of underground mines and provide fresh airflow and remove the contaminated air but also lower the heat and humidity of the working surface. Poor ventilation in the work area is one of the main causes of high temperatures and heat damage on the underground working surface. When the ventilation is poor, the high temperature can affect the physical and mental health and the work efficiency of mine employees.

2.2.1. Ventilation Networks Are Complex and Changeable. The layout of the ventilation network is a core component of the mine ventilation system and determines its efficiency. The underground environment is complex and variable as underground mining explorations increase. In many cases, the layout of the originally planned ventilation network undergoes tremendous changes as the mine expands. As a result, the underground ventilation network needs to be optimized to avoid ventilation problems. For example, the simultaneous mining of multiple middle segments results in problems such as changes in the working surface, difficulty in providing proper airflow, the continuous extension of mine ventilation lines, the accumulation of waste rock in the ventilation tunnels, and the ventilation issues caused by the accumulation of wastewater. In addition, the airflow volume is affected by increased resistance, lack of planning for the extraction of a large number of goafs without timely filling and closing, and the increase in the number of crossroads lanes caused by wind, air leakage, and short circuits.

2.2.2. Insufficient Power of Ventilation Equipment. The volume of the airflow at the mining face and driving face of the underground mine depends on the capacity of the underground ventilation fans. In many mines, the ventilation capacity of the underground ventilation equipment is incompatible with the mine ventilation system, and this is a common problem in underground mining. As a result, the lack of fresh air affects the safety of the workers.

With the continuous expansion of underground mining, the number of downhole mining operations is also increasing; this requires an expansion of the ventilation requirements of the working surface and in many cases, the underground ventilation network is insufficient, which results in poor ventilation. The existing wind turbine equipment does not have the capacity to supply sufficient airflow and the increased temperatures and sewage gases seriously affect the physical and mental health of the staff. According to statistics [29], the average power consumption of mine ventilation equipment accounts for about 30% of the total electricity consumption of the mine. In order to ensure the economic and efficient operation of ventilation fans, the capacity of the ventilation equipment and the number and location of the fans have to be adjusted to the requirements to reduce the operating costs and ensure adequate airflow.

2.2.3. Misalignment of Ventilation Structures. The ventilation equipment, the ducts, barriers, and the adjustment of the ventilation equipment play important roles in the regulation of the airflow in the mine. Ventilation structures fall into two categories based on the airflow: The first type of ventilation structure allows the airflow to pass through and this structure includes an air inlet, an air deflector, and an air bridge. In the second type of structure, the airflow is not passing through the system and those components include dampers, air curtains, air walls, and wellhead closures [24]. The main function of ventilation structures in underground mines is to ensure the flow of fresh air so that all working surfaces in the underground wells are reached.

In many underground ventilation systems, the structures are installed improperly or components are missing, which affects the underground airflow negatively and results in difficulties in regulating the airflow and poor ventilation. Common problems encountered in mine ventilation systems include the low quality of ventilation structures, which lead to air leakage, short circuits, and a reduction in the airflow capacity. The structures are affected by the blasting vibration, transport equipment, and malfunctions. In some cases, daily maintenance of the facilities is not performed and the regulations are disregarded. Therefore, in order to ensure the stable operation of the underground mine ventilation

