The Spatiotemporal Evolution Patterns of Thermal Environment in Fully Mechanized Caving Faces of Deep Mine

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Abatract：With the increase in mine depth, the original rock temperature rises under the influence of the geothermal gradient. High temperature surrounding rock heat dissipation leads to an increase in working face temperature, seriously affecting mining production safety. Using distributed fiber optic temperature measurement to study the thermal characteristics of the working face during production, maintenance, and shutdown.The results show that during production, the working face airflow temperature exhibits a "V"-shaped trend, decreasing first and then increasing, while during maintenance, it shows an "L"-shaped trend with an initial decrease followed by stabilization. The air cooler in the intake airway significantly reduces the airflow temperature during production, with a maximum cooling power of 1260 kW, a cooling range of 9.5°C, and an effective cooling length of 150 m for a single air cooler. During production, in the range of 105 m from the upper end of the working face, the temperature rise rate is faster at 0.04°C/m, while in the range of 105 m to 270 m, the average temperature rise rate is 0.02°C/m. The cooling load for the 2302N working face during production and maintenance is calculated as 239.79 kW and 159.86 kW, respectively, determining the need for three sets of cooling devices at distances of 65 m, 140 m, and 230 m from the upper end of the working face. This research provides theoretical support for optimizing temperature control strategies and heat hazard management processes on the working face.

Key words: *High temperature mine; fully mechanized caving face; air flow temperature; high temperature heat damage; convection heat transfer*

1. Introduction

With the increasing depth of coal mining, the rise in ground temperature has led to the increasingly serious issue of heat hazards in mines, significantly impacting the safety of mine production [1,2]. The exchange of heat between the mine airflow and underground heat sources through convection heat transfer, thermal conduction, and thermal radiation increases the heat content of the airflow, affecting the working face environment[3].

The mining activities at the face cause changes in heat dissipation from the heat source, and the thermal environment of the working face changes accordingly. During the production period of the working face, the coal cutter operates to expose the fresh coal body, and the stripped coal body is transported out of the working face by the scraper conveyor. The exposed fresh coal body has higher temperature, and through convective heat exchange with the wind flow, the heat of the working face increases. With the movement of the coal cutter, the area of the exposed fresh coal wall gradually increases, and the heat exchange area between the fresh coal wall and the wind flow gradually increases, resulting in a dynamic increase in the heat of the working face. During the maintenance period of the working face, the coal cutter stops running. The temperature of the coal wall gradually decreases under the effect of prolonged ventilation, and the temperature difference between the wind flow and the coal wall changes dynamically, and the ambient temperature of the working face also changes dynamically.

Therefore, analyze the type of heat source and heat exchange mode of high geothermal comprehensive discharge face, test the temperature of wind flow under different states of comprehensive discharge face on site, analyze the change rule of wind flow temperature in time and space, get the temporal and spatial heat dissipation characteristics of the heat source of the comprehensive discharge face, and provide theoretical basis for the arrangement of cooling system in high temperature mines [4].

Scholars both domestically and internationally have conducted relevant research on the variation patterns of airflow in high-temperature mines. Zhou Xihua et al. studied the coupling mechanism of airflow field and temperature field, analyzed the impact of the shearer on the airflow in the mining face, and determined the variation pattern of the airflow temperature in mine recovery working faces[5,6]. Yi Xin et al. analyzed the influencing factors of seasonal heat hazards in mines, proposed the concept of seasonal heat hazards, and classified them into four categories based on the size of the original rock temperature [7]. Ma Heng calculated the temperature of different types of roadway airflow, compared the measured temperature of roadway airflow with the calculated results, and obtained a calculation method suitable for mine temperature calculation [8]. Qiang et al. constructed a simulated roadway experiment platform using concrete based on similarity theory, experimentally studied the unstable heat transfer coefficients of surrounding rocks under different wind speeds and ventilation conditions, and derived a calculation model for the temperature of the original rock layer at different depths [9]. Zhou simulated and analyzed the cooling effects of six different fan arrangements using ANSYS Fluent, evaluating the cooling efficiency of each model based on the average temperature of the roadway cross-section, the three-dimensional distribution of roadway temperature, and velocity streamlines [10]. Guo numerically simulated the airflow temperature on the working face of two ventilation systems, established a heat transfer model between the surrounding rocks and the airflow, and analyzed the heat transfer characteristics between the airflow and surrounding rocks on the working face under different ventilation modes [11].

Mining depth leads to an increase in the heat released by the mine, making the thermal environment on the airflow working face more severe. For more efficient heat hazard management, it is essential to understand the variation patterns of airflow temperature on the working face. Determining the areas with the greatest impact on airflow temperature and providing a theoretical basis for the optimal allocation and layout of the cooling system are crucial [12-14]. This study conducts on-site observations of the airflow temperature on the working face intake air, working face airflow, and return airway airflow using fiber optic temperature measurement technology. The analysis focuses on the variation characteristics of airflow temperature on the working face during normal production and shutdown maintenance periods, as well as under different air cooler operating conditions. This research aims to identify efficient cooling methods applicable to the working face.

2 Overview of working face

The 2302N fully mechanized mining face is located at the -810 level, with a length along the strike of 1562 m and an inclined length of 270 m. The working face adopts the positive full-negative pressure ventilation method with the intake air from the upper flat roadway and the return air from the lower flat roadway. The total air volume of the 2302N working face is 2391 m^3/min. According to the thermal environment analysis of the mine, the main sources of heat include heat dissipation from the surrounding rocks, heat dissipation during the transportation of coal and gangue, heat dissipation during the operation of mechanical equipment, heat dissipation from water influx, and heat dissipation from the old goaf. To address the high-temperature heat hazards on the working face, a centralized underground cooling system is employed. Φ219 pipelines are installed in the upper roadway of the working face, and four 450 kW air coolers are installed in the intake airway to cool the airflow. The flow rate of the cooling water is 141 m^3/h, with a velocity of 1.06 m/s. Φ159 pipelines are installed in the lower roadway of the working face. Three 300 kW air coolers are installed 230 m south of the cutting eye in the lower flat roadway, and 1 300 kW air cooler and 1 450 kW air cooler are installed 200 meters north of the first conveyor belt junction and at the conveyor head, respectively. The water flow rate in the cooling pipeline of the lower flat roadway is 143 m^3/h, with a velocity of 1.73 m/s.

