Development of an Efficient Cooling Strategy in the Heading Face of Underground Mines

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Abstract: Heat damage in deep mines is severe and can lead to adverse health effects. The existing refrigeration schemes for the heading face in excavation roadways aim to cool the whole cooling region. However, the ratio of the area occupied by workers to that of the cooling region is quite small. A great quantity of energy for refrigeration is doomed to waste. In this study, a new cooling strategy for building a non-uniform environment in the heading face was developed. A certain quantity of well-designed tracking air coolers were distributed in the excavation roadway near the heading face. The air cooler tracked the constantly moving workers and blew cold air to them. Economic analysis based on estimation of the cooling load for this cooling strategy was conducted. The airflow in the excavation roadway was numerically simulated to estimate the cooling effect. An average energy saving of approximately 30% could be realized. The thermal environment for the workers whether near the heading face or in the roadway improved. This cooling strategy should be considered in all of mine cooling.

Keywords: heading face; excavation roadway; high-efficient cooling; air cooler; mine cooling system

1. Introduction

Fossil-fuel energy, which accounts for 87% of the market share, still dominates as the leading role of the world’s energy consumption structure [1]. Among all kinds of fossil-fuel energy, coal consumption is the fastest growing [2–4]. With the over-exploitation of mines, the mining depth continuously increases [5]. The virgin rock temperature rises with mining depth [6]. The heat of the surrounding rocks is transferred to the airflow because of the large temperature difference between them, and the thermal environment of the mines continues to deteriorate [7–9]. Heat damage then inevitably occurs. Continuous high temperature can cause adverse health effects [10]. Health symptoms of heat damage include but are not limited to fervescence, heatstroke, and nervous system disease [11–13]. The labor productivity of the workers decreases, while the accident rate increases [14,15]. To improve the thermal environment and ensure personnel life and health safety, mine cooling is necessary.

The main methods to solve heat damage in mines include non-artificial refrigeration and artificial refrigeration [16,17]. Ventilation is the most common cooling method for non-artificial refrigeration. Other cooling measures, such as control of heat sources and individual protection, are supplemented to obtain a better cooling effect. However, when the heat damage is serious enough, ventilation cannot significantly lower the airflow temperature, and artificial refrigeration should be adopted [18]. Artificial refrigeration, which is also called mechanical refrigeration, is a process by which heat is removed from a location using an artificial heat exchange system [19–21]. The mechanical refrigeration system mainly comprises a refrigeration unit, a pipeline for cold transmission, and a terminal air conditioning unit [22,23]. The air cooler is one of the most common terminal units in the mine, whose layout and operating parameters can significantly affect the cooling effect of the mechanical refrigeration system. The air cooler comprises a fan and a heat exchanger. The fan forces air through the cooling coils of...
the heat exchanger. The airflow is cooled because of the heat exchange between the airflow and the cooling coils. The cold airflow is then blown to the roadway. The cooling load for a typical deep mine can reach up to 7000 kW [20]. Generally, a typical mine contains numerous high-temperature working faces and heading faces for cooling.

The heading face is one of the most serious operation points of heat damage in mines [24]. A heading face is a roadway that is first exploited in preparation for the mining face. Heat in the heading face is mainly produced from the surrounding rock, mechanical and electrical equipment, water flow, oxidation of coal, and blasting. As the heading face is a single end tunnel, it is difficult to release heat from the above heat sources to the external environment, and the temperature of the heading face is quite high.