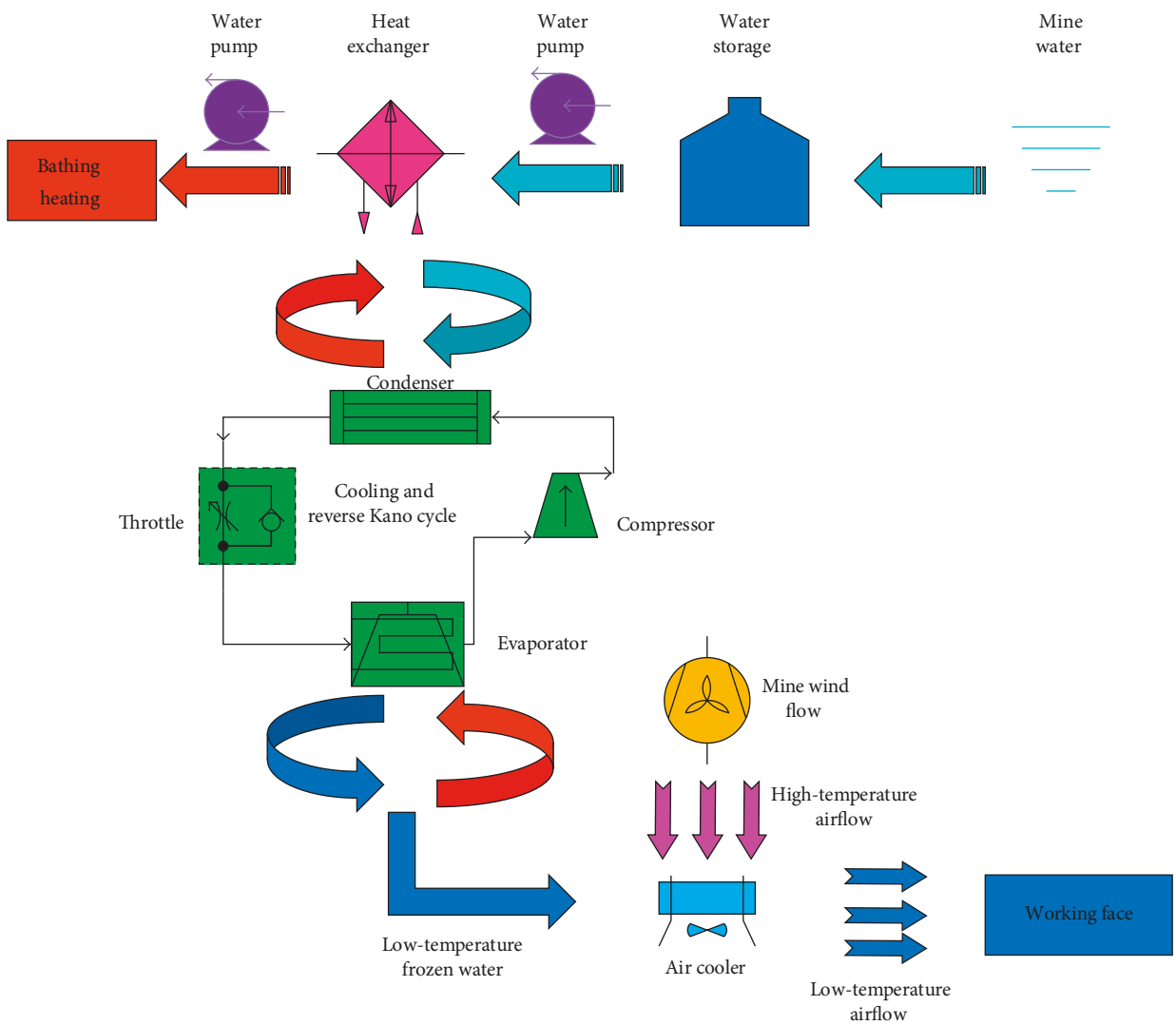


Figure 2: Cooling system of mine water as cold source.

system, the layout of the ventilation equipment should be well planned. The maintenance and management of the mine ventilation equipment should be regulated to ensure sufficient underground fresh airflow.

3. Refrigeration and Cooling System with Auxiliary Cooling of Mine Water Source

In the natural environment, water sources such as groundwater, surface water, and atmospheric precipitation cause water inflow or water seepage during the mining and production process in underground mines. Mine water influx exists in most underground mines. In order to make full use of the natural cold energy/heat energy contained in the underground water source, we can extract heat from deep well and high-temperature water [30] and extract cold energy from shallow low-temperature water [31, 32] to make use of it. The use of mine water for this purpose can be categorized based on the amount of the inflow water into high, medium, and low. The cooling principle is based on the fact that the mine water is a source of cold energy that can be used in a downhole centralized cooling system. An example of an extraction system to extract the cold energy from the water and use the principle of heat exchange to reduce the high air temperatures on the operating surface is shown in Figure 2.

The cooling system that uses the mine inflow or seepage as the cold source includes three parts: the cooling source, refrigeration, and cooling. The core component is the cooling source, which provides a continuous cooling capacity for the refrigeration unit and for air conditioning. This technology can be used to produce chilled water in the air cooler to achieve a heat exchange and cool the operating surface.

The process of extracting cold from mine water: a water pump is used to pump the low-temperature water from the underground. Three filtration systems and a simple coarse filter are used to filter the corrosive water that is moved from the source to the cooling station, through three antiheat systems from high pollution, high ore cooling, and corrosive mine water. At the same time, the initial high pressure of the

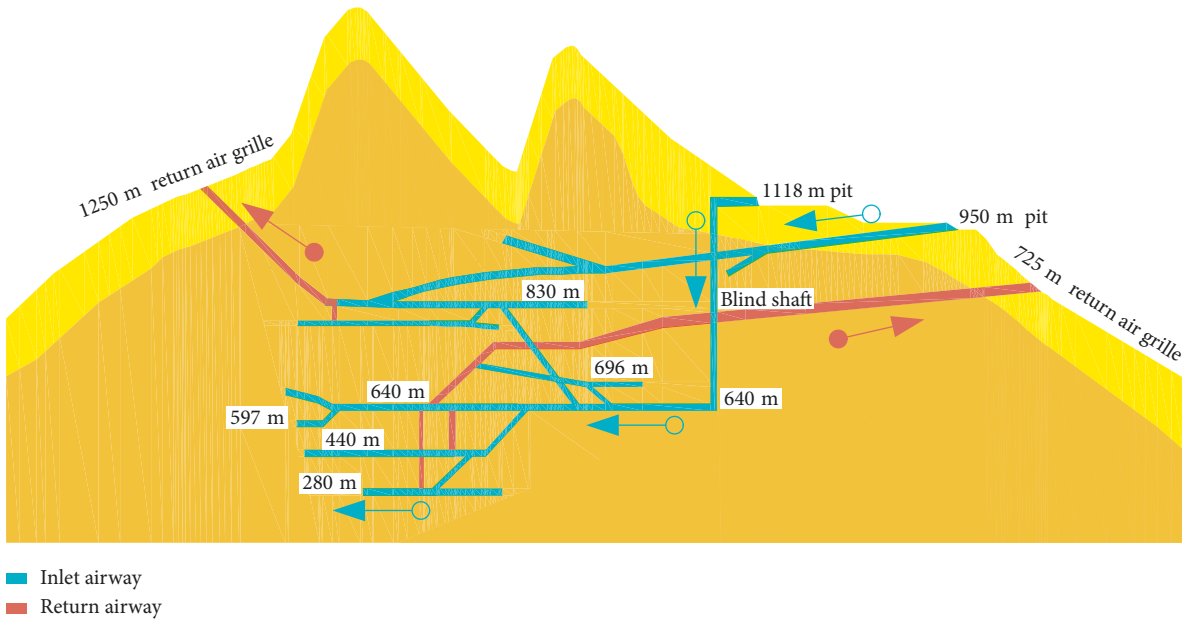


Figure 3: Current status of exploitation in Jinqu Gold Mine.

water is reduced when it enters the cooling system to reduce the damage to the system.