3 Field test method

3.1 Observation object and method

To study the variation patterns of airflow temperature on the fully mechanized mining face in high-temperature mines, fiber optic temperature measurement is arranged along the direction of the airflow from the intake airway to the return airway end on the working face. The airflow temperature during normal production and shutdown maintenance periods on the working face is monitored continuously for five days, and relevant data are recorded. The production status of the working face during the testing period is shown in Table 1.

July 30 and July 31 are the normal production period of the working face, and there are four shifts during the normal production period, from 0:00 to 12:00 is the production period of the working face, and from 12:00 to 24:00 is the maintenance period of the working face. on August 1 and August 2 is the time of stoppage of mining and maintenance of the working face, and the working face is in the state of stoppage of production in the period of this date.

Table.1 Working teams during monitoring

Date / Time	July 30	July 31	August 1st	August 2 st	August 3 st
0:30	Production time	Production time	Shutdown maintenance		Production time
6:30	Production time	Production time			Production time
12:30	Repair time	Repair time			Repair time
18:30	Repair time	Repair time			Repair time

3.2 Temperature measuring optical fiber layout scheme

The working face fiber optic temperature measurement system consists of pulse laser, WDM, temperature sensing fiber, APD (Avalanche Photodiode) photodetector, 16-bit high-speed data acquisition card and signal processing system. The temperature sensing fiber optic cable is connected to the underground DTS substation, and the DTS substation realizes the demodulation of temperature signals, display and storage of the results, and then sends the collected temperature information to the monitoring host in the uphole safety monitoring center via the industrial Ethernet ring network under the mine, and the temperature measurement system is shown in Figure 1.

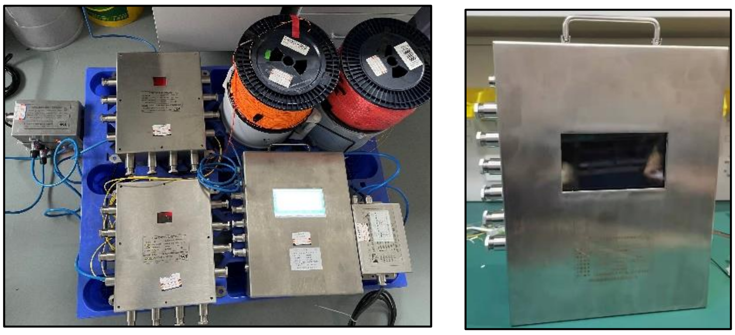


Figure.1 Distributed Fiber Optic Temperature Measurement System

The temperature-sensitive optical cable is deployed starting from the intake airway and then enters the working face, forming a "U"-shaped arrangement. The temperature-sensitive optical fiber is fixed at the front end of the bracket, leaving a 0.8m margin between each bracket to facilitate the movement of the working face and ensure the smooth progress of temperature measurement work. The light arrangement is shown in Figure 2.

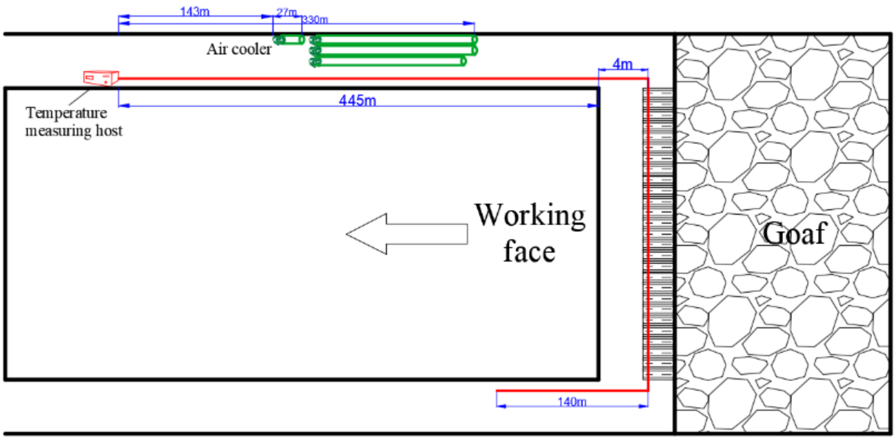


Figure.2 Layout of distributed optical fiber temperature measurement system at working face

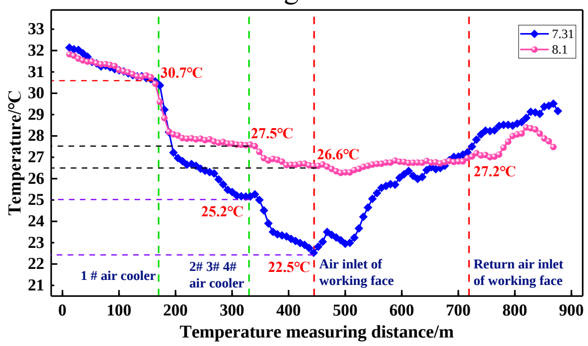
The distributed fiber optic temperature measurement host is installed at a distance of 445m from the intake corner of the working face. The temperature-sensitive optical fiber is deployed from this point along the direction of the airflow on the working face, positioned at the front end of the working face bracket. The temperature-sensitive optical fiber is 4.1m away from the front coal wall and has a deployment length of 270m on the working face. After passing through the working face, it transitions to a deployment length of 140m in the return airway. In the intake airway of the working face, three air coolers are installed to cool the intake air. The outlet position of the air duct of the 1st air cooler is 170m away from the temperature measurement host, and the outlet positions of the air ducts of the 2nd, 3rd, and 4th air coolers are 330m away from the temperature measurement host.

