Research Article

Efficiency Improvement and Application of the Groundwater Heat Pump Cooling System in Linglong Gold Mine

Chunlong Wang,1 Li Cheng,1 Yingjie Hao,1 Mingwei Jiang,1 Kexu Chen,1 and Kun Shao2

1Deep Mining Laboratory of Shandong Gold Group Co., Ltd., Laizhou, Shandong, China
2Shandong Institute of Advanced Technology, Jinan, Shandong, China

Correspondence should be addressed to Chunlong Wang; 416773656@qq.com

Received 2 March 2022; Accepted 4 May 2022; Published 19 May 2022

Academic Editor: Qiqing Wang

Copyright © 2022 Chunlong Wang 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.

Deep thermal damage in mines has had a significant impact on mining efficiency and safety. Local cooling technology can effectively mitigate the problem of heat hazard prior to the formation of the return air system. Aiming at the problem of heat damage in the Lingbei transportation tunnel at the Linglong Gold Mine’s -870 m level, a local cooling system based on water source heat pump is constructed. The basic parameters for the local cooling system are determined using measured data, calculation analysis, and numerical simulation. The refrigeration, water supply, heat discharge, and cooling systems are then optimized by utilizing underground water inflow, installing thermally insulated drainage pipelines, and adding an auxiliary pressure fan. Finally, a local cooling system based on groundwater heat pump is established. Once the system is stable, the overall temperature and humidity of the Lingbei transportation tunnel are significantly reduced; the working face temperature is reduced to 26.4°C, the relative humidity is reduced to 61%, compared with that before cooling, the decline reached 11.9°C and 37%, respectively, and the average temperature within 100 m of the working face is reduced to below 28°C, which meets the requirements for safe production. The system addresses the critical issues of water supply, heat removal, and cooling in the local cooling system, lowers investment and operating costs, increases refrigeration efficiency, and serves as a reference for similar mines’ deep mining processes.

1. Introduction

Deep heat damage is becoming an increasingly serious problem as mining depths increase. While adequate mine ventilation can help alleviate the problem of elevated temperatures, until the return air system is perfected, measures such as increasing air volume, adjusting ventilation mode, and reducing equipment heat dissipation will be ineffective at preventing heat damage [1, 2]. Since the 1970s, when deep well cooling technology was developed, artificial cooling technology has advanced rapidly. The two most common types of artificial cooling technology are ice cooling and water cooling [3–5]. When utilizing ice cooling systems, Suncun Coal Mine, Pingmei Six Coal Mine, and Tangkou Coal Mine all use centralized ice cooling systems [6–8]. Ice has a lower melting point than water and a faster rate of transport. The disadvantage is that the latent heat released during the ice phase change process is greater, increasing the likelihood of pipe blockage accidents. Meanwhile, at Guqiao Coal Mine, Zhaolou Coal Mine, Huainan Coal Mine, and other mines, water cooling systems are used [9–11]. Water cooling, also known as mine air conditioning, is the most widely used cooling method today. The above two technologies can be used to reduce the underground temperature in the application of mine refrigeration.

However, there are some disadvantages to water cooling and ice cooling technologies, including complex structures, high construction and maintenance costs, and significant energy loss. Numerous researchers have addressed this issue by maximizing underground water inflow and proposing
groundwater heat pump refrigeration technology that utilizes groundwater as a cold source [12–22]. Professor Manchao et al. proposed a new deep well cooling mode called High Temperature Exchange Mechanical System (HEMS), which utilizes mine water inflow as a cold-water source. This mode has been applied in Zhangshuanglou Coal Mine, Sanhejian Coal Mine, and Xuzhou Coal Mine [23–26].

Heat damage control has a remarkable effect. Its principle of operation is to utilize the mine water inflow to extract cooling capacity from it via the energy extraction system to exchange heat with the high-temperature air on the working face, thereby lowering the working face’s temperature and humidity. Simultaneously, the replaced heat returns to the surface via water and makes maximum use of it [27]. Numerous scholars have since conducted extensive analysis and optimization on the HEMS cooling system: Pingye proposed three distinct modes of heat damage control and a temperature control technology evaluation system [28–30]. Yi analyzed and studied the temperature field distribution characteristics in Jiahe deep stope in order to develop the HEMS system’s design basis [31]. Shengbin and Yanyan and Pingye performed back analysis and thermal load calculation [32, 33]. Fan and Li used horizontal circulation cold source cooling technology to address cold source scarcity [34, 35]. Zhenyuan and Xingxing et al. improve the heat transfer performance of the HEMS system by analyzing the equipment composition and water composition [36, 37].

