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BUILDING A NON-HOMOGENEOUS THERMAL ENVIRONMENT FOR ENERGY SAVINGS IN THE FACE OF DEEP MINES

Heat exhaustion of mining environments can cause a significant threat to human health. The existing cooling strategies for the mine face aim to cool the whole face. However, the necessary cooling space for the face is small, with a considerable amount of energy for cooling being wasted. Necessary cooling space is a space occupied by the workers in the face. This study proposed to build a non-homogeneous thermal environment for cost-effective energy savings 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 solved numerically to estimate the cooling effect. The results revealed that an average energy saving of approximately 35% could be achieved. The thermal environment of the necessary 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 strategy, non-homogeneous environment, air cooler, necessary cooling space

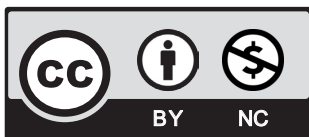
Nomenclature

- a – turbulent coefficient
- c_p – specific heat at constant pressure (kJ/(kg·K))
- d – vertical distance between the tracking air cooler and the worker (m)
- d_0 – equivalent diameter of outlet of the tracking air cooler (m)
- g – gravity acceleration (m/s²)

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H	– cooling range of the tracking air cooler (m)
i	– enthalpy value of airflow (kJ/kg)
K_{τ}	– unsteady heat transfer coefficient (kW/(m ² ·°C))
L	– length (m)
l	– distance between the tracking air cooler and the worker (m)
M_B	– mass flow rate of airflow (kg/s)
M_{BT}	– mass flow rate of airflow for the tracking air cooler (kg/s)
n	– quantity of the tracking air cooler
p	– air pressure (Pa)
Q	– cooling load (kW)
S_E	– area of the effective air cooling space (m ²)
S	– area of the face (m ²)
T, t	– temperature of airflow (°C, K)
t_{gu}	– initial temperature of the surrounding rock (°C)
\bar{t}	– average air temperature (°C)
Δt	– temperature difference (°C)
U	– air velocity (m/s)
U	– perimeter (m)
V	– supply air volume (m ³)
v_l	– jet speed at the location of worker (m/s)

Greek variable

κ_{eff}	– effective air thermal conductivity (W/(m·K))
ρ	– air density (kg/m ³)
τ	– viscous stress tensor
ζ	– correction factor
φ	– relative humidity (%)

1. Introduction

Heat exhaustion of mining environments is an increasing concern [1,2]. With the decrease of mineral resources, the mining depth continuously increases [3]. The temperature of the initial surrounding rocks rises with the mining depth [4]. 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 [5,6]. Heat exhaustion aggravates the deterioration of the thermal environment of mines and then causes a significant threat to human health [7]. Workers who work a long time in a high-temperature environment are susceptible to fatigue and heat illness [8-10]. The work efficiency decreases, and the accident is bound to happen more frequently [11,12]. Thus, mine cooling becomes increasingly urgent.

Generally, there are two kinds of cooling methods for mines: non-artificial refrigeration method and artificial refrigeration method [13,14]. For the non-artificial refrigeration method, the airflow is cooled by increasing ventilation and heat discharge. However, this method is only suitable for places where heat exhaustion is not severe. When the temperature of the initial surrounding rocks is high enough, artificial refrigeration should be adopted [5]. Artificial refrigera-

tion is a method in which work is done to remove heat from one location to another by using manual methods [15]. According to the type of secondary refrigerant, the artificial refrigeration system can be divided into a central air conditioning cooling system, ice cooling system, and water cooling system [16,17]. The secondary refrigerant is an intermediate cooling medium that transfers heat from a space to the refrigerant [18]. 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 [19]. 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 [20]. Generally, the face temperature is much higher than other places of mines, and thus it is the key region for cooling [21]. There were mainly three cooling modes for the mine face, as shown in Fig. 1 [22]. 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, inevitably producing a cooling loss. As the heat of the surrounding rocks was transferred to the airflow, the temperature of airflow became very high in the posterior region. 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 cool the airflow therein and had little effect on the face. As for the third layout mode, a certain number of smaller air coolers were uniformly placed in the mine face. Because the smaller air coolers cooled the face immediately, this layout mode could save certain energy and achieve a better cooling effect than other layout modes. However, the mine face was considerably longer and had plenty of heat sources. This cooling strategy also consumed a significant amount of energy [23]. The cooling load for a typical mine face can reach up to approximately 800 kW. Approximately 25% of the total energy consumption of mines originated from mining cooling [3,24].