The process of producing cryogenic water: the refrigeration cooling system consists of a condenser, a throttle valve, an evaporator, and a four-part compressor. The cooling principle is based on the reverse Carnot cycle (Figure 2) and evaporation endothermic cooling. The reverse Carnot cycle consists of two isothermal processes and two isentropic processes. During the cycle, the cooling of the work surface is achieved by evaporation, heat absorption, and condensation of the refrigerant in the circuit, resulting in heat release. The detailed process of the circulation system is as follows: the refrigerant is condensed into a liquid state by using the cold mine water extracted from the underground storage tank. Then, the liquid refrigerant, whose pressure and temperature are lowered by the throttle valve device, flows into the evaporator. The evaporator absorbs the heat from the high-temperature mining operation surface and the water evaporates. During this process, the liquid refrigerant is vaporized from the high-temperature backwater on the working surface and releases the cold energy. The refrigerant is compressed, resulting in high temperature and high pressure of the vapor refrigerant. Finally, the steam refrigerant is liquefied by low-temperature mine water in the condenser. The high-temperature mine water can be used for underground bathing water and heating to improve the energy recycling.

The cooling process on the high-temperature working face is explained as follows: after the chilled water is transported to the air cooler on the working surface of the downhole by an insulated duct, the high-temperature air is transported to the air cooler by a blower for the heat exchange with the chilled water. On the high-temperature working surface, an air exchange occurs and reduces the temperature and humidity of the ambient air in the working environment.

4. Practical Application and Analysis

4.1. Project Overview. The study area is located in the western section of the Great Lakes Valley in Yangping Town, Lingbao City, Henan Province; the gold deposit is located in the northern part of the Laojiachac complex anticline in the Xiaoqinling Mountains. The syncline axis of the Xiyin-Leijia Pass runs through the northern part of the mining area. The terrain is comprised of low elevations in the south and high elevations in the north. The 1118 m deep pit mine at the Jinqu Gold Mine is currently under construction for exploration and infrastructure development. The pioneering method used in this mine pit excavation is the joint development of a blind shaft, a pit, and an incline; the area is dominated by excavation. The middle section of the 1118 m deep pit mine, which is currently being mined, consists of sections at the depths of 640 m, 830 m, 696 m, 597 m, 440 m, and 280 m. The midsections at 440 m and 280 m are the main open mining areas at this time [33]. The mining operation details are shown in Figure 3. The ventilation system of the 1118 m pit mine in Jinqu Gold Mine adopts single-wing diagonal extraction mechanical ventilation, and the local face of the tunnel is adopted with the local fan pressurization ventilation. At the 640 m level, a mine fan with model K40-4-14/90 and rated power of 90 kW is installed as the main fan of the ventilation system. The amount of airflow in the main ventilation shaft of the 1118 m underground pit ventilation system in Jinqu Gold Mine is shown in Table 1.

The depth of the 280 m middle working surface is as high as 838 m. The large depth of the underground mine results in high temperatures of the surrounding rocks in the excavation tunnel. This heats the air in the tunnel and creates a high-temperature working environment by long-distance heat conduction or convection. The large wind resistance generated by the ventilation line and the high airflow pressure causes low wind speeds in the ventilation ducts in

Table 1: Air volume of underground ventilation shaft in 1118 m pit of Jinqu Gold Mine.

Ventilation tunnel	Air volume (m^3/s)	Air speed (m/s)
1118 m pithead inlat air tunnel	22.3	2.1
Blind shaft entry	21.5	2.4
640 m level main air tunnel	21.1	2.3
640 m level leading to the main return air tunnel	18.3	3.4
440 m inclined shaft airway	5.4	1.2
440 m level return air well	5.2	2.1
440 m level working face	0.2	0.07
280 m inclined shaft airway	0	0
280 m level return air well	0	0
280 m level working face	0.1	0.05

the middle section at 280 m. The seepage or inflow of water in the roadway accelerates the evaporation of the high-temperature environment and increases the humidity. The operational environment of high temperatures, high humidity, and low wind speeds in the middle section of the 280 m site has caused serious harm to the underground workers, and this problem has to be addressed.

4.2. Calculation of Heat Dissipation and Cooling Load of Roadway

4.2.1. Heat Release of Surrounding Rock in Well. In the middle section of the 280 m pit, the surface temperature of the surrounding rock of the horizontal mining roadway is in the range of 35–39°C because this area is located at a depth of 838 m. The average wind speed is 2.8 m/s, the distance from the exit of the ventilation equipment to the work surface is 15 m–20 m, the cross section of the roadway is 7.5 m^2, the perimeter of the roadway is 11.6 m, the average air temperature in the west wing roadway is 33.2°C, and the expected temperature after cooling is about 28°C. The heat exchange between the high-temperature surrounding rock and the air in the tunnel is the cause of the high temperature of the 280 m horizontal roadway. The roadway circumference was calculated using the relevant parameters of the 280 m horizontal roadway and (1) and (2). The heat dissipation of the rock is defined as follows:

$$Q_r = K_\tau UL(t_{rm} - t) = \frac{1.163}{((1/9.6 \times 2.8) + 0.0441)} \times 11.6 \times 18 \times \frac{(37-28)}{1000} = 26.88 \ \text{(kW)}. \tag{11}$$

According to the relevant data from the mine pit monitoring at 1118 m of Jinqu Gold Mine and (3), (4), and (5), the heat absorbed by the latent heat in the mine airflow is 17.82 kW.

4.2.2. Heat Dissipation of Electromechanical Equipment. The degree of mechanization of the mining face at the 280 m level roadway tunnel is relatively high and the heat emitted by the electromechanical equipment during normal operations accounts for a large part of the heat of the mining operation surface. The excavation work requires mechanical and electrical equipment, including three YT28 rock drilling machines with a power of 0.8 kW, a rake loader with a model of P-30 and power of 18.8 kW, one DBKJNO-6/2 × 15 kW counter-rotating local fan pressure inlet and withdrawable fan each, and transport equipment with a power of 40 kW. And mining equipment was calculated using the equipment specification and (6):

$$Q_d = \sum \varphi N_d = 3 \times 0.8 \times 0.6 + 18.8 \times 0.4 + 2 \times 15 \times 0.3 + 40 \times 0.2 = 25.96 \ \text{(kW)}. \tag{12}$$