Generally, the ventilation modes for the excavation roadway can be classified into two types: Forced ventilation and exhaust ventilation. Taking the forced ventilation as an example, there are two schemes for cooling the heading face, as shown in Figure 1 [25]. The first cooling scheme involves an air cooler installed after the local fan in the roadway. Then, the cold airflow is transported by a heat insulation duct to the heading face for a long distance [26]. However, when the cold airflow arrives at the heading face, the airflow temperature has significantly increased due to violent heat exchange between the airflow and heat sources. To obtain a better cooling effect, the second cooling scheme is developed. A quantity of small air coolers are laid out in the heading face. As the transport distance of the cold airflow is much lower than that of the first cooling scheme, less cold loss is produced for this cooling scheme. However, for both the above two cooling schemes, the phenomenon of “back heating” occurs in the long-distance tunneling roadway. The temperature in the heading face is lower, while those in the middle and posterior region of the roadway are much higher. To ensure a fine thermal environment for all the workers, more energy must be consumed. Previous studies showed that more than a quarter of the energy for mining was consumed by the mine cooling [1,27].

![Figure 1](image)

**Figure 1.** Layout mode of the air cooler for cooling the heading face at various locations: (a) Roadway; (b) Heading face.

The above studies show that the aim of the present cooling schemes is to cool the whole heading face. However, the workers therein only occupy a small area of the face, and a large quantity of energy is wasted. Unfortunately, none of the existing studies have reported a highly effective cooling scheme for the workers. To save energy and improve the thermal environment for the workers, a new cooling strategy for building a non-uniform environment was developed in this study. This cooling strategy cooled the space occupied by workers and ignored the ineffective space. A well-designed air cooler tracks the constantly moving workers and improves their thermal environment. The cooling load for this strategy was calculated and economic analysis was conducted. The airflow in the excavation roadway was numerically solved to estimate the cooling effect of this new cooling strategy.

2. **Principles of the New Cooling Strategy in the Heading Face**

2.1. **Highly Effective Cooling Strategy for the Workers in the Heading Face**

Figure 2a presents a schematic diagram of the new cooling strategy. This cooling strategy focuses on the space occupied by workers and ignores the spaces not occupied by workers. For this purpose,
a small air cooler was designed to track a worker who moved or remained fixed in the excavation roadway. Each air cooler controlled a certain range of the cooling region. For a long-distance excavation roadway, most workers were located near the heading face. Thus, the cooling region was in front of the roadway, as shown in Figure 2a. A quantity of tracking air coolers were distributed in the cooling region to guarantee a fine thermal environment for the workers. When workers entered the control range of the tracking air coolers, the air coolers began to work and supplied cold airflow to them. For other air coolers, no person entered their control range and they did not work. Thus, the cooling area for the new cooling strategy significantly decreased compared to that for the traditional cooling strategy, and this cooling strategy could save a great amount of energy.

![Schematic diagram of the new cooling strategy](image)

Figure 2. Schematic diagram of the new cooling strategy: (a) Layout mode of the tracking air cooler (top view) in the excavation roadway; (b) constitution of the tracking air cooler (side view).

For this new cooling strategy, the tracking air cooler was developed to improve the benign thermal environment for the constantly moving workers. This study only considered the general case, and the following assumptions were adopted:

(a) All the workers are located near the heading face of the excavation roadway.
(b) There is only one worker in the control range of each tracking air cooler.

Figure 2b shows the operating principle of the tracking air cooler. When a person enters the control range of the tracking air cooler, the infrared detector receives the person’s signal and transmits it to the controller. The controller takes the programmable logic controller (PLC) as the core control unit. Meanwhile, the PLC control unit starts the air door, and cold air is blown to the person. The controller also controls the spindle to continually rotate with the worker so that the air cooler ensures a benign thermal environment for the person. When the person leaves the control range of the last air cooler, the infrared detector receives the signal for the person to leave, and the last air cooler closes. Meanwhile, the person enters the control range of the next air cooler, and the infrared detector receives the person’s signal and transmits it to the controller. The air door opens by the PLC control unit. A schematic diagram of the cooling process of the tracking air cooler is shown in Figure 3. The cooling range of two neighboring air coolers was connected to each other.