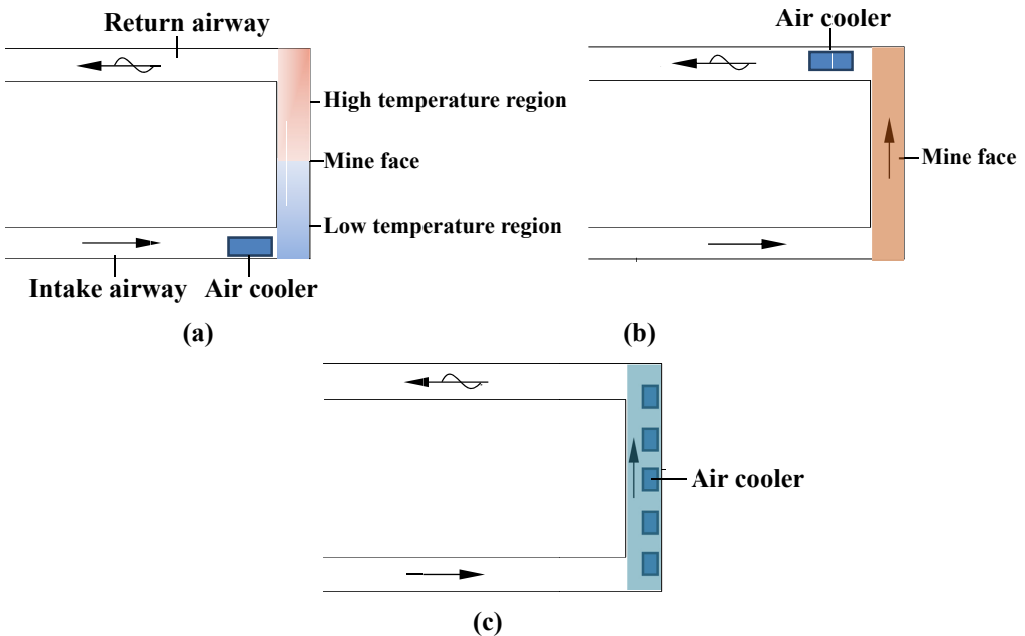


Fig. 1. Layout mode of the air cooler in the mine face: (a) intake airway; (b) return airway; (c) mine face

The above review reveals that the existing cooling strategies aim to cool the whole face and build a homogeneous thermal environment. However, there is only a small area occupied by workers in the face, thus a significant amount of energy is wasted. Recently, there hasn't been a study on a cooling strategy focusing on the personnel located in the face. For cost-effective energy savings and obtaining a benign thermal environment, a new cooling strategy of building a non-homogeneous thermal environment in the mine face was proposed in this study. The concept of necessary cooling space, which was defined as a space occupied by the personnel in the face, was put forward for the first time. A novel tracking air cooler was designed to track the worker who constantly moved in the face, which improved the thermal environment of the necessary cooling space. The cooling load and economic efficiency for this new cooling strategy were estimated. A 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.

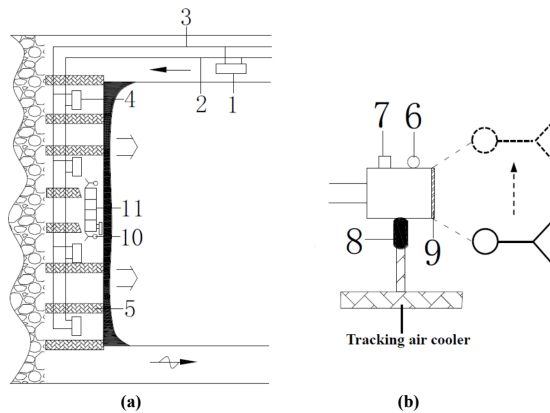
2. Principles of the non-homogeneous thermal environment

This section focuses on the basic principles for building a non-homogeneous thermal environment, followed by a cooling load calculation. The energy analysis for this cooling strategy is also addressed.