4 Results and discussion

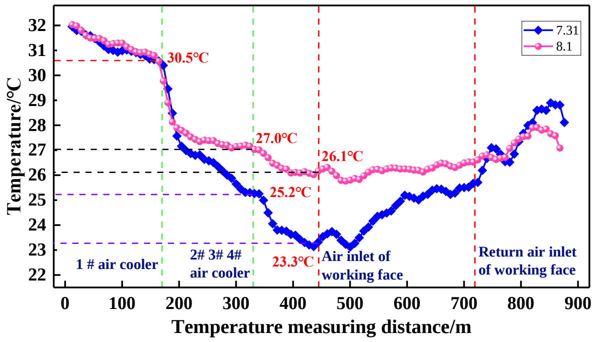
4.1 Variation law of air flow temperature in working face

4.1.1 Overall air flow temperature distribution of working face

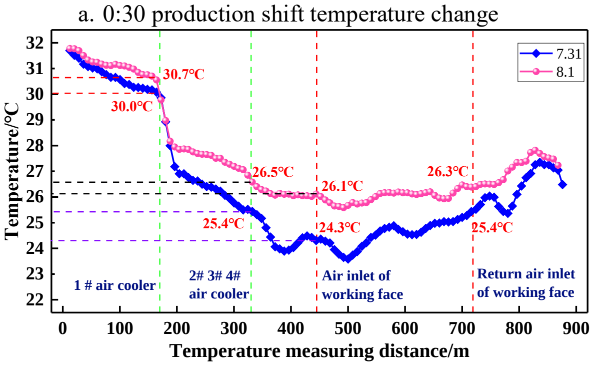
Comparative analysis of wind flow temperatures at four moments during July 31 and August 1 shows the variation in Figure 3.



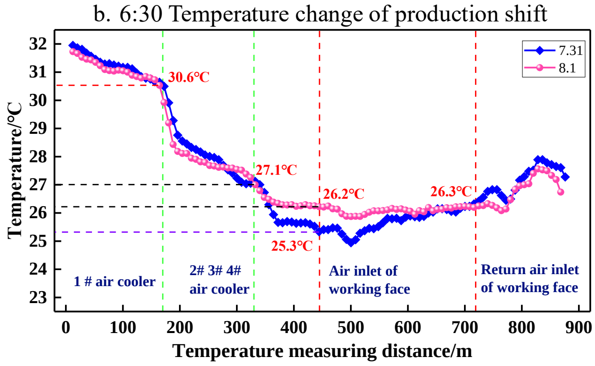
a. 0:30 production shift temperature change



b. 6:30 Temperature change of production shift



c. 12:30 Temperature change of maintenance shift



d.18:30 Temperature change of maintenance shift

Figure. 3 Overall temperature distribution of working face

During production, the temperature variation of the airflow from the intake airway to the return airway exhibits a "V-shaped" distribution trend. In the working team during production, the "V" shaped variation of the airflow temperature is even more pronounced. During production, the coal-cutting machine on the working face operates to cut the coal wall, exposing fresh coal. The temperature difference between the freshly exposed coal and the airflow on the working face is significant. According to Newton's cooling law, the temperature difference between fluid and solid is a primary factor affecting convective heat transfer efficiency. Therefore, the heat dissipation from the freshly exposed coal wall causes an increase in the temperature of the airflow on the working face.

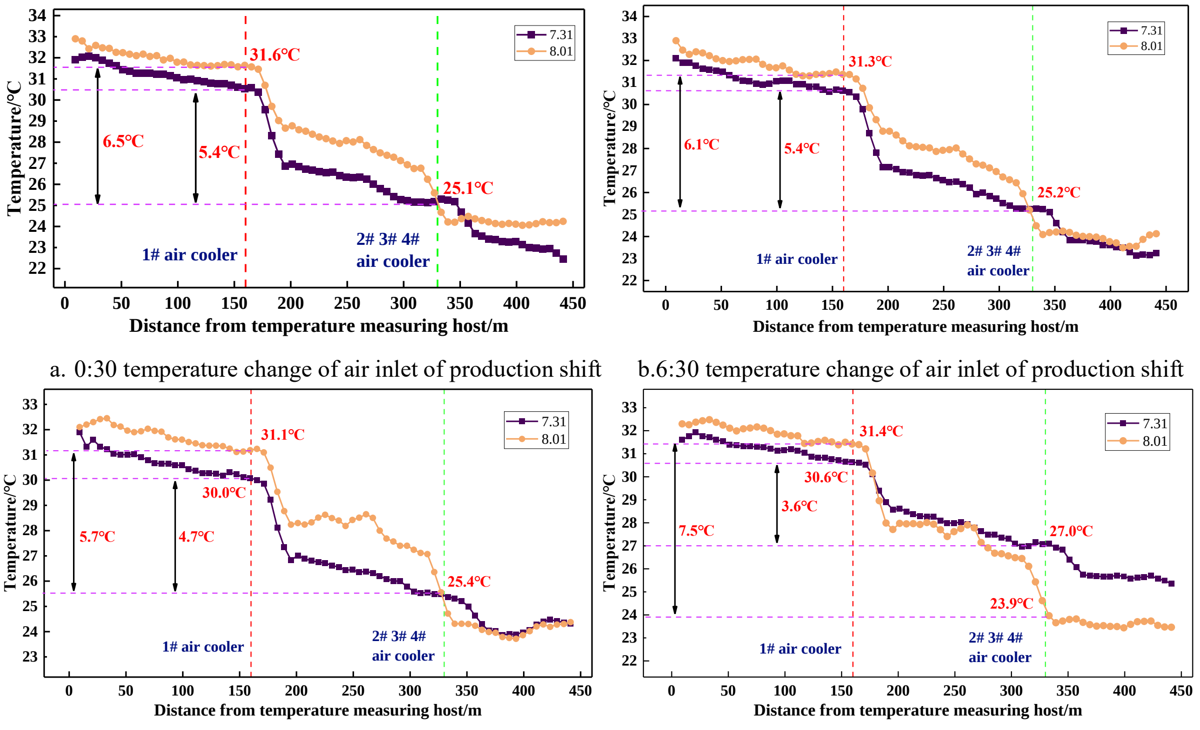
During maintenance shifts, the intake air temperature from the intake airway to the upper end of the working face airflow is essentially the same as that during production shifts. However, the temperature rise of the airflow after entering the working face is slower compared to the temperature rise during production. Contrasting the temperature of the airflow during the early stages of the maintenance shift and after 6 hours, the temperature rise of the airflow on the working face gradually decreases. During the shutdown period on the working face, the airflow temperature exhibits an "L"-shaped trend. After passing through the air cooler in the intake airway, the airflow temperature decreases.

