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Building a non-homogeneous environment for high effective cooling in the face of deep mines

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Abstract

Heat exhaustion of mining environments can cause a great threat to human health. The existing cooling strategies for the mine face aim to cool the whole face. However, the area of effective air-cooling space for the face is small, and a great amount of energy for cooling is ineffective. Effective air-cooling space is a space occupied by the workers in the face. This study proposed to build a non-homogeneous environment for high effective cooling in the face. An inlet air cooler was laid out in the intake airway to cool the whole face to some extent, and the tracking air cooler was designed to track the worker who constantly moved to improve the thermal environment. The cooling load and air distribution for this cooling strategy were investigated. In addition, the airflow in the face was numerically solved to estimate the cooling effect. The results revealed that an average energy saving of approximately 35% could be achieved. The thermal environment of the effective air-cooling space within at least 10 m was significantly improved. This cooling strategy should be taken into account in mine cooling.

Keywords: mine face, cooling system, non-homogeneous environment, air cooler, effective air-cooling space

Nomenclature			
a	turbulent coefficient	S	area of the face (m^2)
c_p	specific heat at constant pressure ($\text{kJ}/(\text{kg}\cdot\text{K})$)	T, t	temperture of airflow ($^{\circ}\text{C}$, K)
d	vertical distance between the tracking air cooler and the worker (m)	t_{gu}	initial temperature of the surrounding rock ($^{\circ}\text{C}$)
d_0	equivalent diamater of outlet of the tracking air cooler (m)	$-$	average air temperature ($^{\circ}\text{C}$)
g	gravity acceleration (m/s^2)	Δt	temperature difference ($^{\circ}\text{C}$)
H	cooling range of the tracking air cooler (m)	U	air velocity (m/s)
i	enthalpy value of airflow (kJ/kg)	U	perimeter (m)
K_{τ}	unsteady heat transfer coefficient ($\text{kW}/(\text{m}^2\cdot^{\circ}\text{C})$)	V	supply air volume (m^3)
L	length (m)	v_l	jet speed at the location of worker (m/s)
l	distance between the tracking air cooler and the worker (m)	<i>Greek variable</i>	
M_B	mass flow rate of airflow (kg/s)	κ_{eff}	effective air thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$)
M_{BT}	mass flow rate of airflow for the tracking air cooler (kg/s)	ρ	air density (kg/m^3)
n	quantity of the tracking air cooler	τ	viscous stress tensor
p	air pressure (Pa)	ξ	correction factor
Q	cooling load (kW)	φ	relative humidity (%)
S_E	area of the effective air cooling space (m^2)		

1 Introduction

Heat exhaustion of mining environments has caused increasing concern (Sasmito et al. 2015). With the decrease of mineral resources, the mining depth continuous increases (Crawford et al. 2019). The temperature of initial surrounding rocks rises with the mining depth (Du et al. 2013a; Yi et al. 2019). Meanwhile, the electromechanical equipment can also release a large amount of heat. These heat sources transfer heat to airflow in mining environments and the heat damage inevitably happens (Maurya et al. 2015). Heat exhaustion aggravates deterioration of the thermal environment of mines and then causes a great threat to human health (Su et al. 2009; Guo et al. 2014). Workers who work long time in the high

temperature environment are susceptible to fatigue and heat illness (Katavoutas et al. 2016). The work efficiency then decreases and the accident is bound to happen more frequently (Armstrong and Lopez 2007; Kasap 2011). Thus, Mine cooling becomes increasing urgent.

Generally, there are two kinds of cooling methods for mines: non-artificial refrigeration method and artificial refrigeration method (Chatterjee et al. 2015; Bellas and Tassou 2005). For the non-artificial refrigeration method, the airflow temperature is lowered by increasing ventilation and heat discharge. However, this method is only suitable for places where the heat exhaustion is not serious. When the temperature of initial surrounding rocks is high enough, the artificial refrigeration method should be adopted (Ji et al. 2019). Artificial refrigeration is a method in which work is done to remove heat from one location to another by using manual methods (Waltrich et al. 2011). According to the type of secondary refrigerant, the artificial refrigeration system can be divided into central air conditioning cooling system, ice cooling system, and water cooling system (Wang et al. 2017; Chen et al. 2016). The secondary refrigerant is an intermediate cooling medium that transfers heat from a space to the refrigerant (Bao et al. 2014). The basic components of a critical water cooling system include a refrigeration unit, a chilled water pipeline, a cooling water pipeline, and an air cooler (Kusiak and Li 2010). The air cooler is a key component for cooling, whose type, layout and operating parameters have a significant impact on the effect of the cooling system.