2.1. Building the non-homogeneous thermal environment

For achieving energy savings and an ideal cooling effect for the workers, the air cooler should focus on the necessary cooling space and deprioritize the redundant cooling space. Necessary cooling space is a space occupied by the workers in the face. The necessary cooling space may be a fixed space, for example, the space occupied by the driver of the pump station, or a constantly moving space, for example, the space occupied by the shearer driver. Whether fixed or moving workers, the occupied areas by them are equal. In contrast, a redundant cooling space is a space where there are no workers. Because the mine face is long and narrow, the redundant cooling space is much larger than necessary. Note that the space occupied by the equipment is also needed to cool for its safety. For simplification, the space occupied by workers was representative of the necessary cooling space in this study.

Fig. 2 illustrates the basic principles to build the non-homogeneous thermal environment in mine faces. The system was composed of an inlet air cooler in the intake airway, an inlet pipe of chilled water, a return pipe of cooling water, and a certain number of small tracking air coolers. The chilled water was transported to the air cooler by the chilled water pipe where the air cooler cooled the face. The tracking air cooler was used to cool the necessary space in the face. When a worker moved to the control area, the air cooler started to blow the low-temperature air. Other air coolers did not work, and the redundant cooling space was ignored. When the worker moved, the air cooler constantly tracked him. Once the worker left the control area 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, creating the necessary cooling space. The inlet air cooler was used to bring the temperature down in the whole face. It could prevent the excessive temperature difference between the necessary cooling space and redundant cooling space. Overheating in the redundant cooling space might affect 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 thermal environment in the face:
 (a) arrangement of the air coolers; (b) composition of the tracking air cooler

The difficulty of building the non-homogeneous thermal environment was how to guarantee the fine cooling effect for the personnel who kept moving. 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 control 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 area of the tracking air cooler, the infrared detector sensed the 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 necessary cooling space. When the worker moved, the electric spindle continuously rotated and tracked him according to the infrared signal so that the air door was kept facing the worker. When the worker left the control area 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 necessary cooling space and deprioritized the redundant cooling space, this cooling strategy had a large energy-saving potential.

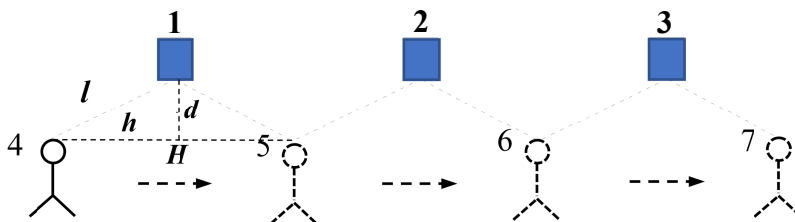


Fig. 3. Cooling process of the new cooling strategy in the face

2.2. Cooling load calculation

The cooling load to build the non-homogeneous thermal environment in mine faces was composed of two parts: the cooling load for the background airflow in the face and the necessary cooling space. Thus, the total cooling load can be summarized as:

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

where, Q is the total cooling load (kW), Q_1 is the cooling load for the background airflow (kW), Q_2 is the cooling load for the necessary cooling space (kW). Q_1 was estimated as:

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

where, M_B is the mass flow rate of the airflow (kg/s), i_1 is the enthalpy value of the inlet airflow before cooling by the inlet air cooler (kJ/kg), i_2 is the enthalpy value of the inlet airflow after cooling by the inlet air cooler (kJ/kg). i was estimated as [25]:

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

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 [25]:

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

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

temperature of outlet airflow in the face ($^{\circ}\text{C}$), K_r 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 of the airflow ($\text{kJ}/(\text{kg} \cdot \text{K})$), 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. Generally, the initial temperature of the surrounding rock is dynamically changing. For simplification, it was assumed to be a constant value.