![Schematic diagram of cooling process of the tracking air cooler](image)

Figure 3. Schematic diagram of cooling process of the tracking air cooler.
2.2. Cooling Load and Economic Analysis

The cooling load for this new cooling strategy was estimated by the ratio of the area occupied by the workers to that of the cooling region for the excavation roadway:

\[ Q = \xi \frac{Q_1 S_W}{S}, \]  

(1)

where \( Q \) is the cooling load for the new cooling strategy (kW), \( Q_1 \) is the cooling load for the traditional cooling strategy (kW), \( S_W \) is the area occupied by the workers (m\(^2\)), \( S \) is the area of the cooling region, and \( \xi \) is the modified coefficient. \( Q_1 \) was estimated as

\[ Q_1 = M_B (i_1 - i_2), \]  

(2)

where \( M_B \) is the mass flow rate of the airflow in the heading face (kg/s), \( i_1 \) is the average enthalpy value of the airflow before cooling (kJ/kg), and \( i_2 \) is the average enthalpy value of the airflow after cooling (kJ/kg). \( i \) was estimated as \[ i = c_0 (\varphi / B) + [1.005 + c_1 (\varphi / B)] i + [c_2 (\varphi / B)] i^2, \]  

(3)

where \( i \) is the average temperature of airflow in the cooling region (\(^\circ\)C), \( \varphi \) is the relative humidity (RH, %), and \( c_0, c_1, \) and \( c_2 \) are constant coefficients.

To estimate the economical efficiency of the new cooling strategy, a real heading face of mines was used as a case to calculate the cooling load. The length of the cooling region for the heading face was 50 m, and the width and height were 3.6 and 3.1 m, respectively. Thus, the area of the cooling region for the heading face was 180 m\(^2\). The diameter of the ventilation duct was 0.6 m, and the air speed at the outlet of the duct was 12 m/s. The mass flow rate of the airflow was 4.14 kg/s. The average temperature and RH of the airflow in the cooling region were set as 26 \(^\circ\)C and 98%, respectively. Then, the cooling load for the traditional cooling strategy was estimated as 112 kW.

In the heading face, 2 workers drove the roadheader, and 6 workers pushed the hydraulic support forward. In addition, 13 workers were fixed near the electromechanical equipment. The average value of the body width for the worker was 0.5 m. The maximum cooling distance of the tracking air cooler was assumed to be 8 m. The cooling area for the new cooling strategy was calculated as 84 m\(^2\), which was much less than the area of the cooling region (180 m\(^2\)). The value of \( \xi \) was set as 1.5. According to Equation (1), the cooling load of the new cooling strategy was 78.4 kW. This cooling strategy could save up to approximately 30% of energy and had a large potential of energy saving.

3. Numerical Simulation of Airflow for the New Cooling Strategy

3.1. Physical Model

In this section, the airflow in the cooling region of the excavation roadway was simulated to estimate the cooling effect for the new cooling strategy. Two ventilation types, i.e., forced ventilation and exhaust ventilation, were considered. This study only simulated the case when the person was facing the tracking air cooler. For the sake of simplification, the following assumptions were adopted:

(a) The airflow is regarded as an incompressible fluid, and the dissipative heat caused by work of the viscous force of the fluid is neglected;
(b) The thermal environment of the roadway is in equilibrium;
(c) The influence of the conveyor, hydraulic support, and irregularity of the roadway on the flow field is neglected;
(d) The airflow is fully turbulent and satisfies the Boussinesq hypothesis.
Figure 4 shows the physical model with the forced ventilation based on an actual heading face. The length of a typical excavation roadway was greater than 1 km, while the dimensions of the cross-section of the roadway were only several meters. It was difficult to provide the whole heat profile. On the other hand, for the long-distance excavation roadway, most workers were located near the heading face. Thus, the cooling region was in front of the roadway. In this study, only the airflow in cooling region was simulated. The dimensions of the cooling region for the excavation roadway were 36 m × 4 m × 3.1 m. A ventilation duct with a diameter of 0.6 m was hung at a height of 1.9 m from the bottom of the roadway, which was 0.6 m away from the side wall. The length of the ventilation duct was 29 m. The dimensions of the roadheader and the tracking air cooler were 10 m × 2 m × 1.5 m and 1 m × 0.5 m × 1.5 m, respectively. Four tracking air coolers were equidistantly distributed on one side of the roadway to improve the thermal environment for the workers in the cooling region. As the roadheader stopped the cold airflow, another air cooler was installed on the other side of the roadway. Thus, there were five tracking air coolers distributed in the roadway. The distance between two neighboring air coolers was 10 m. For simplicity, other electromechanical equipment was not considered.