The mine face is a long and narrow working space and has plenty of equipment and workers (Guo et al. 2010). Generally, the temperature of face is much higher than other places of mines, and thus it is the important region for cooling. There were mainly three layout modes of the air cooler for cooling the face, as shown in Fig. 1 (Guo and Chen 2013). When the air cooler was laid out in the intake airway (Fig. 1(a)), the cold airflow was transported to the face for a long distance, and a certain of cooling loss was inevitably produced. The temperature of airflow had been very high in the posterior region of the face because of the heat exchange between the airflow and the surrounding rocks. In order to achieve a benign cooling effect, more energy should be consumed. The air cooler which was laid out in the return airway (Fig. 1(b)) was used to cold the airflow there and had little effect on the face. As for the third layout mode, a quantity of smaller air coolers were uniformly laid out in the face. Because the smaller air coolers cooled the face immediately, this layout mode could save a certain energy and achieve a better cooling

effect than other layout modes. However, the mine face was quite long and had plenty of heat sources, this cooling strategy also consumed a great amount of energy (Abdelaziz et al. 2011). The cooling load for a typical mine face can reach up to 300 kW. Approximately 25% of the total energy consumption of mines originated from the mining cooling (Crawford et al. 2019; Du et al. 2013b).

Fig. 1 Layout mode of the air cooler for mine cooling at various locations: (a) intake airway; (b) return airway; (c) mine face

The above review reveals that the existing cooling strategies aim to cool the whole face and build a homogeneous thermal environment. However, there are only a small area occupied by workers in the face, thus, a great amount of energy is ineffective. Until the present time, there is no study on a high effective cooling strategy focusing on the workers in the face. For cost-effective energy savings and obtaining benign thermal environment, a new cooling strategy of building non-homogeneous environment for high effective cooling in the mine face was proposed in this study. The concept of effective air-cooling space was put forward for the first time. A novel tracking air cooler was designed to track the worker who constantly moved in the face and improve the thermal environment of the effective air-cooling space. The cooling load and economic efficiency for this new cooling strategy were estimated. Numerical simulation of the airflow in the face was performed to compare the cooling effect

between the new cooling strategy and the traditional cooling strategy.

2 Principles for building the non-homogeneous environment in the face

In this section, the basic principles for building the non-homogeneous environment are presented first, followed by cooling load calculation. The economic analysis for this cooling strategy is then addressed.

2.1 Building the non-homogeneous environment and tracking air cooler

To achieve high effective cooling to the workers in the face, the air cooler should focus on the effective air-cooling space and deprioritize the ineffective air-cooling space. Effective air-cooling space is a space occupied by the workers in the face. The effective air-cooling space may be a fixed space, for example, the location where the driver of the pump station is, or a constantly moving space, for example, the location where the shearer driver is. Whether fixed or moving workers, the occupied areas of them are equal. In contrast, ineffective air-cooling space is a space where no worker was. Because the mine face is long and narrow, the ineffective air-cooling space is much larger than the effective air-cooling space. Note that the space occupied by the equipment is also needed to be cooled for its safety. In this study, the space where workers occupied was as a representative of the effective air-cooling space.