4.2.3. Heat Dissipation of Ore in Transportation. The transportation of the ore results in increases in the heat as the ore cools during transport and contributes to the high air temperatures in the roadway. According to existing records, the amount of ore transported per unit time is 8 kg/s. The length of the roadway for a single-head tunnel is 650 m. The initial rock temperature of the mining face is 37°C on average. The average wet-bulb temperature in the roadway is 33.3°C. According to (7), the heat dissipation of the transported ore is

$$Q_k = 0.0024L^{0.8}(t_r - t_{wm})mC_m = 0.0024 \times 650^{0.8} \times (37 - 33.3) \times 8 \times 0.97 = 12.26 \ \text{(kW)}. \tag{13}$$

4.2.4. Heat Energy Release due to Air Pressure Differences. The vertical distance between the 1118 m deep pit and the 280 m horizontal working face in the Jinqu Gold Mine is 838 m. If we assume adiabatic conditions, the air temperature rises by about 1°C for every vertical downward flow of 102 m. The results show that the heat released due to the air pressure difference is significantly lower than that of the well. The warming of the air has a certain influence. As the air flows downward towards the working surface, the high temperature results in thermal expansion of the air and reduces the density of the air. Based on the given parameters, the mass flow rate G of the air is 2.7 kg/s. The heat released due to the air pressure differences can be obtained using (10):

$$Q_{heating} = \frac{\Delta Z}{427} G = \frac{838}{427} \times 0.5 \times 2.7 = 2.65 \ \text{(kW)}. \tag{14}$$

4.2.5. Calculation of Required Cooling Capacity. The required cooling load for minimizing the thermal damage in underground mines usually refers to the required cooling capacity of the working areas such as the mining operation surface and the chamber. In this study, the 280 m horizontal west wing heading face is used as an example to calculate the required cooling capacity of the heading face; the mass flow rate of the air at the exit of the wind tunnel is 5.3 kg/s, and the flow rate is relatively stable. A wind turbine failure was ignored here. The required cooling capacity of the working area is calculated using the following equation:

$$Q_{\text{cooling}} \geq G(h_2 - h_1) + \sum Q_{\text{heating}}, \tag{15}$$

where Q_{cooling} is the required cooling capacity of the excavation work surface, G is the quality of the airflow at the cold location, h_2 is the enthalpy of the wind at the cold location, h_1 is the enthalpy of the wind at the cool-down destination, and $\sum Q_{\text{heating}}$ is the total surface heat. The hottest dry-bulb temperature of the air at the 280 m horizontal heading face is 34.6°C, and the humidity is greater than 90%. If the dry-bulb temperature is 28°C, the unit mass enthalpy is 30.6 kW. However, in engineering practice, it is often necessary to increase the safety factor to prevent the loss of the cooling capacity during transportation. As a result, the cooling capacity of the work surface is insufficient and is generally about 1.2. Equation (15) is used to calculate the required cooling capacity of the working surface of the head:

$$\begin{aligned} Q_{\text{cooling}} \geq 1.2 \times [5.3 \times 30.6 + (2.65 + 12.26 + 25.96 \\ + 26.88 + 17.82)] = 297.3 \ \ (\text{kW}). \end{aligned} \tag{16}$$

Therefore, the required cooling capacity of the 280 m middle-end heading face is 297.3 kW.

4.3. Optimization of Underground Ventilation System and Effect Analysis

4.3.1. Ventilation Network Optimization. The current ventilation system in the 1118 m pit mine in the Jinqu Gold Mine is optimized with regard to the ventilation line, network layout, and broken area of ventilation tunnel and consists of the following improvements: (1) reasonably optimizing downhole ventilation line: expanding 280 m horizontal diameter 0.25 m air return guide hole diameter into 1.4 m air return well, form 280 m level and 640 m horizontal airflow loop and promoting natural wind circulation at 280 m level; (2) optimizing the effective flow section of airflow: clearing the waste rock and sewage accumulated in the ventilation tunnel in time, increasing the effective ventilation area of the ventilation tunnel, ensuring the smooth flow of the downhole, and reducing the ventilation resistance.

4.3.2. Ventilation Equipment. The fans are important components of the downhole ventilation system because they draw the air into the mine. The fans are important components of the downhole ventilation system because they draw the air into the mine. The following midsection fan optimization and improvement measures are implemented: (1) The existing two wind turbines with a power of 11 kW, which were used for supplying air to the midsection of the 280 m section, are replaced with two wind turbines with a combined power of 21 kW to increase the blowing power. The radial distance between the blades of the fan is equipped with a special diffuser. (2) The size and material of the air duct are changed by replacing the unit with a diameter of 300 mm with a rigid air duct with the diameter of 500 mm to reduce the wind resistance. (3) In the middle of the 280 m section, a series-connected 11 kW axial fan was added to pressurize the relay. It is worth noting that when adjusting the fan power, it must be ensured that the ingoing fan power is less than the outgoing fan power.

4.3.3. Optimization of Ventilation Structure. The optimization of the downhole ventilation structures consists of the following improvements: (1) A damper is installed at the opening of the ventilation roadway leading to the 830 m deep mining area in the middle section of the 640 m section to prevent the fresh airflow. (2) A controllable and adjustable mine ventilation window is installed in the 640 m middle section of the 640 m–440 m inclined shaft to allow a sufficient amount of fresh air to flow smoothly to the middle of the 440 m and 280 m middle sections.