Upon entering the working face, the airflow temperature remains relatively constant. The temperature difference between the inflow and outflow airflow on the working face is at most 0.7°C. Interestingly, the temperature of the airflow increases after entering the return airway of the working face.

During the maintenance shift, the working face is in a relatively static state, and the intake air temperature on the working face is relatively stable. The coal wall on the working face stops being exposed, and the temperature difference between the airflow and surrounding rocks gradually decreases with ventilation time, resulting in a mild weakening of convective heat transfer between them. In the early stages of maintenance, the airflow temperature on the working face continues to rise gradually along the flow direction. However, as the maintenance time increases, the temperature rise along the airflow path slows down and essentially stabilizes. Comparing the airflow temperatures on August 1st and July 31st at 18:30, they are basically the same. After about 12 hours of coal cutting machine shutdown during the production period, the heat dissipation from the working face coal wall stabilizes, and the temperature of the airflow entering the working face essentially stabilizes.

4.1.2 Air flow temperature distribution in air inlet roadway of working face

In the intake airway from the self-measured temperature initial point to the upper end of the working face, four air coolers are installed to cool the airflow. The variation pattern of the airflow temperature in the intake airway is illustrated in Figure 4.



a. 0:30 temperature change of air inlet of production shift

b.6:30 temperature change of air inlet of production shift

c.12:30 temperature change of air inlet of maintenance time

d.18:30 temperature change of air inlet of maintenance time

Figure.4 Temperature change of air inlet roadway in working face

During the production period of the working face, the air coolers in the air intake lane were in continuous full power operation; during the maintenance period of the working face, the air coolers in the air intake lane were affected by the maintenance, and some of them were in the shutdown state, which resulted in a smaller decrease of the temperature of the wind flow in the air intake lane. As a result, the temperature of airflow at 340m position was different on different dates.

It can be observed that the airflow temperature measured from the temperature measurement host position is 32°C. Within the range from the temperature measurement host to the position of the 1st air cooler, the airflow temperature experiences a slight decrease. After passing through the 1st air cooler, the temperature dramatically decreases over a short distance. In the 26m range from the air cooler outlet, the temperature drops from 30.7°C to 27.2°C. The temperature further decreases after passing through the 2nd, 3rd, and 4th air coolers. The outlet of the air coolers adopts an extended air duct, and the air duct outlet extends to 115m from the working face. When the airflow reaches the intake end of the working face, the temperature drops below 26°C. According to the design parameters of the air coolers, the energy for handling the airflow volume of a single air cooler is 550 m^3/min. With a designed working face airflow of 2391 m^3/min, simultaneous operation of the four air coolers can achieve a full airflow cooling in the intake airway. The temperature of the airflow entering the working face stabilizes at 25°C. Taking the temperature change at 0:30 during normal production on the working face as an example, the airflow temperature decreases by 1.4°C from the temperature measurement point to the outlet of the 1st air cooler. During the same time in the maintenance shift on the working face, the airflow temperature decreases by 1.3°C. After passing through the 1st air cooler and until the next group of air coolers, the airflow temperature decreases by approximately 6°C. After passing through the 2nd, 3rd, and 4th air coolers, the temperature further decreases. The temperature reduction is more significant during the production shift on the working face, and the airflow temperature remains stable before reaching the upper end of the working face. The refrigeration and cooling power of the air coolers in the intake airway of the working face is calculated based on the temperature reduction, airflow, and the calculated cooling amount in the intake airway.

Based on the principles of heat transfer and the law of mass conservation, the formula for calculating the cooling capacity of the airflow is obtained, as shown in Equation 1[15,16].

$$Q_J = q \times \rho \times C_p \times \Delta t \tag{1}$$

q, Airflow, m^3/h；ρ, Air density, kg/m^3；C_p, Specific heat capacity of air, J/(kg/°C); △t, 空冷器进出口风流温度，℃。

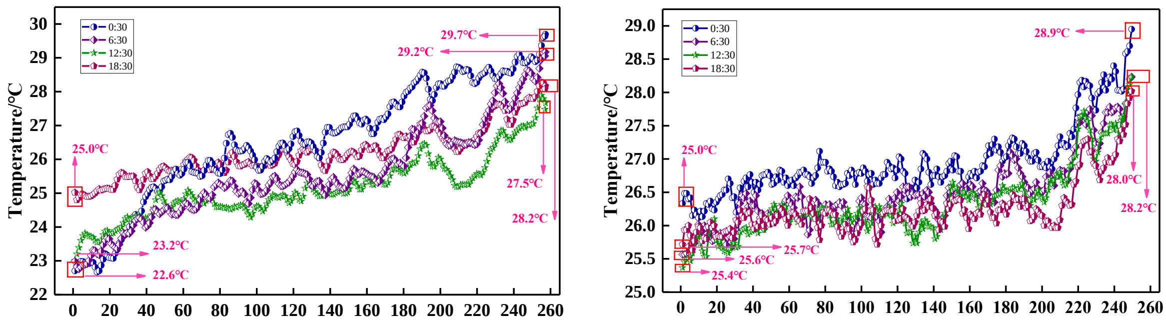
According to the inlet airflow temperature and outlet airflow temperature of each air cooler monitored by the distributed fiber-optic temperature measurement system, calculate the temperature difference △t of the airflow of a single air cooler, q choose the rated airflow of a single air cooler, 10.83 m^3/s; C_p choose1000 kJ/ (kg·K), and calculate the cooling capacity of the air cooler according to Equation (1). Calculate the refrigeration power of each air cooler in the air inlet lane of the working face, and the sum of the refrigeration power of each air cooler is the total refrigeration capacity.