Q_2 was estimated as:

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

where, S_N 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). Considering the heat exchange between the cold air in the necessary cooling space and the hot air in the redundant cooling space, the correction factor was added to the calculation formula to estimate the accurate cooling load.

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

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

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

To estimate the economical efficiency of the new cooling strategy, a fully mechanised coal face was used as an example to calculate the cooling load. 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. 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 drove 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 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 the third section. The area of necessary 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 [26]. According to Eq. (4), the temperature and relative humidity of the inlet airflow was 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 thermal 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 redundant 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. The cooling load of the tracking air coolers (Q_2) was estimated as 50.45 kW, based on Eq. (5). Thus, the total cooling load for building the non-homogeneous thermal environment was approximately 149 kW, which was only 65% of that for cooling the whole face. Thus, this new cooling strategy had great potential in saving energy.

3. Air distribution for building the non-homogeneous thermal environment

In this section, to obtain a benign thermal environment, the air distribution for building the non-homogeneous thermal 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 [25]:

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

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:

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

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:

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

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

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

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

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

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

The supply air volume of each tracking air cooler was estimated as [25]:

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

where, V is the supply air volume of the tracking air cooler (m^3/s), Δt is the temperature difference of airflow between the outlet of the tracking air cooler and the worker ($^{\circ}\text{C}$).

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:

$$v_l = \frac{0.48V/S}{al/d_0 + 0.147} \quad (13)$$

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. Fluid dynamics simulation of the non-homogeneous thermal environment

4.1. Geometric model and boundary conditions

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

- (a) Airflow was assumed as incompressible, and the heat dissipation caused by the work of the viscous force of the fluid is negligible.
- (b) Airflow field of the face is uniformly distributed in the vertical direction.
- (c) Irregularity of the mining wall has no impact on airflow.
- (d) The airflow is entirely turbulent and satisfies the Boussinesq assumption.

According to the above assumptions, the working surface can be simplified into a two-dimensional space. The geometric model is shown in Fig. 4, based on an actual fully mechanized coal face. This case was independent of that in section 2.2. The heat exhaustion of the mine face for this case was more serious than that in section 2.2. The length and width of the intake and return airways were both 70 m and 4 m. 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. To simplify the simulation, other mechanical equipment was not taken into consideration.

Quadrilateral grid cells were generated by an integrated computer engineering and manufacturing code (ICEM, version 18.0.0) for CFD. A total of 100 thousand grids were created, and the average grid size was 3.5 cm. Three different quantities of grids, i.e., 50 thousand, 100 thousand, and 300 thousand, were adopted to conduct grid independence analysis. There were slight differences in the airflow temperature between the three quantities of grid cells, and the deviation was less than 10%. Hence, the grid cells were sufficiently adequate for all the numerical solutions. To capture the near-wall effect, the grids near the mine face walls and the shearer were refined. All the values of y^+ of the first near-wall grids were less than five.

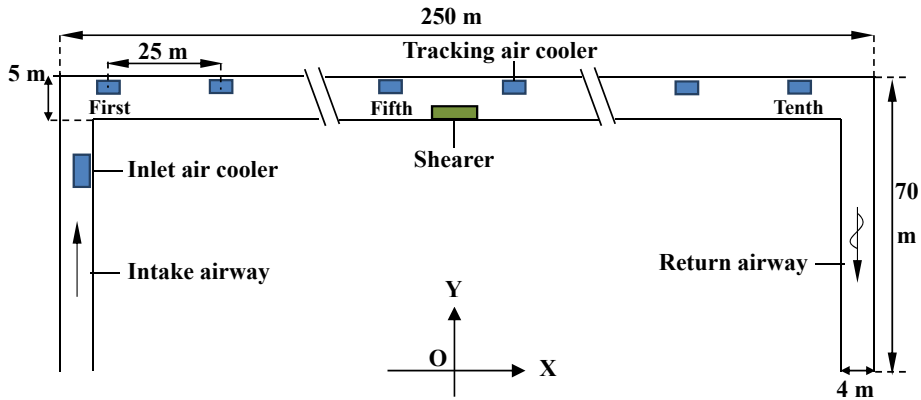


Fig. 4. Geometric model of the mine face for CFD simulations

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

$$\nabla \cdot \rho \mathbf{U} = 0 \tag{14}$$

$$\nabla \cdot \rho \mathbf{U} \mathbf{U} = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} \tag{15}$$