While HEMS has the advantages of low energy consumption and low investment, optimizing the refrigeration system’s operation efficiency is a critical issue in application. Thus, this paper’s research object is Lingbei’s high temperature and high humidity problem at -870 m elevation in the Lingshan mining area of the Linglong Gold Mine. The cooling capacity is derived from underground water gushing at -870 m without interfering with the original drainage system and is used to exchange heat with the high-temperature gas in the working face. Along with on-site system optimization, a set of local cooling systems based on high-efficiency groundwater heat pumps is established. Overall, it can serve as a model for similar mines’ use of cooling technology.

2. Establishment of a Local Cooling System

2.1. Current Situation of Heat Damage in Mines. Linglong Gold Mine is located in Yantai City, Shandong Province, China, as illustrated in Figure 1. The specific project is the Lingshan mining area -870 m horizontal Lingbei development project. Due to its deep location and lack of a perfect return air system, a significant heat damage problem arises, which has had a negative impact on the deep and middle section’s mining efficiency and safety. The total length of the transportation tunnel exceeds 700 m, and the distance is considerable. The working face’s heat source is primarily the surrounding rock, equipment heat dissipation, and water gushing through the fracture zone heat dissipation. The working surface temperature can reach 38.3°C, and the relative humidity can reach 98%. The 6-line of the Lingbeï transportation tunnel is currently constructing the exploration hole. When the borehole passes through the Lingbei fault zone, a large amount of water gushes out, and the water temperature reaches 39°C, resulting in the transportation tunnel being extremely hot and humid and having poor visibility.

According to the current state of heat damage in the Lingshan mining area, simply increasing air volume will not suffice to meet local cooling demands. Following field investigation and detection of water quality, a large amount of water is gushing from the prospecting hole of the 3.5-line -870 m horizontal transportation tunnel, with good water quality and a low temperature. As a result, a local cooling system using groundwater heat pump technology is being constructed to cool the Lingbei transportation tunnel.

2.2. Air Supply Temperature Calculation. The air inlet temperature of the working face (start temperature), the temperature of the working face’s upper corner, the temperature of the working face’s lower corner (end temperature), the distance between the measuring points, and the air relative humidity are all measurable using the calculation model of the thermal load back analysis method of working face. The working face’s air supply temperature \( T'_C \) is calculated using the back analysis algorithm [32].

The start temperature \( T'_A \) (air supply temperature) of the working face can be determined using the heating rate and the cooling control’s target temperature at the end of the working face:

\[
T'_A = T'_C - \beta_2 \Delta T_{BC} \cdot \frac{L_{BC}}{100} - \beta_1 \Delta T_{AB} \cdot \frac{L_{AB}}{100},
\]

\[
\Delta T_{AB} = \frac{T_B - T_A}{L_{AB}} \cdot 1000,
\]

\[
\Delta T_{BC} = \frac{T_C - T_B}{L_{BC}} \cdot 1000.
\]

where \( T'_A \) is the cold air temperature (outlet temperature of refrigeration unit), \( °C \), \( T'_C \) is the lower corner temperature of working face after cooling, \( °C \), \( \Delta T_{AB} \) is the temperature rise rate of air flow in air inlet tunnel, \( °C/km \), \( \Delta T_{BC} \) is the air flow temperature rise rate of working face, \( °C/hm \) (1 hm = 100 m), \( \beta_1 \) and \( \beta_2 \) are the correction coefficient of temperature rise rate, \( T'_A \) is the tunnel inlet air temperature before cooling, \( °C \), \( T_B \) is the corner temperature of working face before cooling, \( °C \), \( T_C \) is the lower corner temperature of working face before cooling, \( °C \), \( L_{AB} \) is the control point AB distance, m, and \( L_{BC} \) is the control point BC distance, m.

The control’s target temperature is set to 26–28°C. Due to the absence of a special air-return tunnel in the Lingbei transportation tunnel, the temperature of the working face is stable, and the temperature difference is small, resulting in a temperature rise rate of 0 for section BC of the working face. The total length of the AB of the Lingbei transportation tunnel is 700 m. Due to the absence of a return air system, the temperature rise rate correction coefficient is greater than that of an air-return tunnel, taking 2.2. The air supply temperature range, calculated using formulas, is 9.0 ~ 17.0°C, based on the field-measured Lingbei temperature.
2.3. Numerical Simulation and Analysis. The -870 m horizontal geometric model is established using the numerical simulation software Fluent by combining field measured data and calculation results. As illustrated in Figure 2, the model makes the following assumptions: the Lingbei transportation tunnel is simplified to a standard tunnel model with dimensions of 50 m × 2.2 m × 2.4 m; air is supplied to the tunnel via a ventilation duct with a diameter of 0.45 M, and sewage air naturally returns due to pressure difference; the effect of stope unevenness and roughness is ignored. Due to the turbulent nature of the air flow in the tunnel and the large velocity gradient, the RNG k-ε turbulence model is chosen. The mass conservation equation, the momentum conservation equation, and the turbulent flow energy dissipation rate equation all govern the flow of fluid in a subtunnel. The flux is calculated using a second-order upwind discrete scheme, and the pressure and velocity coupling are calculated using the stable SIMPLEC algorithm. According to the actual conditions of the mine, No. 5/2×5.5 type of fan is selected, with an air volume of 150~210 m³/s. Therefore, the wind speed is 5.5~7 m/s, and the average wind speed is 6 m/s.