Fig. 2 illustrates the basic principles for building non-homogeneous environment in the mine face. The system was composed of an air cooler in the intake airway, an inlet pipe of chilled water, a return pipe of cooling water, and a quantity of small tracking air coolers in the face. The chilled water was transported to the air cooler by the chilled water pipe and then the air cooler cooled the face. The tracking air cooler was used to cool the effective air-cooling space and improve the thermal environment for workers. When a worker entered the control range of a tracking air cooler, the air cooler began to work and blew cold air to the worker. Other air coolers did not work and the ineffective air-cooling space was ignored. When the worker moved, the air cooler constantly tracked him. Once the worker left the control range of the tracking air cooler and entered that of the next one, the last air cooler automatically stopped and the next one began to work, as shown in Fig. 3. Thus, the benign thermal environment for the worker could be guaranteed. The inlet air cooler was used to cool the whole face to some extent. It could prevent the

excessive temperature difference between the effective air-cooling space and ineffective air-cooling space. Overheating in the ineffective air-cooling space might affect the human thermal comfort.

1. Inlet air cooler, 2. Inlet pipe of the chilled water, 3. Return pipe of the cooling water, 4. Tacking small air cooler, 5. Hydraulic support, 6. Infrared detector, 7. Controller, 8. Electric spindle, 9. Air door, 10. Worker, 11. Shearer

Fig. 2 Schematic diagram of building the non-homogeneous environment in the face: (a) layout mode of the inlet and tracking air coolers; (b) constitution of the tracking air cooler

The difficulty of building non-homogeneous environment was how to guarantee the benign thermal environment for the constantly moving workers. For this purpose, the tracking small air cooler was designed. The tracking object was the workers in the face. Each air cooler controlled a certain area and the areas of two adjacent air coolers were mutually related, as shown in Fig. 3. The tracking small air cooler could be placed between the two columns of the hydraulic support in the face.

The tracking air cooler was composed of an infrared detector, a controller, an electric spindle, and an air door (Fig. 2). When a worker arrived at the control range of the tracking air cooler, the infrared detector sensed worker's signal and transmitted the signal to the controller. Then the controller opened the air door and the air cooler blew the cold airflow to the effective air-cooling space. When the worker

moved, the electric spindle continuously rotated and tracked with him according to the infrared signal so that the air door was kept facing to the worker. When the worker left the control range of the air cooler, the air door and electric spindle closed and the next air cooler began to work (Fig. 3). Because the tacking air cooler accurately cooled the effective air-cooling space and deprioritized the ineffective air-cooling space, this cooling strategy could save a great amount of energy.

2.2 Cooling load calculation

The cooling load for building the non-homogeneous environment in the face was composed of two parts: the cooling load for the background airflow in the face and that for the effective air-cooling space. Thus, the total cooling load can be summarized as:

$$Q=Q_1+Q_2 \quad (1)$$

$$Q_1 = M_B (i_1 - i_2) \quad (2)$$

$$i = c_0 (\varphi / B) + [1.005 + c_1 (\varphi / B)] t_{in} + [c_2 (\varphi / B)] t_{in}^2 \quad (3)$$

where, t_{in} is the temperature of inlet airflow in the face ($^{\circ}\text{C}$), φ is the relative humidity (%), c_0 , c_1 , c_2 are constant coefficients. t_{in} was estimated as:

$$t_{in} = t_{out} e^{RK(\Phi)} - \frac{e^{RK(\Phi)} - 1}{R} \left(T + \frac{\sum Q_M}{M_B c_p} \right) \quad (4)$$

where, $R = \frac{K_{\tau} UL}{M_B c_p} + \frac{N_y}{B - P_m} V\varphi$, $V\varphi = \varphi_{out} - \varphi_{in}$, $E = \frac{N_y}{B - P_m}$, $T = R t_{gu} - \frac{N_y \varepsilon' V\varphi}{B - P_m}$, t_{out} is the

temperature of outlet airflow in the face ($^{\circ}\text{C}$), K_{τ} is the unsteady heat transfer coefficient between surrounding rocks and airflow ($\text{kW}/(\text{m}^2 \cdot ^{\circ}\text{C})$), c_p is the specific heat at constant pressure of air ($\text{kJ}/(\text{kg} \cdot \text{K})$), L and U are the length and perimeter of the face (m), t_{gu} is the initial temperature of the surrounding rock ($^{\circ}\text{C}$), φ_{in} and φ_{out} are the relative humidities of the inlet and outlet airflow in the face (%), B , N_y , P_m , $K(\Phi)$ and ε' are constant coefficients.