4.3.4. Analysis of Implementation Effect of Ventilation System Reform Project. The 1118 m pit ventilation system of Jinqu Gold Mine has been rebuilt over a period of more than six months and the optimization of the ventilation system has basically been completed. Compared with the original ventilation system, the advantages of the existing ventilation system are mainly reflected in the following aspects: (1) The 280 m return air guide hole with a horizontal diameter of 0.25 m has become a 1.4 m diameter return air well, which promotes the circulation of 280 m horizontal natural wind currents. (2) The parameters of the main fan of the mine and the radial spacing of the blades have been optimized, which has increased the total intake air volume of the mine. (3) The air duct leading to the single-headed excavation work surface is replaced with a diameter of 300 mm. The rigid air duct made of a material reduces the ventilation resistance of the airflow. (4) Abandoned roadway of downhole ventilation system has been closed, which solved the phenomenon of downhole airflow short circuit and fresh airflow loss in the original ventilation system. (5) The installation of ventilation structures in the downhole ventilation system is added, the trend of the downhole air flow is reasonably adjusted, the air volume is allocated on every job surface in accordance with the demand, and the waste or shortage of fresh air flow in the underground is avoided. The results of the actual measurement of the air volume at each level and on the working surface after the optimization of the underground mine ventilation system are compared with those before the transformation are shown in Table 2.

4.4. Thermal Damage Control Cooling Technology.

In this study, we designed a cooling system for the 640 m middle section using cold mine water as a source for the heat treatment of the 280 m horizontal working face of the 1118 m deep pit in the Jinqu Gold Mine. The details of the downhole centralized cooling system and the process are shown in Figure 4.

(1) The water storage tank at the 640 m level is used as the cooling source of the downhole cooling system. A filtration system is used at the cooling water pump station to filter out the impurities in the gushing

Table 2: The measured air volume of main roadway before and after transformation of ventilation system.

Ventilation tunnel	Preoptimized air volume (m^3/s)	Optimized air volume (m^3/s)	Changing of air volume (m^3/s)
1118 m pithead inlet air tunnel	22.3	37.0	+15.7
Blind shaft entry	21.5	36.3	+14.8
640 m level main air tunnel	21.1	35.1	14.2
640 m level leading to the main return air tunnel	18.3	12.1	−6.8
440 m inclined shaft airway	5.4	22.5	+17.4
440 m level return air well	5.2	10.2	+5.4
440 m level working face	0.2	2.9	+2.7
280 m inclined shaft airway	0	6.8	+6.8
280 m level return air well	0	6.2	+6.2
280 m level working face	0.1	3.0	+2.9

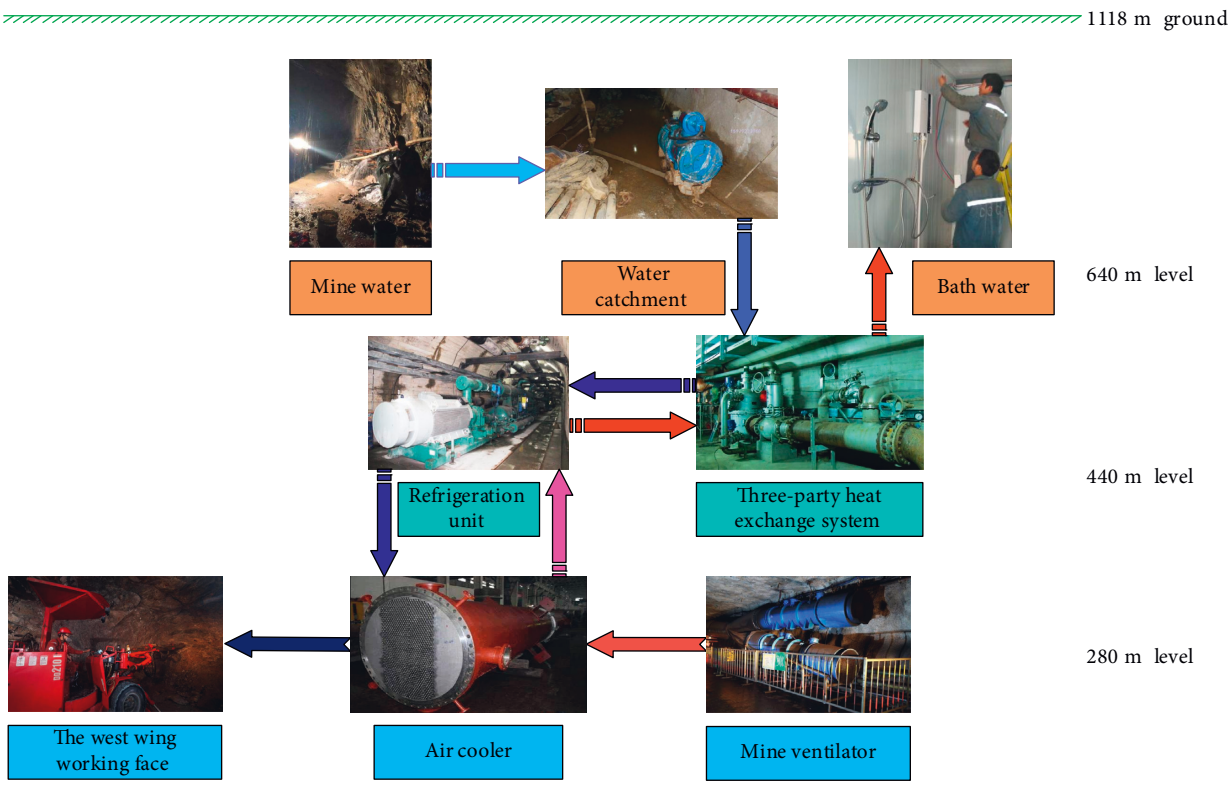


Figure 4: Design of cooling system for 1118 m pit in Jinqu Gold Mine.

water and the cold water is then pumped to the 440 m level to the heat exchange station.

(2) Three heat exchange systems are installed at the 440 m level to preliminarily purify the highly polluted and highly mineralized inflow water, extract the cold energy to be sent to the refrigeration unit, and convert the water pressure. The high water pressure caused by the difference in the height of the water source and destination is converted to low water pressure to reduce damages to the pipeline and the refrigeration unit.

(3) In the 440 m horizontal return-ventilation wells, cooling chillers are set up to further cool the chilled water, which is supplied to the air cooler at the 280 m horizontal mining surface.