The ANSYS ICEM CFD software (Version 18.0.0; ANSYS Corp., USA) was used to create the mesh. Approximately 1.1 × 10^5 tetrahedral grid cells were generated. Three different quantities of grids, i.e., 1.5 × 10^5, 3.0 × 10^5, and 6.0 × 10^5, were adopted to conduct grid-independence analysis. The results showed that there were only slight differences in the airflow temperature between the three quantities of grid cells, and the deviation was less 10%. Therefore, we concluded that the mesh with the quantity of 3.0 × 10^5 was enough for the numerical investigation.

In the heading face, the mass, momentum, and energy transport for the airflow proceed all the time. The turbulence model is a key component for simulating the flow in the excavation roadway. The previous study showed that the simulation values for the standard k-ε model were closest to the experimental data [30]. Thus, the standard k-ε model was chosen in this study. The inlet of the duct and the outlet of the roadway were set as the velocity-inlet and outflow, respectively. The solid walls were treated as a no-slip condition for flow. The wind duct was considered as the thermal insulation material. The boundary conditions of temperature and air speed are summarized in Table 1.

| Item                  | Temperature (°C) | Air Speed (m/s) |
|-----------------------|------------------|-----------------|
| Inlet airflow         | 27               | 12.00           |
| Heading face wall     | 40               | -               |
| Roadheader wall       | 50               | -               |
| Roadway wall          | 37               | -               |
| Tracking air cooler   | 20               | 3.00            |

The geometry and boundary conditions were solved by a commercial computational fluid mechanics software program, Fluent (Version 18.0.0; ANSYS Corp., USA). The equations were coupled
by the Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm. When the relative residuals reached $1.0^{-6}$, the equations were considered as convergence. Each simulation required approximately 7500 iterations.

3.2. Temperature Distribution of the Airflow in the Heading Face

To estimate the cooling effect of the new cooling strategy, the airflow temperature cooled only by ventilation was compared with that by the new cooling strategy. Figure 5 shows the temperature distribution of airflow in the heading face cooled only by forced ventilation. The cooling region was divided into four sub regions. At the inlet of the cooling region (Region 1), the airflow temperature was quite high, and the value ranged from 34.5 °C to 35.0 °C (Figure 5b). The temperature slightly decreased in Region 2, and the average value was 34.0 °C. For Region 3, because the roadheader released a great amount of heat to the airflow, the airflow temperature increased to 35.0 °C. The temperature value in Region 4 significantly decreased due to ventilation cooling, and the minimum value was 32.3 °C. Thus, ventilation cooling only cooled the region near the heading face to some extent. However, the temperature in the front and middle of the cooling region was still quite high. The above regions should be further cooled. This study only simulated the temperature distribution near the heading face. In the future, more dedication will be devoted to providing the heat profile for the whole excavation roadway.

Figure 5. Temperature distribution of airflow in the cooling region for the heading face cooled only by forced ventilation: (a) temperature contour at the plane of $X = 1.25$ m; (b) variation of the temperature with the Z axis at the line of $X = 1.25$ m, $Y = 1.5$ m.