Q_2 was estimated by the ratio of the area of effective air-cooling space to that of the face:

$$Q_2 = \xi (Q_3 - Q_1) \frac{S_E}{S} \quad (5)$$

where, S_E is the area of the effective air cooling space (m^2), S is the area of the face, (m^2), ξ is the correction factor, Q_3 is the cooling load for cooling the whole face (kW).

According to Eqs. (1), (2) and (5), the cooling load for building the non-homogeneous environment was summarized as:

$$Q = \frac{M_B}{S} [S (i_1 - i_2) + S_E \xi (i_2 - i_3)] \quad (6)$$

where, i_3 is the the enthalpy value of the inlet airflow for cooling the whole face (kJ/kg).

2.3 Case study and economic analysis

In this section, a fully mechanized coal face was used as a case to estimated the cooling load for building the non-homogeneous environment. The length and width of the face were 120 m and 2.5 m, respectively. The average perimeter of the section was 10 m. The average rock temperature was 36 °C and the unstable heat transfer coefficient of the surrounding rock was 3.856×10^{-3} kW/(m²·°C). The air volume of the face was 350 m³/min and the air density was 1.221 kg/m³. The average static pressure of air was 1.12×10^5 Pa. The temperature and relative humidity of the inlet airflow before cooling were 27 °C and 95% and those of the outlet airflow were 32 °C and 98%, respectively. The total heat dissipation of various absolute heat sources in the face was approximately 100 kW.

In the mine face, two workers driven the shearer to move back and forth, and four hydraulic support workers pushed the support forward. There were 11 workers located in the vicinity of the machine and at the end of two roadways and their working positions were relatively fixed. The body width of the worker and the average distance between the tracking air cooler and the worker were assumed to be 0.5 m and 5 m, respectively, according to Eq. (10) in third section. The area of effective air-cooling space was then estimated as 42.5 m², which was much less than that of the face (300 m²)

The temperature and relative humidity of the outlet airflow in the face after cooling were set as 26 °C and 98%, respectively, based on the Coal mine safety regulation in China (Homer 2009). According to Eq. (4), the temperature and relative humidity of the inlet airflow were estimated as 17.75 °C and 100%, respectively. Thus, the cooling load for cooling the whole face was 227.7 kW.

For building the non-homogeneous environment, the higher the temperature of background airflow, the lower the cooling load. However, in order to prevent the excessive temperature difference between the effective and the ineffective air-cooling spaces, the outlet temperature and relative humidity of the background airflow were set as 29 °C and 100%, respectively. According to Eq. (2), the cooling load of

the inlet air cooler (Q_1) was 98.31 kW. The value of ξ was set as 1.5. According to Eq. (5), the cooling load of the tracking air coolers (Q_2) was estimated as 50.45 kW. Thus, the total cooling load for building the non-homogeneous environment was approximately 149 kW, which was only 65% of that for cooling the whole face. Thus, this new cooling strategy could save approximately 35% of energy compared to the traditional cooling strategy and had great potentiality in energy saving.

3 Air distribution for building the non-homogeneous environment

In this section, to obtain benign thermal environment, the air distribution for building the non-homogeneous environment was investigated. The cooling range, quantity, and supply air volume of the tracking air cooler were determined by the heat balance equation.

As shown in Fig. 3, the heat balance equation between the outlet of the tracking air cooler and the worker was established as (Hartman et al. 2012):

$$M_{BT} (i_{T2} - i_{T1}) = K_{\tau} UL (t_{gu} - \bar{t}) + \frac{\sum Q_M}{L} l \quad (7)$$

where, M_{BT} is the mass flow rate of the airflow for the tracking air cooler (kg/s), i_{T1} is the enthalpy value of the outlet airflow for the tracking air cooler (kJ/kg), i_{T2} is the enthalpy value of the airflow at the location of the worker (kJ/kg), l is the distance between the tracking air cooler and the worker (m), $\sum Q_M$ is the total heat dissipating capacity for various heat sources in the face (kW), $\bar{t}$ is the average air temperature between the outlet of the tracking air cooler and the worker (°C). Based on Eq. (7), l was estimated as:

$$l = \frac{M_{BT} (i_{T2} - i_{T1}) L}{K_{\tau} UL (t_{gu} - \bar{t}) + \sum Q_M} \quad (8)$$