(4) The air cooler at the 280 m level precools the air flowing through the air cooler using the chilled water so that the low-temperature air flows to the work surface and exchanges the heat with the high-temperature air on the work surface to cool the work surface.

4.5. Analysis of Practical Application. After the implementation of the heat damage control and cooling measures at the 1118 m pit mouth and 280 m horizontal high-temperature working surface of the Jinqu Gold Mine, taking the 280 m horizontal west wing working surface as an example, the temperature and humidity of the underground 280 m level working environment were analyzed using the comparative analysis method. The layout of the monitoring

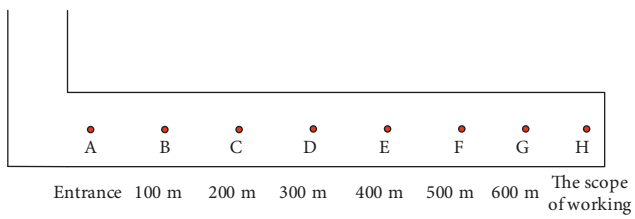


Figure 5: Layout of measuring points in the west tunnel of the middle section of 280 m.

Table 3: Temperature and humidity monitoring data before and after cooling.

Monitoring point	Temperature (°C)		Relative humidity (%)	
	After cooling	Before cooling	After cooling	Before cooling
A	29.2	32.3	79	92
B	29.5	32.9	81	95
C	30.1	33.5	83	94
D	29.9	33.9	86	97
E	29.2	34.1	84	95
F	28.6	33.7	84	93
G	28.1	33.2	80	92
H	27.6	32.7	76	90

points is shown in Figure 5. The temperature and humidity of the air near the monitoring points are shown in Table 3.

Figure 6 shows the cooling effect at the monitoring points at the 280 m horizontal west wing driving head, through which the low-temperature airflow is directly sent to the working face of the driving head. The temperature of the working face is 32.7°C prior to cooling and 27.6°C after cooling with a cooling rate of 5.1°C. Prior to the implementation of the cooling measures, the relative humidity in this location was as high as 90%; after cooling, the relative humidity is 76% and the dehumidification amplitude is 14%.

5. Concluding Remarks

(1) Based on the analysis of traditional cooling technology in underground mines, a downhole cooling system using mine water as the cooling source is proposed. By using the natural sources of low-temperature water infiltration or seepage in underground mines, the operating costs of the cooling system are reduced. In addition, the use of inflow water also solves the problem of heat condensation and cooling system emissions and reduces the occurrence of underground thermal damage.

(2) The underground ventilation system and operating procedures were optimized, which improved the airflow and volume in the underground mining areas. The results of the optimization and reconstruction show that the effective air volume of the west wing in the 280 m midsection increased from 0.9 m^3/s prior to the optimization to 3.2 m^3/s after the optimization; this improved the working environment in this area.

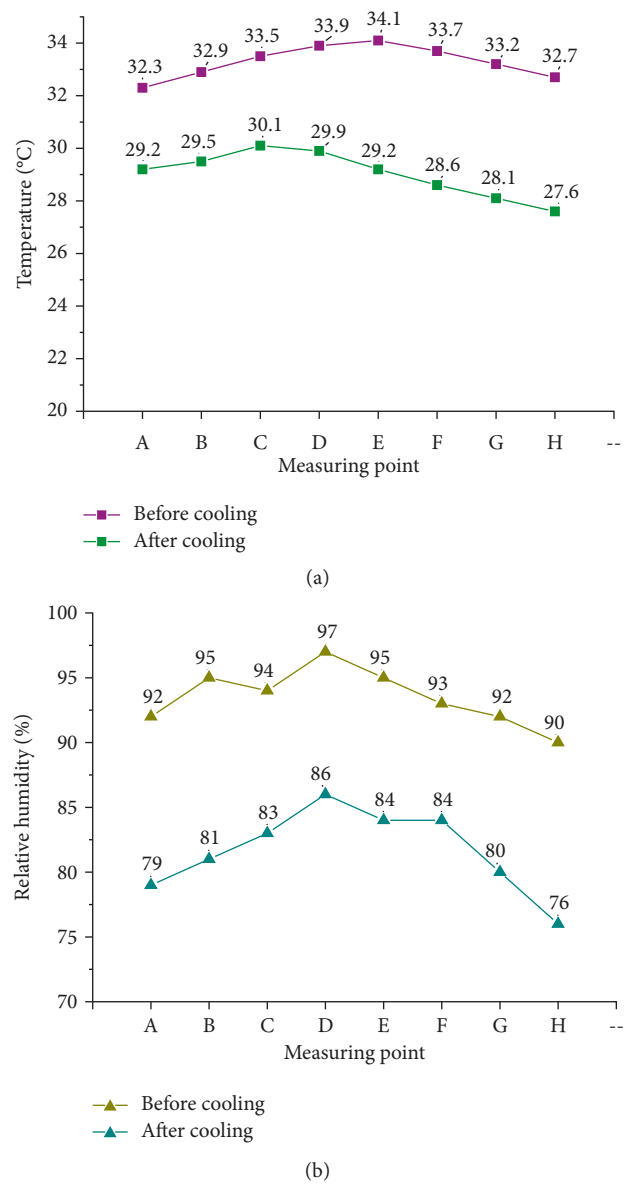


Figure 6: Comparison of temperature and humidity on the working face. (a) Before operation. (b) After operation.

(3) A heating and cooling system using cold mine inflow water was built in the Jinqu Gold Mine. The 280 m middle working face was treated for thermal damage. The practical results showed that the temperature on the working face of the west wing target area was maintained at 28°C, the temperature of the heading face was reduced by 5.4°C, and the relative humidity on the working face was reduced by 15%. The results demonstrate the positive effects of the cooling system on the environmental conditions in the mine.