Table 2. Total Cooling Capacity of the Air Coolers in the Intake Airway During Different Periods

Date \ Time		0:30	6:30	12:30	18:30
7.31	Temperature Difference of the Airflow Before and After Cooling /°C	6.5	6.1	5.7	7.5
	Total Cooling Capacity of the Air Coolers×10^3/W	1092.0	1024.8	957.6	1260.0
8.01	Temperature Difference of the Airflow Before and After Cooling /°C	5.4	5.4	4.7	3.6
	Total Cooling Capacity of the Air Coolers×10^3/W	907.2	907.2	789.6	604.8

4.1.3 Air flow temperature distribution in mining face

After passing through the upper end, the airflow enters the working face. During the mining process on the working face, the airflow temperature continues to rise due to mining influences. The airflow temperature variation curves during the production shift and maintenance shift on the working face are shown in Figure 5.



a. July 31st　　　　b. August 1st

Figure 5. Changes in the Airflow Temperature on the Working Face During Production and Maintenance Periods

During the flow process, the temperature of the airflow gradually rises. At the upper end, it reaches a minimum of 24.83°C, while at the lower end, it reaches a maximum of 32.59°C. The maximum temperature difference between the upper and lower ends can reach 7.76°C, with a maximum average temperature rise rate of 0.030°C/m. During the maintenance shutdown period, the minimum temperature difference between the upper and lower ends is only 2.1°C, with an average temperature rise rate of 0.008°C/m. During the shutdown maintenance period, the temperature difference between the two ends of the working face gradually decreases with the extension of the shutdown time, stabilizing at around 2.2°C. After normal production is resumed, the temperature difference between the two ends gradually increases, reaching 6.5°C after 2 days, close to the level during normal production. During the maintenance shift in normal production, the temperature difference between the two ends of the working face is around 4°C, which is 2.5°C lower than during mining. The temperature of the airflow on the working face during the coal mining shift is higher than during the maintenance shift, and the minimum temperature occurs during the maintenance shutdown period. The temperature rise trend during normal coal mining on the working face is steeper, while it is more gradual during the maintenance shutdown period. Therefore, the heat generated by the electrical equipment on the working face and the heat generated by the coal cutting process are the main sources of heat on the working face, which is the primary factor for the continuous temperature rise [17,18].

Table.3 Temperature difference and average heating rate at both ends of the working face

Classification	Time	July 30th	July 31th	August 1st	August 2st	August 3st
Average heating rate	00:30	0.029°C/m	0.027°C/m	0.011°C/m	0.012°C/m	0.024°C/m
	06:30	0.030°C/m	0.023°C/m	0.008°C/m	0.016°C/m	0.025°C/m
	12:30	0.018°C/m	0.016°C/m	0.009°C/m	0.015°C/m	0.016°C/m
	18:30	0.019°C/m	0.012°C/m	0.008°C/m	0.012°C/m	0.016°C/m

July 31st is a normal working day for the working face. Comparing the temperature distribution of the working face during production and maintenance periods, the overall temperature of the working face shows a noticeable increasing trend during production. On August 1st, during the shutdown period of the working face, the temperature variation trend is relatively stable within the first 220m in front of the 2302 working face, with a gentler temperature rise compared to the production period. Within a thickness of 40m on the working face, there is a significant increase in the airflow temperature. During the shutdown period, the main heat sources on the working face are the heat dissipation from the working face coal wall and the temperature rise caused by air leakage from the goaf. The temperature rise of the airflow within the first 210m in front of the working face is due to the heat dissipation from the coal wall, and the high-temperature airflow carried by the air leakage from the goaf within the last 50m behind the working face mixes with the working face airflow, causing an increase in the airflow temperature.

The heat added by the airflow when passing through the working face can be calculated using the following formula[19-21]:

$$Q_G = m \cdot C_p \cdot \left(T_{out} - T_{in}\right) \quad (2)$$

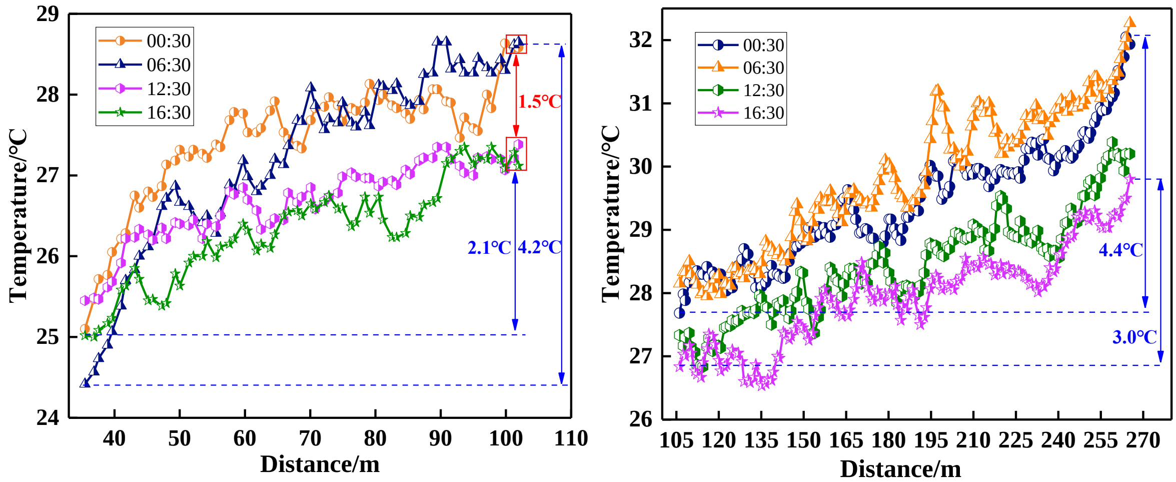
Q is the heat added by the airflow, W; *m* is the mass flow rate of the airflow, kg/s; C_p is the specific heat at constant pressure of the airflow，kJ/(kg·°C); T_{in} is the temperature of the incoming airflow, °C; T_{out} is the temperature of the outgoing airflow, °C.