The cooling range of the tracking air cooler could be calculated by l and the vertical distance between

the tracking air cooler and the worker:

$$H = 2h = 2 \sqrt{\frac{(M_B L)^2 (i_{T2} - i_{T1})^2}{\left[(K_\tau UL)(t_{gu} - \bar{t}) + \sum Q_M \right]^2} - d^2} \quad (9)$$

where, H is the cooling range of the tracking air cooler (m), d is the vertical distance between the tracking air cooler and the worker (m).

After the cooling range of the tracking air cooler was determined, the quantity of tracking air cooler in the face was estimated as:

$$n = \frac{L}{2 \sqrt{\left[\frac{M_B L (i_{T2} - i_{T1})}{(K_\tau UL)(t_{gu} - \bar{t}) + \sum Q_M} \right]^2 - d^2}} \quad (10)$$

However, the estimated value of n from Eq. (10) might not be a integer, the quantity of tracking air cooler was further estimated as:

$$n = \begin{cases} \frac{L}{2h}, & \text{when } n \text{ is a integer} \\ \left\lceil \frac{L}{2h} \right\rceil + 1, & \text{when } n \text{ is a non-integer} \end{cases} \quad (11)$$

The supply air volume of each tracking air cooler was estimated as (Hartman et al. 2012):

$$V = \frac{S_E \sum Q_M}{Sc_p \rho \Delta t} \quad (12)$$

where, V is the supply air volume of the tracking air cooler (m³/s), Δt is the temperature difference of

airflow between the outlet of the tracking air cooler and the worker (°C).

The blowing form of airflow for the air cooler could be approximately treated as a free jet. The jet speed at the location of the worker was estimated as:

$$v_l = \frac{0.48 \frac{V}{S}}{\frac{al}{d_0} + 0.147} \quad (11)$$

where, v_l is the jet speed at the location of the worker (m/s), d_0 is the equivalent diameter of outlet of the tracking air cooler (m), a is the turbulent coefficient of outlet airflow for the tracking air cooler.

4 Numerical simulation of airflow for the non-homogeneous environment

4.1 Geometric model and boundary conditions

To estimate the cooling effect of the new cooling strategy, computational fluid dynamics (CFD) simulations of the airflow in the mine face were performed. For simplicity, this study only conducted the case when the worker was face to the tracking air cooler and the air cooler did not rotate. Other assumptions are as follows:

- (a) Two-dimensional space.
- (b) Airflow field of the face is uniformly distributed in the vertical direction.
- (c) Irregularity of the mining wall has no impact on airflow.

According to an actual fully mechanized coal face, the geometric model shown in Fig. 4 was created. The length and width of the intake and return airways were both 70 m and 4 m and those of the mine face were 250 m and 5 m, respectively. The dimensions of the shearer were 10 × 1.5 m. The vertical distance of the inlet air cooler from the mine face was 20 m. Ten tracking air coolers were equidistantly distributed in the mine face, according to Eq. (10). The distance between two adjacent tracking air coolers was 25 m. For simplicity, other electromechanical equipment was not considered.

Quadrilateral grid cells were generated by an integrated computer engineering and manufacturing code (ICEM, version 18.0.0) for CFD. Totally 100 thousand grids were created and the average grid size was 3.5 cm. To capture the near-wall effect, the grids near the mine face walls and the shearers were refined. All the values of y^+ of the first near-wall grids were less than five. Three different average grid sizes were tested for grid-independence. The comparison results of flow simulations from the three grid sizes showed no significant difference.