Data Availability

The experimental data listed in this paper are measured and obtained from the Jinqu Gold Mine in Henan Province, China. The temperature, humidity, and wind speed of

various monitoring points are measured in the downhole working environment over a period of one month before/after the optimization of the ventilation and heat damage control. The optimization of ventilation and thermal hazard control techniques in the paper can be applied to underground mines with similar problems. 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.

Acknowledgments

This work was supported by 15JK1414 (Special Scientific Research Project of Shaanxi Provincial Education Department, titled "Theoretical research on temporal and spatial 4D information model construction of open pit mine") and 2016JM5088 (Foundation Project of Natural Science Foundation of Shaanxi Province, titled "Theoretical study on temporal and spatial deduction model of mining production information in open pit mine").

References

[1] H. P. Xie, H. W. Zhou, D. J. Xue et al., "Research and consideration on deep coal mining and critical mining depth," *Journal of China Coal Society*, vol. 37, no. 4, pp. 535–542, 2012.

[2] J. X. Lai, X. L. Wang, J. L. Qiu, J. X. Xie, and Y. B. Luo, "A state-of-the-art review of sustainable energy based freeze proof technology for cold-region tunnels in China," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 3554–3569, 2018.

[3] J. X. Lai, X. L. Wang, J. L. Qiu et al., "Extreme deformation characteristics and countermeasures for a tunnel in difficult grounds in southern Shaanxi, China," *Environmental Earth Sciences*, 2018, In press.

[4] W. H. Zhou, H. Y. Qin, J. L. Qiu et al., "Building information modelling review with potential applications in tunnel engineering of China," *Royal Society Open Science*, vol. 4, no. 8, pp. 170–174, 2017.

[5] M. C. He and P. Y. Guo, "Deep rock mass thermodynamic effect and temperature control measures," *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 12, pp. 2377–2393, 2013.

[6] A. P. Sasmito, J. C. Kurnia, E. Birgersson, and A. S. Mujumdar, "Computational evaluation of thermal management strategies in an underground mine," *Applied Thermal Engineering*, vol. 90, pp. 1144–1150, 2015.

[7] J. X. Lai, H. Zhou, K. Wang et al., "Shield-driven induced ground surface and Ming Dynasty city wall settlement of Xi'an metro," *Tunnelling and Underground Space Technology*, 2018, In press.

[8] J. L. Qiu, Y. L. Xie, H. B. Fan, Z. C. Wang, and Y. W. Zhang, "Centrifuge modelling of twin-tunnelling induced ground movements in loess strata," *Arabian Journal of Geosciences*, vol. 10, no. 22, p. 493, 2017.

[9] J. L. Qiu, X. L. Wang, S. Y. He, H. Q. Liu, J. X. Lai, and L. X. Wang, "The catastrophic landside in Maoxian County, Sichuan, SW China, on June 24," *Natural Hazards*, vol. 89, no. 3, pp. 1485–1493, 2017.

[10] J. X. Lai, S. Y. He, J. L. Qiu et al., "Characteristics of seismic disasters and aseismic measures of tunnels in Wenchuan earthquake," *Environmental Earth Sciences*, vol. 76, no. 2, pp. 76–94, 2017.

[11] J. X. Lai, S. Mao, J. L. Qiu et al., "Investigation progresses and applications of fractional derivative model in geotechnical engineering," *Mathematical Problems in Engineering*, vol. 2016, Article ID 9183296, 15 pages, 2016.

[12] S. R. Hu, J. C. Peng, C. Huang et al., "An overview of current status and progress in coal mining of the deep over a kilometer," *China Mining Magazine*, vol. 20, no. 7, pp. 105–110, 2011.

[13] H. Y. Qu, H. W. Liu, R. F. Pei et al., "Geochemical characteristic overview of the Shizishan ore-field at Tongling city, Anhui province, China," *Contributions to Geology and Mineral Resources Research*, vol. 26, no. 3, pp. 239–248, 2011.

[14] C. Q. Cheng, L. B. Dong, and S. D. Xu, "Simulation and optimization of deep stope mining sequence in hongtoushan copper mine," *Metal Mine*, vol. 9, pp. 66–68, 2016.

[15] M. Asghari, P. Nassiri, M. Reza Monazzam et al., "Weighting criteria and prioritizing of heat stress indices in surface mining using a Delphi technique and fuzzy AHP-TOPSIS method," *Journal of Environmental Health Science and Engineering*, vol. 15, no. 1, pp. 1–11, 2017.

[16] J. L. Qiu, X. L. Wang, J. X. Lai, Q. Zhang, and J. B. Wang, "Response characteristics and preventions for seismic subsidence of loess in Northwest China," *Natural Hazards*, vol. 92, no. 3, pp. 1909–1935, 2018.

[17] J. L. Qiu, H. Q. Liu, J. X. Lai et al., "Investigating the long term settlement of a tunnel built over improved loessial foundation soil using jet grouting technique," *Journal of Performance of Constructed Facilities*, vol. 42, no. 5, pp. 112–134, 2018.

[18] S. Mahdevari, K. Shahriar, and A. Esfahanipour, "Human health and safety risks management in underground coal mines using fuzzy TOPSIS," *Science of the Total Environment*, vol. 488-489, pp. 85–99, 2014.

[19] H. N. Wang, J. L. Peng, and Z. Cheng, "Analysis of ventilation and cooling in high temperature mine," *Nonferrous Metals Engineering*, vol. 3, no. 3, pp. 34–37, 2013.

[20] Y. P. Yuan, X. K. Gao, H. W. Wu et al., "Coupled cooling method and application of latent heat thermal energy storage combined with pre-cooling of envelope: method and model development," *Energy*, vol. 119, pp. 817–833, 2017.

[21] P. Y. Guo and C. Chen, "Field experimental study on the cooling effect of mine cooling system acquiring cold source from return air," *International Journal of Mining Science and Technology*, vol. 23, no. 3, pp. 453–456, 2013.