In high-temperature fully mechanized mining faces, the temperature exhibits varying heating rates along the ventilation direction during production. Within the 105m range in front of the working face, the temperature rise rate is faster due to the significant temperature difference between the airflow and the coal wall. The maximum temperature rise rate during a production shift is 0.04°C/m. As the airflow moves along the working face, the temperature gradually increases, resulting in a gradual decrease in heat transfer generated by convective heat exchange, leading to a slowing down of the temperature rise rate.

Table 4. Heat Gain in Ventilation at Different Working Faces Over Time

Date(7.31)		Inlet and Outlet Airflow Temperature Difference /°C	Wind flow increases the heat /W	Date (8.01)		Inlet and Outlet Airflow Temperature Difference /°C	Wind flow increases the heat /W
Time	0:30	7.1	6378.5	Time	0:30	3.9	3503.7
	6:30	6.6	5929.3		6:30	2.6	2335.8
	12:30	4.3	3863.0		12:30	2.8	2515.5
	18:30	3.2	2874.8		18:30	2.3	2066.3

In the range of 105m to 270m along the working face, influenced by air leakage from the goaf, the average temperature rise rate of the working face airflow is 0.02°C/m. To accurately analyze the cascading temperature rise characteristics of the working face, the temperature variation along the airflow direction can be divided into two segments. Analyzing the temperature in these two segments separately is illustrated in Figure 6. According to the temperature variations in these two segments, it is observed that the primary cause of airflow temperature rise in the first segment is the heat and moisture exchange resulting from the exposure of fresh coal walls during the mining process. In the second segment, the high-temperature heat carried by air leakage from the goaf is the main factor causing the temperature rise in the working face airflow.

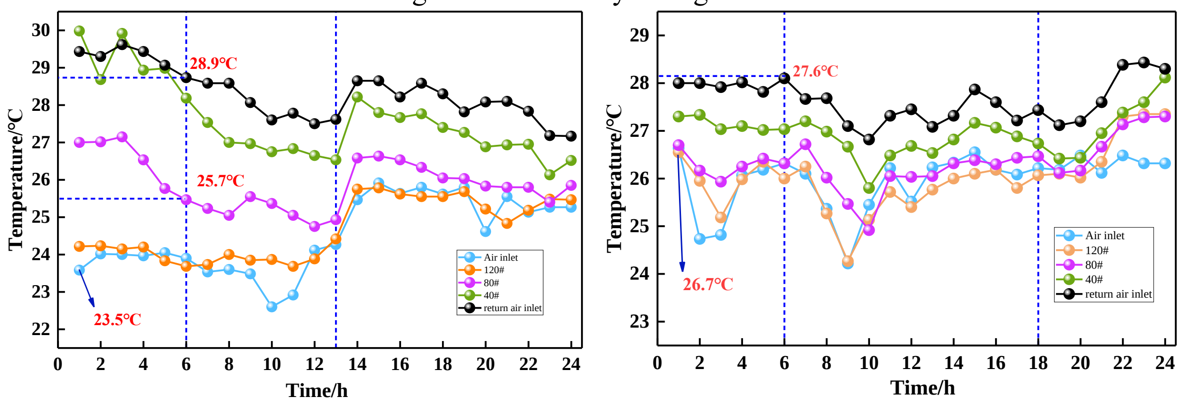


a. The first temperature rise step   b. Second temperature rise ladder section

Figure.6 Temperature Cascading Variation of Working Face Airflow During Production

4.2 Air flow temperature of working face changes with time

Select the upper end, the 40th, the 80th, the 120th and the lower end of the working face as the monitoring points, and the temperature change data of each measuring point within 24 hours to obtain the change of air flow temperature with time as shown in Figure 7. The temperature change of the working face at five measuring points in four different days shows a trend of low temperature at the upper end and high temperature at the lower end. The temperature rising trend in the upper end area of the 80 frame of the working face is relatively slow, and the temperature rising speed from the 80 frame to the lower end area is accelerated. On the 30th of July, the air flow temperature of the working face is affected by the cooling effect of the air cooler in the air inlet tunnel. The air flow temperature is relatively low, and the air flow pressure in the initial section of the working face is relatively high. The heat in the goaf is affected by the air flow pressure, which makes it difficult to gush out. When the air flow enters the working face, the moisture content is relatively low, and the convection heat transfer between the air flow and the coal wall of the working face is relatively strong.



a. July 31   b. August 1

Figure.7 Time varying curve of wind temperature at different positions of working face

In the process of air flow along the front of the working face, in addition to the convective heat transfer with the coal wall of the working face, because the coal body of the working face is relatively wet, the convective mass transfer is generated by the differential pressure of water vapor, and the latent heat exchange occurs between the high temperature coal wall and the air flow. The friction resistance between the air flow and the working face wall causes the air flow speed to slow down near the coal wall, and the pressure of the air flow to decrease. When the air flow pressure and the air pressure in the goaf reach balance, the pressure of the working face air flow continues to flow downward and gradually decreases, resulting in the gradual emission of heat in the goaf, and the amount of emission gradually increases. At the same time, the heat and moisture exchange between the air flow and the heat source of the working face leads to the increase of the air flow enthalpy value, the decrease of the difference between the air flow temperature and the heat source temperature, and the reduction of the heat exchange efficiency, thus causing the air flow temperature of the working face to rise faster in the later stage.