To model the airflow in the mine face, the governing equations of fluid flow must be solved. The conservation equations for mass, momentum, and energy are summarized as:

$$\nabla \cdot \rho \mathbf{U} = 0 \quad (12)$$

where, ρ is the air density (kg/m^3), $\mathbf{U}$ is the air velocity (m/s), p is the air pressure (Pa), $\boldsymbol{\tau}$ is the viscous stress tensor, $\mathbf{g}$ is gravity acceleration (m/s^2), κ_{eff} is the effective air thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$), T is the air temperature (K), and Pr_t is the turbulent Prandtl number.

The airflow inside the mine face was turbulent, and the re-normalization group (RNG) $k-\epsilon$ model was adopted for turbulence modeling. The boundary conditions of temperature, heat flux, and air speed are shown in Table 1. Because the temperature of the mining wall was higher than that of the airflow, the wall dissipated heat to the airflow. The temperature and air speed of airflow for the tracking and inlet air coolers were estimated by the equations in the second and third sections.

Table 1 Boundary conditions for CFD simulations

Item	Temperature (°C)	Heat flux (W/m ²)	Air speed (m/s)
Inlet airflow	32	-	1.00
Wall of intake airway	34	200	-
Wall of return airway	35	400	-
Coal wall	35	600	-
Goaf wall	36	500	-
Shearer wall	50	800	-
Inlet air cooler	25	-	1.50
Tracking air cooler	22	-	2.34

All the variables were discretized using the second-order upwind scheme. Each simulation required approximately two thousand iterations for convergence tolerance of 1.0E-6 for all variables. The Fluent software program (version 18.0.0) was adopted to solve the governing equations.

4.2 Numerical results

To validate the cooling effect of the new cooling strategy, the temperature distribution of airflow cooled only by the inlet air cooler was compared with that by both the inlet and tracking air coolers.

Fig. 5 present the temperature distribution of airflow in the mine face cooled only by the inlet air cooler. The airflow temperature increased from 30.3 °C at the inlet to 31.6 °C at the outlet of the face, as shown

in Fig. 6. In the vicinity of the shearer, the temperature rapidly increased from 30.8 °C to 31.5 °C within the range of 15 m. Although the value of airflow temperature decreased approximately 2 °C, compared to that before cooling, it was still quite high. The airflow temperature should be further reduced.

Fig. 5 Temperature distribution of airflow in the face cooled only by the inlet air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

Figs. 6 to 8 compares the temperature distribution of airflow in the mine face when the worker located in the control range of different tracking air coolers. Fig. 6(b) shows the airflow temperature versus the displacement of the mine face when the worker located in the control range of the first tracking air cooler.

The airflow temperature increased from 24.8 °C to 28.5 °C within the control range of 15 m. The average temperature decreased approximately 4.5 °C as compared with that only by the inlet air cooler. Thus, the thermal environment of the effective air-cooling space was significantly improved.

(a)

(b)

Fig. 6 Temperature distribution of airflow in the face when the worker was located in the control range of the first tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

When the worker entered the control range of the fifth tracking air cooler (Fig. 7), the airflow temperature increased from 24.5 °C to 28 °C within the control range of 10 m. Because the fifth tracking air cooler was near the shearer, the high temperature of shearer wall has an impact on the cooling effect

of the air cooler. Thus, the airflow temperature suddenly increased to 30 °C within the next 5 m. The thermal environment of the effective air-cooling space within the control range of 10 m was significantly improved. Similarly, when the tenth tracking air cooler worked (Fig. 8), the airflow temperature increased from 24.8 to 30 °C within the control range 15 m. The value of the airflow temperature at the outlet of the face was higher than other places. This was mainly because heat was aggregated at the return airflow corner and the temperature therein was much higher than that of the cold airflow. The results indicated that the airflow temperature near the shearer and at the outlet of the face should be further decreased to improve the thermal environment.