$$\nabla \cdot (\rho c_p \mathbf{U} T) = \nabla \cdot \left(\kappa_{eff} + \frac{c_p \mu_t}{Pr_t} \right) \nabla T \tag{16}$$

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 ($\text{W/(m}\cdot\text{K)}$), T is the air temperature (K), and Pr_t is the turbulent Prandtl number.

The airflow inside the mine face was turbulent, and the RNG $k-\epsilon$ model was used for turbulence modelling. The previous study indicated that the simulation results for the RNG $k-\epsilon$ model were closest to the experimental data [27]. The boundary conditions of temperature, heat flux, and airspeed are shown in Table 1. The temperature of the mining wall was higher than

TABLE 1

Boundary conditions of the CFD simulation

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

that of the airflow, and the wall dissipated heat to the airflow. The temperature and airspeed of the airflow for the tracking and inlet air coolers were estimated by the equations in the second and third sections of this study.

All the variables were discretized using the second-order upwind scheme. The pressure and velocity were coupled by the Semi-Implicit Pressure-Linked Equation (SIMPLE) algorithm. Each simulation required approximately two thousand iterations for convergence tolerance of $1.0E-6$ for all variables. The Fluent software was adopted to solve the governing equations.

4.2. Numerical results

In this section, the cooling effect of this new cooling strategy was compared with that by the traditional cooling strategy. For this simulation, the new cooling strategy refers to the cooling task by both the inlet and tracking air coolers, while the traditional cooling strategy refers to that only by the inlet air cooler. Fig. 5 presents 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 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.

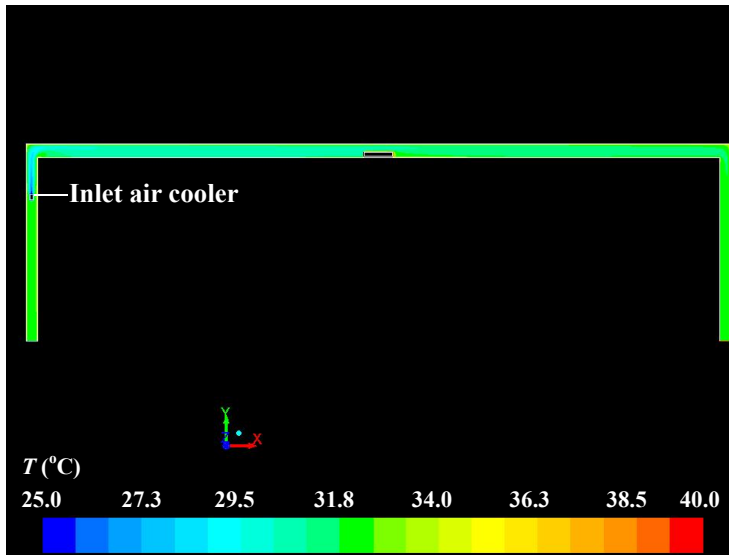
Figs. 6 to 8 compare the temperature distribution in the mine face when the worker moved to the control area for different tracking air coolers. Fig. 6(b) shows the airflow temperature versus the displacement of the mine face when the worker entered the control area of the first tracking air cooler. The airflow temperature increased from 24.8°C to 28.5°C within 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 necessary cooling space was significantly improved.