Compared with the upper air temperature before the 120 # hydraulic support, the air temperature of the working face is less affected by the heat source of the working face. After the No. 80 hydraulic support, the temperature of the air flow is rising due to the impact of mining activities. During the shutdown period, the air flow temperature at each point of the working face gradually decreased with the increase of the shutdown time, and the temperature difference between the two ends gradually decreased, and gradually stabilized at 2.1 ℃ on August 1.

4.3 Distribution law of air flow and humidity in working face

The moisture content and relative humidity of the air flow are monitored along the path of the air flow in the working face, and the change trend is shown in Figure.8 and Figure.9. Before the air flow in the air inlet tunnel of the working face reaches the cooling area, the air flow from the wellhead to the air inlet tunnel is affected by the dust removal spray and the surrounding rock moisture exchange, and the air flow humidity gradually increases. When entering the air inlet tunnel of the working face, the air flow moisture content reaches 25g/kg, and the relative humidity reaches more than 80%. When the air flow passes through the air cooler in the air inlet tunnel, the temperature of the heat exchange pipe is lower than the air flow temperature, and the water vapor humidity on the pipe wall surface is lower than the air flow humidity, so the heat flow realizes cooling and dehumidification.

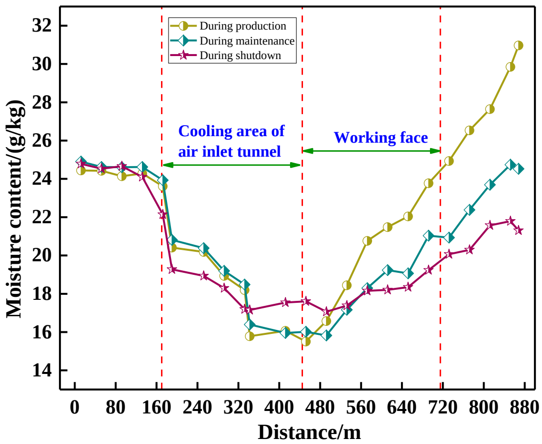


Figure.8 Air flow moisture content

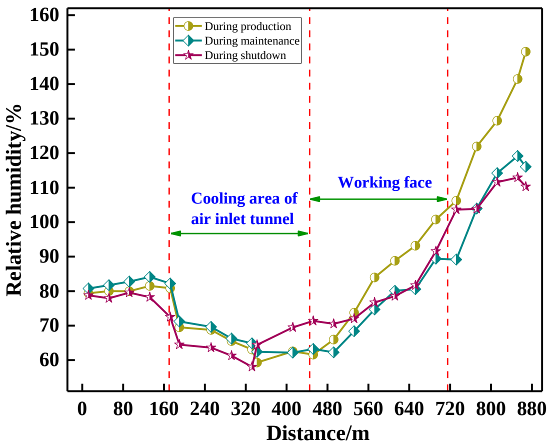


Figure.9 Relative humidity of air flow

In the process of air flow along the working face, the moisture content of the air flow and the moisture content of the surrounding rock wall have a large difference. At the same time, affected by the effect of temperature difference, the moisture exchange process between the air flow and the wet wall is intensified, resulting in the continuous increase of air flow humidity. In the area near the return air corner of the working face, affected by the air leakage in the goaf, the air flow inside the goaf flows into the working face and mixes with the air flow in the working face, resulting in an intensified trend of air flow humidity rise.

4.4 Heat variation law of working face

4.4.1 Change of air flow enthalpy at working face

The enthalpy of increase of the airflow represents the sum of heat increase of the airflow, and the distributed fiber optic in the paper measures the temperature is only the temperature change of the airflow caused by heat exchange. However, the humidity of the underground air is large, and the moisture exchange caused by the humidity difference will also cause the heat change of the wind flow. Therefore, it is necessary to use the enthalpy of the wind flow to represent the heat of the wind flow, which can more accurately grasp the change rule of the heat of the wind flow in different periods.

The air flow in the working face will be affected by the heat dissipation of surrounding rock, mechanical heat dissipation, and heat generated during coal cutting during the flow process, resulting in the change of air flow energy. The macroscopic performance is the increase of air flow temperature. The air flow enthalpy of the working face is measured and calculated during the production shift, maintenance shift and shutdown maintenance, as shown in Figure 10. The enthalpy value of the air flow before the air cooler is relatively stable. Around 170m, the specific enthalpy value of the air flow decreases rapidly due to the refrigeration of the first air cooler, and the enthalpy value decreases by 8kJ/kg. After being cooled by the other three air coolers at 330m, the air flow temperature decreased again, and the specific enthalpy of the inlet air reached the minimum value near the upper end. The operation of a large number of electrical equipment and coal cutting activities in the working face will release a large amount of heat, resulting in a significant increase in the specific enthalpy value of the air flow through the working face. The specific enthalpy value of air flow in the normal production shift is greater than that in the maintenance shift, and the specific enthalpy value of air flow in the maintenance shift is greater than that in the working face during the shutdown maintenance.