The geometric model specifies that the air supply temperature should be between 9.0 and 17.0°C when the surrounding rock wall temperature is 38.3°C, and the air supply wind speed is 6 m/s. To determine the temperature field’s variation law, a numerical simulation calculation is performed for the two conditions.

The temperature distribution of the tunnel under the condition of air supply temperature of 9°C is depicted in Figure 3. The monitoring point (a) is the working face, and the average temperature is 22.16°C. The monitoring point (b) is 10 m away from the working face, and the average temperature is 25.08°C. The monitoring point (c) is 25 m away from the working face, and the average temperature is 26.95°C. The monitoring point (d) is 50 m away from the working face, and the average temperature is 28.09°C. The temperature of the tunnel within 10 m of the working face is the lowest, and the average temperature is 23.67°C. Within 50 m of the working face, the average temperature is 26.46°C. The simulation results show that the tunnel temperature within 50 m of the working face is lower than 28°C.

The temperature distribution of the tunnel under the condition of air supply temperature of 9°C is depicted in Figure 4. The average temperatures of monitoring points (a), (b), (c), and (d) are 26.15°C, 28.20°C, 29.76°C, and 30.62°C, respectively. The average temperature within 50 m of the working face is 29.40°C. From the simulation results, it can be seen that the average temperature of the tunnel within 10 m of the working face is lower than 28°C, and that of other areas of the tunnel is higher than 28°C.

The simulation results indicate that with a 9.0°C air supply temperature, the average temperature of the simulated tunnel is less than 28°C, which complies with safety regulations. When the air supply temperature is 17.0°C, the average temperature of the simulated tunnel exceeds 28°C. Due to the simulation process considering only the heat release from surrounding rock and disregarding heat release from mechanical equipment, groundwater heat dissipation, and other factors, the average temperature of the tunnel is higher than the numerical simulation temperature at the set air supply temperature. As a result, the optimal air supply temperature is set to 9.0°C, which also serves as a reference point when selecting equipment.

2.4. Principle and Operation of the Cooling System. The MB21B underground air conditioning unit was selected for local cooling based on the calculation analysis and numerical simulation results shown in Figure 5. The temperature range of the unit, as shown in Table 1, is between 9 and 25°C.
which is sufficient to meet the refrigeration requirements of the Lingbei transportation tunnel.

As illustrated in Figure 5, the cooling system is composed of four components: a refrigeration system, a water supply system, a heat removal system, and a cooling system. The compressor receives low-pressure steam from the refrigeration system and discharges it to the condenser. Simultaneously, the gushing water is directed to the condenser, which absorbs the refrigerant’s heat and condenses the high-pressure refrigerant steam into high-pressure liquid. After passing through the filter and throttling mechanism, the high-pressure liquid flows through the filter and throttling mechanism, and the refrigerant’s heat is absorbed by the water. Meanwhile, the self-contained fan continuously forces air into the evaporator’s fins for heat exchange and exhausts the cooled air through the ventilation duct to the tunnel working face. The hot water discharged from the refrigeration unit flows through the ditch to the tunnel low temperature zone.

Figure 2: The -870 m horizontal tunnel geometric model.

Figure 3: Temperature distribution diagram of tunnel under the condition of air supply temperature of 9°C.

Figure 4: Temperature distribution diagram of tunnel under the condition of air supply temperature of 17°C.
water tank, where it is cooled before being released to the surface.

In field applications, the refrigeration effect is poor, and the operating costs are high. The primary concerns are as follows:

1. For the MD21B underground air refrigeration unit to operate optimally, three conditions must be met: an adequate water supply, a low water supply temperature, and a large exhaust air volume. In the field application, due to insufficient water supply, heat exchange, and other factors, the outlet temperature is significantly higher than the set return temperature (10°C), and the lowest is only 18.7°C, which is insufficient to meet the cooling requirements of the transportation tunnel and working face.