Figure 6 presents the airflow temperature when the first tracking air cooler worked. The temperature ranged from 21 °C to 27 °C within the control range of 10 m, which decreased about 10 °C compared to that only by ventilation. Thus, the thermal environment for the workers significantly improved. To achieve highly effective cooling to the personnel in the heading face, the air cooler focused on the space occupied by the personnel and ignored the space not occupied by workers. Thus, the airflow temperature outside of the control range of the first air cooler (up to 30 °C) was much higher than that in the control range.
The value of the temperature increased in front of the cooling region. The results showed that the thermal environment in the posterior of the cooling region was improved to some extent, and the temperature in the front of the cooling region near the heading face was higher. This might be because the second air cooler was further away from the outlet of the air duct than the first air cooler. The value of the temperature increased in front of the cooling region. The results showed that the thermal environment in the posterior of the cooling region was improved to some extent, and the temperature in the front of the cooling region should be further decreased. Other tracking air coolers had similar results.

**Figure 6.** Temperature distribution of airflow in the cooling region for the heading face when the worker was located in the control range of the first tracking air cooler with forced ventilation: (a) temperature contour at the plane of $X = 1.25$ m; (b) variation of the temperature with the $Z$ axis at the line of $X = 1.25$ m, $Y = 1.5$ m.

When the second air cooler worked, as shown in Figure 7, the temperature in the posterior of the cooling region significantly decreased, with the temperature range from 25 °C to 30 °C. However, the temperature in the front of the cooling region near the heading face was higher. This might be because the second air cooler was further away from the outlet of the air duct than the first air cooler. The value of the temperature increased in front of the cooling region. The results showed that the thermal environment in the posterior of the cooling region was improved to some extent, and the temperature in front of the cooling region should be further decreased. Other tracking air coolers had similar results.

**Figure 7.** Temperature distribution of airflow in the cooling region for the heading face when the worker was located in the control range of the second tracking air cooler with forced ventilation: (a) temperature contour at the plane of $X = 1.25$ m; (b) variation of the temperature with the $Z$ axis at the line of $X = 1.25$, $Y = 1.5$ m.
Figure 8 shows the temperature distribution of airflow in the heading face cooled only by exhaust ventilation. For simplification, the variation in temperature with the displacement was not presented. The cooling region was divided into two sub regions. For Region 1, the airflow temperature was layered vertically. The temperature value in the upper area was approximately 38.5 °C, which was slightly higher than that in the lower area (38.0 °C). The temperature distribution in Region 2 was more homogeneous compared to that in Region 1. The results showed that the airflow temperature with the exhaust ventilation was higher than that with the forced ventilation.

Figure 8. Temperature distribution of airflow in the cooling region for the heading face cooled only by exhaust ventilation.

Figure 9 presents the airflow temperature when the first tracking air cooler worked with exhaust ventilation. The cooling effect of the new cooling strategy with exhaust ventilation was better than that with forced ventilation. The temperature in the vicinity of the heading face was approximately 25 °C, which was much lower than that for the forced ventilation (Figure 6). Figure 10 shows the temperature distribution when the second tracking air cooler worked with exhaust ventilation. The temperature value ranged from 24 °C to 27 °C within the control range of 15 m, which decreased about 3 °C compared to that by forced ventilation. The thermal environment in the leeward direction of the air cooler significantly improved.

Figure 9. Temperature distribution of airflow in the cooling region for the heading face when the worker was located in the control range of the first tracking air cooler with exhaust ventilation: (a) temperature contour at the plane of X = 1.25 m; (b) variation of the temperature with the Z axis at the line of X = 1.25, Y = 1.5 m.
was inevitably wasted, and a benign thermal environment for the workers could not be guaranteed. Who were far from the heading face. There were a lot of cooling schemes; however, no study considered the deep mine was much higher than 26 °C. Actually, the temperature value in the heading face for the deep mine was much higher than 26 °C, as shown in Section 2.2. In this study, the temperature of the cooling region in the heading face was assumed to exceed the regulations of the Coal Mine Safety Regulation in China. Thus, once a person enters the control range of the tracking air cooler, the air door opens and then cold air is blown to the person. In addition, thermal hazards should be mitigated.