Fig. 7 Temperature distribution of airflow in the face when the worker was located in the control range

of the fifth tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

Fig. 8 Temperature distribution of airflow in the face when the worker was located in the control range of the tenth tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

5 Discussion

5.1 Main findings of this study

This study proposed to build a non-homogeneous environment for high effective cooling in the mine

face. The results revealed that this new cooling strategy could save a great amount of energy for cooling and significantly improve the thermal environment for the workers. Although some previous studies reported plenty of cooling strategies, no prior published literatures have considered to focus on the area occupied by workers and ignore the ineffective area in the face (Crawford et al. 2019; Guo and Chen 2013; Abdelaziz et al. 2011). A great amount of energy for cooling was ineffective. This new cooling strategy would be of help for energy efficiency and cooling effect improvement for mine cooling.

The concept of effective air-cooling space was proposed in this study. Since the mainly purpose of mining cooling was to ensure personnel safety, the area occupied by workers was critical for cooling. In contrast, the ineffective air-cooling space where no worker was could be ignored. After differentiating the effective and ineffective air-cooling spaces, it was helpful to determine the cooling range of the face and estimate the cooling load.

5.2 Limitation of the current study and outline of future research

For this new cooling strategy, the tracking cooler was designed to lay out in the mine face. However, this layout mode was restricted by many conditions such as space, dust, mechanical damage and pipeline laying (Li and Fu 2020). Dust could reduce the cooling effect of the air cooler. As warm air contacted with the coils of the heat exchanger, water film formed on its surface. This water film increased the adhesive of dust on the coils. After run for a long time, the surface of the heat exchanger might be deposited by plenty of dust particles and the performance decreased. In addition, the mine face was constantly moved and the tracking air cooler was also moved following the face. The removability of the tracking air cooler and the matched pipeline should be well designed. Further efforts are required to construct the tracking air cooler and test the practical application effect for the new cooling strategy.

For simplification, this study only conducted the case when the worker was face to the tracking air cooler and the air cooler did not rotated. When a worker moved, the air cooler rotated and tracked with him so that the air door was kept facing to the worker. The distance between the air cooler and the worker was longer than that when the worker was face to the air cooler. Because of the heat exchange between the cold air from the air cooler and the high temperature airflow in the face, the airflow temperature at

the location of the worker was higher than that when the worker was face to the tracking air cooler. This investigation did not consider the above variations. More dedications are required to clarify the above issues.

6 Conclusions

This paper proposed to build a non-homogeneous environment for high effective cooling in the mine face. The tracking air cooler was designed to track the worker for improving the thermal environment. The concept of effective air-cooling space was proposed to determine the cooling area for workers. The cooling load and air distribution for this new cooling strategy were investigated. A numerical simulation of the airflow in the face was performed to estimate the cooling effect. It was found that an average energy saving of approximately 35% could be achieved for this cooling strategy. The airflow temperature was still high when the face was cooled only by the inlet air cooler. When the tracking air cooler worked, the thermal environment of the effective air-cooling space within at least 10 m was significantly improved. The airflow temperature decreased approximately 4.5 °C in the control range of the tracking air cooler compared to that cooled only by the inlet air cooler. This new cooling strategy should be considered in the mining cooling.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Figures

Figure 1

Layout mode of the air cooler for mine cooling at various locations: (a) intake airway; (b) return airway; (c) mine face

1. Inlet air cooler, 2. Inlet pipe of the chilled water, 3. Return pipe of the cooling water, 4. Tacking small air cooler, 5. Hydraulic support, 6. Infrared detector, 7. Controller, 8. Electric spindle, 9. Air door, 10. Worker, 11. Shearer

Figure 2

Schematic diagram of building the non-homogeneous environment in the face: (a) layout mode of the inlet and tracking air coolers; (b) constitution of the tracking air cooler

Figure 3

Schematic diagram of cooling process of the tracking air cooler

Figure 4

Geometric model of the mine face for CFD simulations

Figure 5

Temperature distribution of airflow in the face cooled only by the inlet air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

(a)

(b)

Figure 6

Temperature distribution of airflow in the face when the worker was located in the control range of the first tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

Figure 7

Temperature distribution of airflow in the face when the worker was located in the control range of the fifth tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis

(a)

(b)

Figure 8

Temperature distribution of airflow in the face when the worker was located in the control range of the tenth tracking air cooler: (a) temperature contour; (b) variation of the temperature with the X axis