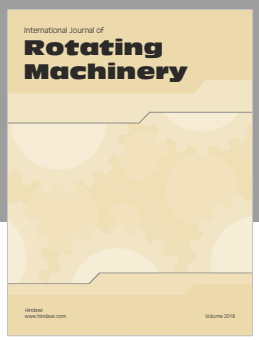
[22] B. B. Shi, L. J. Ma, W. Dong, and F. B. Zhou, "Application of a novel liquid nitrogen control technique for heat stress and fire prevention in underground mines," *Journal of Occupational and Environmental Hygiene*, vol. 12, no. 8, pp. 168–177, 2015.

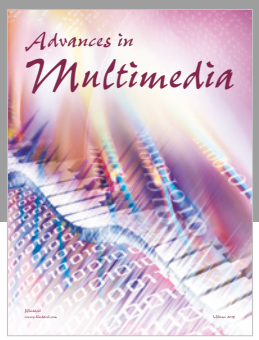
[23] P. Y. Guo, M. C. He, L. G. Zheng, and N. Zhang, "A geothermal recycling system for cooling and heating in deep mines," *Applied Thermal Engineering*, vol. 116, pp. 833–839, 2017.

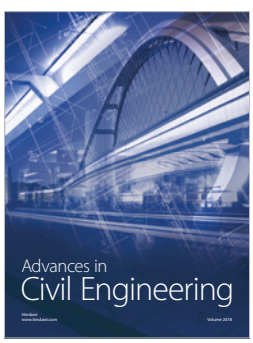
[24] H. N. Wang, B. Peng, J. L. Peng et al., "Analysis of commonly existing ventilation problems and the optimal approach to deal with them in large-size mines," *Journal of Safety and Environment*, vol. 14, no. 3, pp. 24–27, 2014.

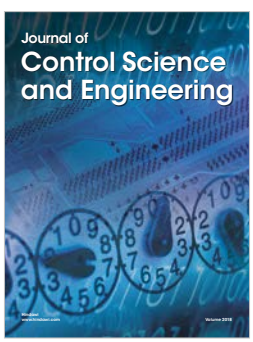
[25] S. H. Zou, K. Q. Li, D. C. Zhang et al., "On the air-partition foe cooling with the heat-insulated plate," *Journal of Safety and Environment*, vol. 16, no. 2, pp. 99–102, 2016.

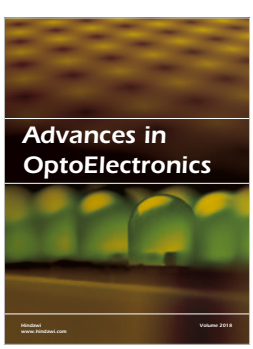
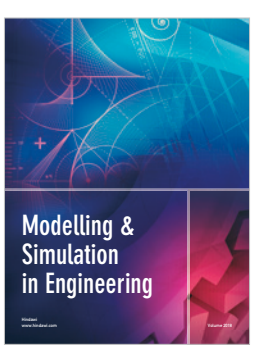
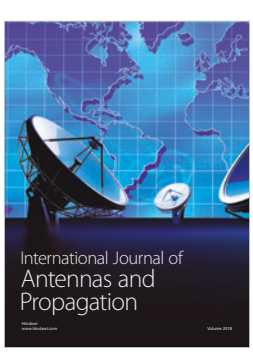
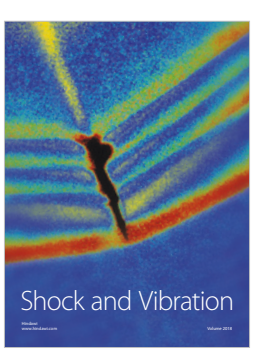
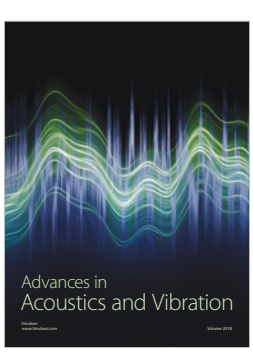
[26] Y. C. Zhang, "Research on treatment technology and cooling effect of thermal damage in Zhuji coal mine," *Safety in Coal Mines*, vol. 46, no. 10, pp. 157–159, 2015.
[27] C. B. Wang, "Heat analysis and initial mining surface air temperature prediction research on Gaojiapu coal mine," *Coal Technology*, vol. 35, no. 11, pp. 210–212, 2016.
[28] Z. X. Li, T. M. Wang, M. Q. Zhang et al., "Construction of air flow heat transfer coefficient and calculation of airflow temperature in mine wet roadway," *Journal of China Coal Society*, vol. 42, no. 12, pp. 3176–3181, 2017.
[29] S. B. Yin, R. H. Shu, and M. L. Zhang, "Application of the mining ventilation system optimization by using equilibrium diagram adjustment method based on the principle of minimum energy," *Journal of Safety and Environment*, vol. 16, no. 5, pp. 120–124, 2016.
[30] S. Jardón, A. Ordóñez, R. Álvarez, P. Cienfuegos, and J. Loredo, "Mine water for energy and water supply in the central coal basin of Asturias (Spain)," *Mine Water and the Environment*, vol. 32, no. 2, pp. 139–151, 2013.
[31] A. P. Athresh, A. Al-Habaibeh, and K. Parker, "The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment," *International Journal of Coal Geology*, vol. 164, pp. 69–76, 2016.
[32] J. Sivret, D. L. Millar, and G. Lyle, "Conceptual overview and preliminary risk assessment of cryogen use in deep underground mine production," *IOP Conference Series: Materials Science and Engineering*, vol. 278, pp. 1–8, 2017.
[33] X. X. Nie and X. B. Wei, "Optimization and practice on the reform schemes of ventilation system in the Jinqu Gold Mine," *Mining R&D*, vol. 37, no. 8, pp. 86–89, 2017.









Hindawi

Submit your manuscripts at
www.hindawi.com