2. The air supply distance is insufficient, and the position is unreasonable: the refrigeration unit is own fan is 3 kW in power, and the air supply volume is 8100 m³/h. If the installation position is close to the working face, the blasting shock wave will cause damage to the equipment. When it is removed from the work surface, the fan power is reduced, the cooling loss is increased, and the cooling effect is diminished.

3. Inadequate water supply: refrigeration equipment requires a minimum of 18 m³/h of water, a temperature of no more than 30°C, and a higher water quality. Due to the fact that the water supply is primarily provided by water gushing from the 3.5-line prospecting hole, which is located a considerable distance from the refrigeration unit, the water supply and pressure are insufficient to meet the equipment requirements. If a dedicated surface water supply pipeline is used, the system’s cost and complexity will be significantly increased.

4. The drainage from the underground refrigeration unit and the water in flow from the line 6 borehole are both extremely hot, and direct discharge to the ditch can increase the tunnel’s temperature and humidity, resulting in more severe heat damage.

3. Optimization of the Cooling System

To maximize the efficiency of the local cooling system, four components are optimized: the refrigeration system, the water supply system, the heat removal system, and the cooling transfer system.

3.1. Location Optimization of the Refrigeration Unit. The total length of the Lingbei transportation tunnel is 700 m. The original refrigeration unit is 75 m from the working face in a -3-line chamber. The detonation wave has a significant impact on the refrigeration unit during the blasting process, resulting in frequent shutdowns. To avoid damaging the unit components during the blasting operation, the cooling loss along the ventilation duct should be kept to a minimum. The refrigeration unit’s location is critical to its efficiency. The refrigeration unit is installed in the chamber of line -1, and the explosion-proof wall is installed in accordance with...
the site’s actual conditions. The location is 175 m from the -4.5-line’s working face, which mitigates the detonation wave’s impact while also meeting the demand for air supply distance.

3.2. Optimization of the Water Supply System. The refrigeration unit must have an adequate supply of water to operate at peak efficiency. Water supply must be at least 18 m³/h, the temperature must not exceed 30°C, and stringent water quality requirements must be applied. Hence, the refrigeration effect is dependent on the availability of low-temperature water. Due to a lack of water gushing from the 3.5-line prospecting hole, the water gushing is used as the primary water source, while the filtered water in the transportation tunnel’s ditch serves as an auxiliary water source, ensuring the refrigeration unit’s normal operation.

According to field measurements, the temperature of the water gushing from the 3.5-line prospecting hole is 26°C, while the temperature of the ditch in the transportation tunnel is 30°C. Both provide high-quality water that can be reused as the primary source of water for the refrigeration unit. As illustrated in Figure 6(a), the floodgate wall is constructed at a 3.5-line chamber to regulate the water volume and increase the water pressure, with the water gushing automatically to the temporary water sump via hydrostatic pressure. As illustrated in Figure 6(b), the 5.5 kW water pump is used to maintain pressure in the temporary water sump to meet the refrigeration unit’s water demand.

3.3. Optimization of the Heat Removal System. The temperature of the refrigeration unit’s drainage water was measured in the field to be 41°C. If the high-temperature water is discharged through the ditch, it will cause secondary heat damage to the Lingbei transportation tunnel, significantly increasing the tunnel’s temperature and humidity. Thus, an insulated drainage pipeline is used to direct the air conditioner’s hot water to the -870 m horizontal system sump, effectively isolating the heat exchange between the hot water and the tunnel’s air environment.

The thermal insulation drainage pipe is installed above the ditch to avoid affecting the temperature of the water in the ditch. As illustrated in Figure 7, the pipeline is suspended parallel and straight to the surface of the Lingbei transportation tunnel, and the inclination angle of the pipeline is used to facilitate natural drainage. Similarly, the above pipeline is used to discharge hot water directly to the system sump from the 6-line prospecting hole. After that, the hot water is discharged directly to the surface via a water pump.

3.4. Optimization of the Cooling Transfer System. The exhaust air volume is also critical in determining the state of operation of the refrigeration unit. The larger the volume of exhaust air, the more efficient the evaporator. The refrigeration unit supplies cold air to the working face via its own 3 kW centrifugal fan, with an air supply distance of between 120 and 150 m. The fan’s air supply effect is poor due to the refrigeration unit is location on the -1-line chamber, 175 m away from the working face. As illustrated in Figure 8, an
auxiliary forced fan with a 15 kW motor is added to the refrigeration unit’s air outlet to increase evaporator efficiency, air supply distance, and volume. The distance between the source of cold air and the outlet wind speed is increased to more than 200 m, while the outlet wind speed is increased to 6.2 m/s.