When the worker moved to the control area of the fifth tracking air cooler (Fig. 7), the airflow temperature increased from 24.5°C to 28°C within 10 m. The fifth tracking air cooler was near the shearer, the high temperature of the 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 temperature of the airflow within 10 m was significantly decreased, and the thermal environment for the workers was significantly improved. Similarly, when the tenth tracking air cooler worked (Fig. 8), the airflow temperature increased from 24.8 to 30°C within 15 m. The value of the airflow temperature at the outlet of the face was higher than in other places. This was mainly because the heat was aggregated at the return airflow corner in the face. 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.

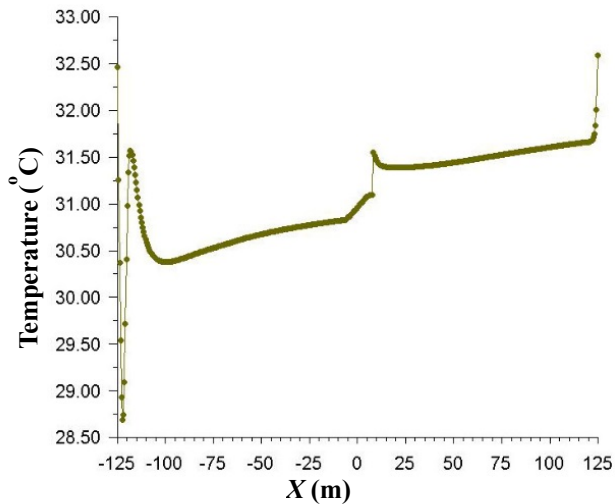
5. Discussion

5.1. Main findings of the current study

This study proposed to build a non-homogeneous thermal environment for highly effective cooling in the mine face. The results revealed that this new cooling strategy had significant



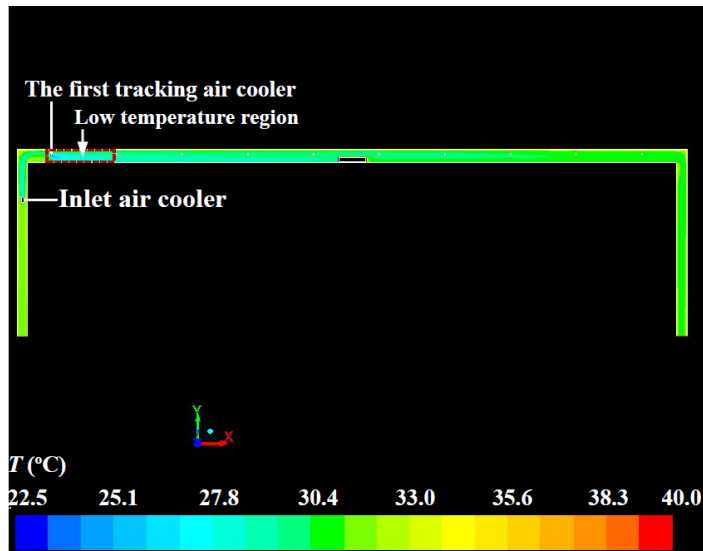
(a)



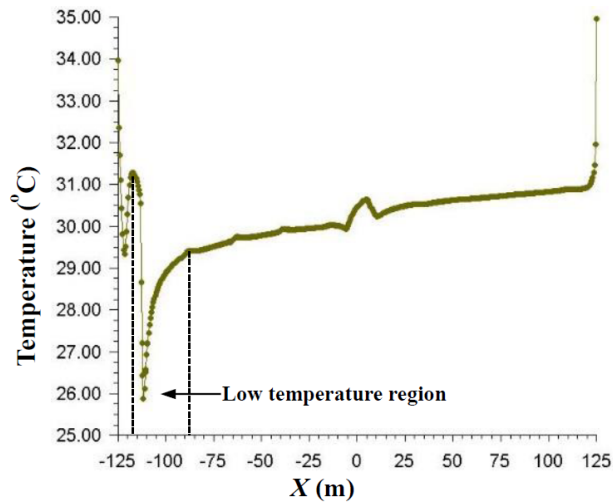
(b)

Fig. 5. Temperature distribution in mine faces cooled only by the inlet air cooler: (a) temperature contour; (b) variation of the temperature with the displacement

potential in saving energy in mine cooling and could improve the thermal environment for the workers. Although some previous studies reported plenty of cooling strategies, no prior published works of literature have considered focusing on the area occupied by workers and ignore the redundant cooling space in the face [3,22-24]. This new cooling strategy would be of help for energy-saving and thermal environment improvement for mine cooling.