4. Discussion

4.1. Main Findings of This Study

This research developed a new cooling strategy in the heading face. The tracking air cooler was designed to track the workers and build a non-uniform environment. The results showed that this cooling strategy had great energy saving potential and a fine cooling effect, particularly for the workers who were far from the heading face. There were a lot of cooling schemes; however, no study considered to cool the area occupied by the workers and ignored the invalid space. A great amount of energy was inevitably wasted, and a benign thermal environment for the workers could not be guaranteed. This study might improve energy and cooling efficiency.

The existing cooling strategies aim to cool the whole cooling region, while the new cooling strategy in this study changed the approach to build a non-homogeneous environment. As the purpose of refrigeration was to improve the thermal environment for the workers, the well-designed tracking air cooler could realize high-efficiency cooling. This new cooling strategy could be popularized in all of mine cooling.

4.2. Limitation of the Current Study and Outline of Future Research

According to the Coal Mine Safety Regulation in China, the temperature of the airflow in the cooling range should not be higher than 26 °C. Actually, the temperature value in the heading face for the deep mine was much higher than 26 °C, as shown in Section 2.2. In this study, the temperature of the cooling region in the heading face was assumed to exceed the regulations of the Coal Mine Safety Regulation in China. Thus, once a person enters the control range of the tracking air cooler, the air door opens and then cold air is blown to the person. In addition, thermal hazards should be mitigated.

Figure 10. Temperature distribution of airflow in the cooling region for the heading face when the worker was located in the control range of the second tracking air cooler with exhaust ventilation: (a) temperature contour at the plane of \( X = 1.25 \) m; (b) variation of the temperature with the \( Z \) axis at the line of \( X = 1.25, Y = 1.5 \) m.
according to several complex indices [31,32]. In this study, only temperature was considered as an indicator to estimate the cooling effect of the new cooling strategy.

To realize high-efficiency cooling, the design and layout mode of the tracking air cooler were the important part. In the heading face, the space was limited, and the air coolers that were laid out therein might cause congestion. The environmental conditions of the heading face were poor. A great amount of dust could be produced when headwork was being performed. Once the dust particles adhered to the surface of the coil of the air cooler, the heat exchange performance significantly decreased. In addition, the heading face and workers were continually moving forward. To guarantee a benign thermal environment, the tracking air coolers should also move with the heading face. This study only provided a new cooling strategy and designed the rudiments of the tracking air cooler. In future studies, the actual manufacture and air distribution of the tracking air cooler should be further investigated.

In the current stage, we concentrated only on the efficient cooling in the heading face of underground mines. However, gas (methane and carbon dioxide) might be released from the surrounding rock to the heading face during the carbonification process. The local airflow from the tracking air cooler could keep the gas in the heading face, and the gas might accumulate there. In the future, more dedication will be devoted to evaluating impacts of the local airflow on the gas accumulation in the heading face.

5. Conclusions

In this study, a new cooling strategy for the heading face in an excavation roadway was developed. A tracking air cooler was designed to improve the thermal environment for workers. The cooling load for this new cooling strategy was compared to that for the traditional cooling strategy. The temperature distribution of the airflow in the heading face was numerically solved. The results revealed that this new cooling strategy could save approximately 30% of energy for mine cooling. When the airflow was cooled only by ventilation, the temperature in the middle and posterior of the cooling region was quite high. For the new cooling strategy, the thermal environment for the workers whether near the heading face or in the roadway was significantly improved. The temperature value decreased up to 10 °C within the control range of 10 m of the tracking air cooler, compared to that only by ventilation. The cooling effect of the new cooling strategy with exhaust ventilation was better than that with forced ventilation. This new cooling strategy could be popularized in all of mining cooling.

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