3.5. System Operation. By optimizing the refrigeration system, water supply system, heat discharge system, and cooling transfer system of the local cooling system, Figure 9 illustrates a formalized formal where the air supply temperature exceeds 9.2°C, the air supply distance exceeds 200 m, and the wind speed exceeds 6.2 m/s. The thermally insulated drainage pipeline transports hot drainage directly to the water bin, minimizing the impact of hot drainage on the tunnel environment. As illustrated in Figure 9, these optimizations ensure that the entire system operates efficiently, that a near-perfect local cooling system is constructed, and that the cooling purpose is accomplished.

4. Effect Analysis

4.1. Analysis of Cooling Effect. As illustrated in Figure 10, according to on-site temperature monitoring statistics, the entire Lingbei transportation tunnel is extremely hot. As a result
of equipment heat dissipation, the temperature near the -4.5-line’s working face is approximately 2°C higher than in other areas of the transportation tunnel. The temperature increases slightly near the 6-line, which is primarily caused by heat and water gushing. The temperature in the Lingbei transportation tunnel is low, about 80 m from the air-return tunnel, and cold air cannot enter far enough through mixed ventilation alone, which has a poor cooling effect on long bending headings. After the local cooling system is stable, the temperature of the -4.5-line’s working face decreases the most, from 38.3 to 26.4°C, a decrease of 11.9°C. Within 50 m of the working face, the temperature ranges between 26.4 and 27.2°C, and the tunnel temperature is less than 28°C within 100 m of the working face. Within 175 m of -1-line (refrigeration unit chamber) and -4.5-line’s working face, the average temperature drops by 9.0°C within 700 m of the Lingbei transportation tunnel, and the average temperature drops by 5.80°C.

4.2. Analysis of Dehumidification Effect. As illustrated in Figure 10, the humidity within 100 m of the -4.5-line’s working face is slightly higher than that of the transportation tunnel, which is primarily affected by production water and high temperatures. The humidity near the Lingbei 6-line is high due to heat water gushing. After stabilizing the local cooling system, the relative humidity near the working face decreases significantly, from 98% to 61%, a 37% decrease. Within 180 m of -1-line (refrigeration unit chamber), the average relative humidity decreases by 31.4% within 700 m of the Lingbei transportation tunnel, and the average relative humidity decreases by 22.4%. The humidity level is significantly reduced because of the use of thermally insulated drainage pipeline for drainage at the 6-line prospecting hole’s water gushing. Temperature and humidity changes prior to and following the installation of the local cooling system demonstrate that the system operates reliably after installation. The temperature and humidity in the Lingbei transportation tunnel and working face have been significantly reduced, resulting in an excellent cooling effect.

4.3. Economic Benefit Analysis. By optimizing the cooling system and using the underground water as the cold source, 432 m³ surface water supply can be saved every day. Therefore, the drainage cost of -870 level sump can be reduced by about 488500 RMB every year. Affected by the high temperature and high humidity environment, the construction efficiency of the -4.5-line’s working face is low, the average monthly construction footage is 70 m, and the monthly mining volume is 997.9 ton. After the cooling, the environment in this area has been significantly improved, and the working efficiency has been significantly improved. The average monthly construction footage of the working face has been increased to 120 m, the mining volume has been increased by 712.8 ton per month, and the annual economic benefit can be increased by about 6.45 million RMB.

5. Conclusion

(1) A local cooling system based on groundwater heat pump technology is designed in response to existing thermal damage at a depth of -870 m in the Linglong Gold Mine, as well as the demand for refrigeration range and the site’s current situation. The optimal air supply temperature is determined using a back analysis algorithm and Fluent numerical simulation, and the local cooling system’s parameter calculation method is determined through field testing. It serves as a starting point for determining comparable technical parameters for local cooling.

(2) The refrigeration unit is operation state that is highly dependent on the amount of available water, the temperature of the water, and the volume of exhaust air. The refrigeration, water supply, heat discharge, and cooling transfer systems are optimized. The refrigeration system’s operation cost is reduced, and its heat emission is reduced through various measures such as optimizing the installation position, maximizing underground water gushing, installing thermal insulation drainage pipeline, and adding auxiliary pressure fans. After stable operation of the system, the overall temperature and humidity of the Lingbei transportation tunnel are also significantly reduced, meeting both safety and fit and comfort requirements.

(3) Through theoretical calculation, numerical simulation, and system optimization, a set of local cooling systems based on groundwater heat pumps is established, serving as a reference for metal mine cooling technology under similar conditions.

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

Conflicts of Interest
The authors declare that they have no conflicts of interest.

References