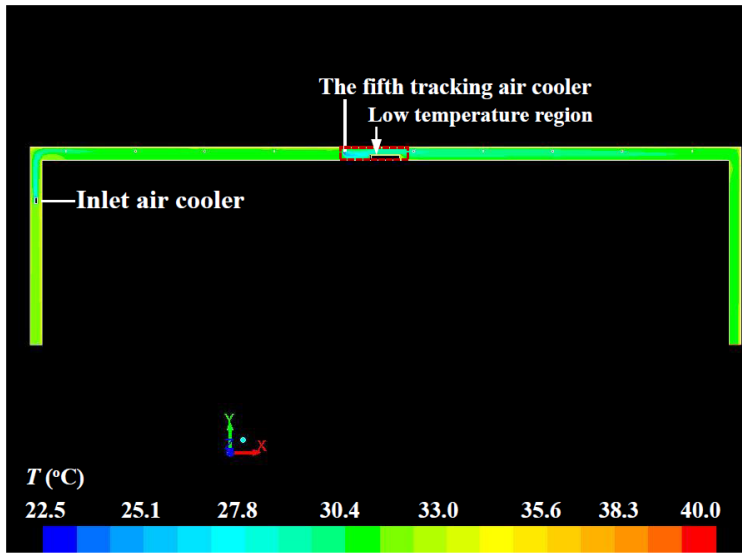
(a)



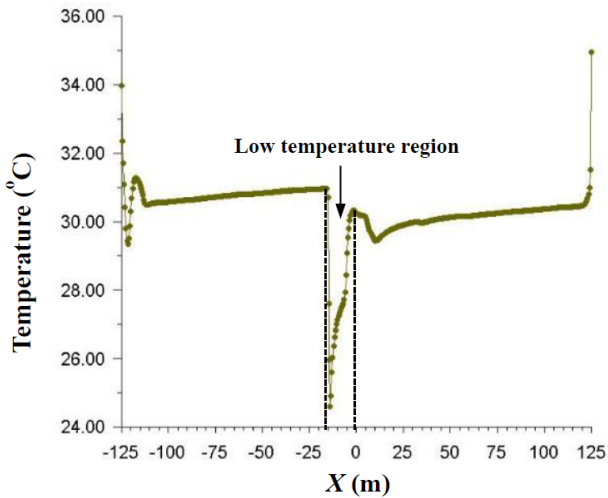
(b)

Fig. 6. Temperature distribution of airflow when a person entered the control area of the first tracking air cooler: (a) temperature contour; (b) variation of the temperature with the displacement

The concept of necessary cooling space was proposed in this study. Since the main purpose of mine cooling was to ensure personnel safety, the area occupied by workers was critical for cooling. In contrast, the redundant cooling space which had no workers was ignored in the study. After differentiating the necessary and redundant cooling spaces, it was convenient to determine the cooling area of the face and estimate the cooling load.



(a)

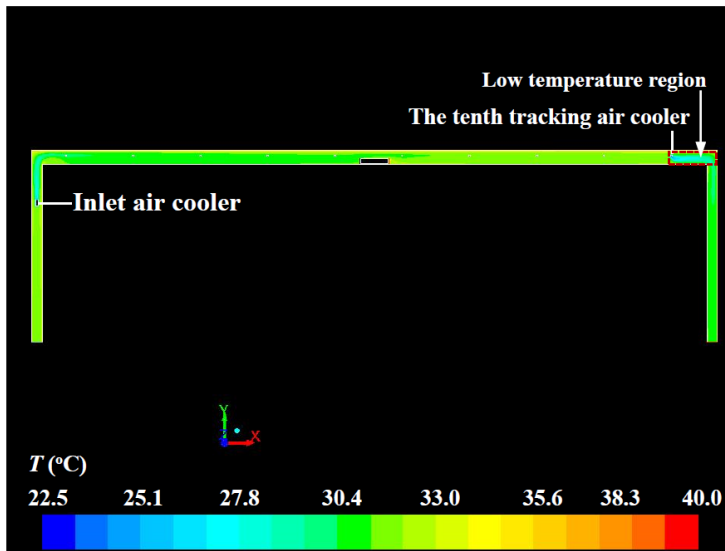


(b)

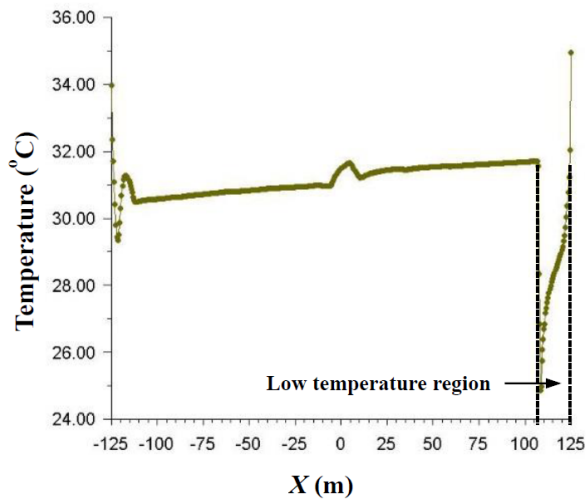
Fig. 7. Temperature distribution of airflow when a person entered the control area of the fifth tracking air cooler: (a) temperature contour; (b) variation of the temperature with the displacement

5.2. Limitation of this study

To build the non-homogeneous thermal environment in the face, the tracking cooler was designed to layout in the mine face. However, this layout mode was restricted by many conditions such as space, dust, mechanical damage and pipeline laying [28]. Dust could reduce the



(a)



(b)

Fig. 8. Temperature distribution of airflow when a person entered the control area of the first tracking air cooler: (a) temperature contour; (b) variation of the temperature with the displacement

cooling effect of the air cooler. As warm air contacted the coils of the heat exchanger, water film formed on its surface. This water film increases the adhesiveness of the dust on the coils. After running for a long time, the surface of the heat exchanger might be deposited by plenty of dust particles and the performance is decreased. In addition, the mine face was constantly moving, including the tracking air cooler to match the face. The removability of the air coolers and the

matched pipeline should be well designed. Further efforts are required to construct the tracking air cooler and test the practical application effect.

The validation of the cooling effect for this new cooling strategy was labour-intensive and capital-intensive. This study only conducted the numerical simulation to estimate the thermal environment of the mine face. In the future, further analysis is required to validate the energy savings and the improvement of the cooling effect by experimental research.

For simplification, the numerical simulation only conducted the case when the worker faced the tracking air cooler, and the cooler did not rotate. When a worker moved, the air cooler rotated and tracked them so that the air door was constantly facing the worker. The distance between the air cooler and the worker was longer than that when the worker faced the air cooler. More heat exchange between the cold air and the heat sources was produced. The airflow temperature at the location of the worker was higher than when the worker was facing the tracking air cooler. This investigation did not consider the above variations. Further analysis is required to clarify the above issues.

When a worker entered the control area of the tracking air cooler, the air cooler started to blow the cold airflow to the necessary cooling space for the worker. There was a dynamic cooling process in the necessary cooling space, and this process might last for several seconds before the stabilization of the air temperature. The numerical simulation was performed to estimate the cooling effect of this new cooling strategy, the stable temperature distribution of airflow in the mine face appeared more meaningful. For simplification, this simulation treated the cooling process as a steady-state. In conclusion, the dynamic variation of temperature distribution in the mine face needs investigating further.

6. Conclusions

This paper proposed to build a non-homogeneous thermal environment for energy savings in the mine face. The tracking air cooler was designed to track the workers for improving the thermal environment. The concept of necessary cooling space was proposed to determine the control 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 necessary 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 cooling strategy should be considered in the mine face.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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