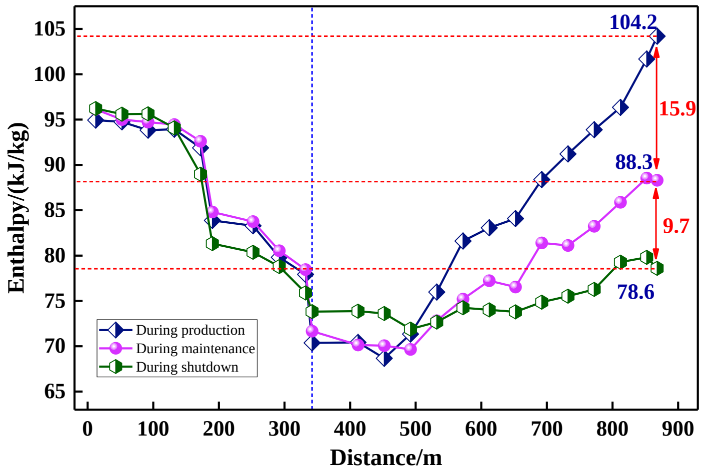
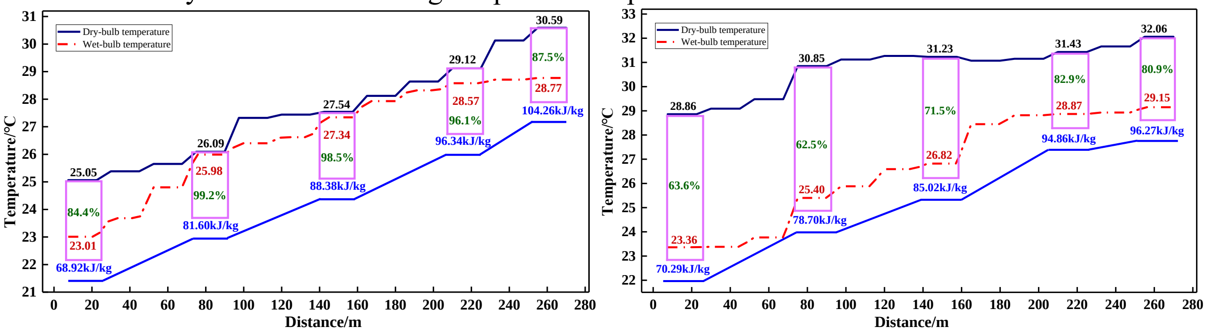


Figure.10 Air flow enthalpy value of working face

To comprehensively contrast the different variations in airflow heat during the production and maintenance periods, the inclination length of the working face is taken as the horizontal axis, and the airflow temperature as the vertical axis. This results in obtaining the heat variation along the working face during coal mining and maintenance.

During coal mining, there is a significant cascading temperature rise with a notable variation in dry bulb temperature. The wet bulb temperature is relatively close to the dry bulb temperature, and the relative humidity of the working face airflow is above 80%. In contrast, during maintenance, the variation in dry bulb temperature of the working face airflow is small. The airflow entering the initial section of the working face exhibits a distinct temperature rise, while the temperature variation in the later section becomes more gradual. The difference between dry bulb temperature and wet bulb temperature is significant, with the relative humidity of the incoming airflow at the working face being 63.6%, and the relative humidity of the return airflow from the working face being 80.9%. The air relative humidity is lower than during the production period.



a. During the coal mining period b. During the maintenance period

Figure.11 Changes in airflow heat under different conditions of the working face.

4.4.2 Calculation of Cooling Load on the Working Face

During production and shutdown periods, the types of heat sources and heat dissipation differ. During production, the increase in heat on the working face is primarily due to the detachment of fresh coal walls, leading to high coal wall temperatures. In contrast, during maintenance, the heat increase is mainly caused by convective heat exchange between the airflow and the coal wall, and the heat generated by convective heat exchange gradually decreases with the extension of ventilation time.

The intake airway of the working face is equipped with cooling air coolers. Based on temperature measurements using infrared thermometers at different times, the lowest air temperature entering the working face after passing through the intake airway cooling is 22.5°C. After entering the working face, the airflow temperature gradually increases. The temperature rise rates of the airflow during production and maintenance periods were obtained earlier.

Referring to the cascading temperature variations of the working face airflow during production and maintenance periods and considering the requirement in the "Coal Mine Safety Regulations" that the working face airflow temperature should not exceed 26°C, a zoning calculation for cooling load is performed. This calculation is applied to determine the cooling load in different zones within the working face during production and shutdown periods. According to the cooling cold load demand of different areas of the working face, the cooling air cooler is arranged in the corresponding area of the working face for supplying the cooling cold load of a single area, so it is necessary to determine the position where the temperature of the wind flow rises to 26°C as the air cooler layout position according to the calculated cold load demand and the temperature rise rate of different areas.

$$Q_Z = M_B\left\{\left(i_f - i_1\right) + \left(i_{11} - i_2\right) + \ldots + \left(i_{n-1,n-1} - i_n\right)\right\} \quad (3)$$

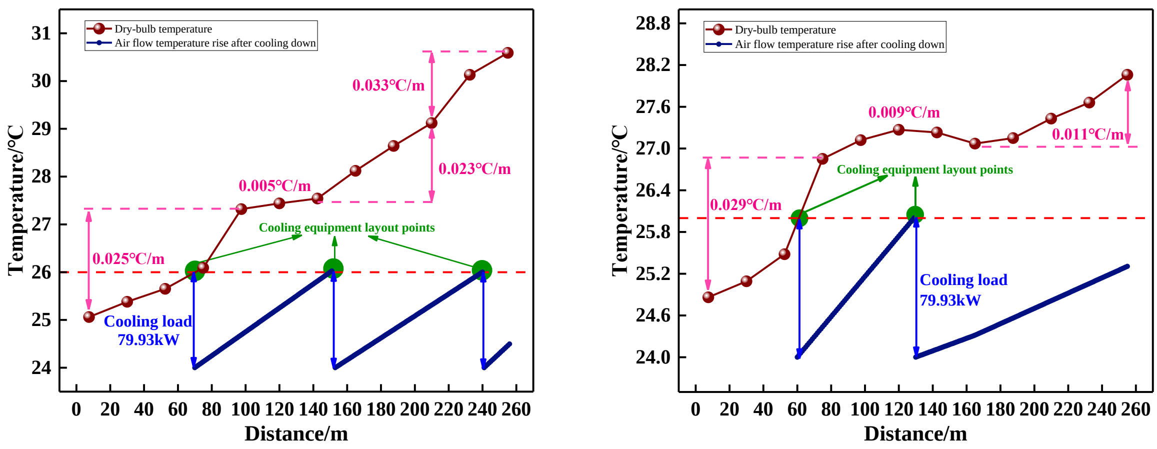
Based on the trend of working face airflow temperature changes during production and maintenance periods, the first cooling system is installed from the inflow of airflow at the working face to a position where the airflow temperature rises to 26°C. At this location, the airflow temperature is reduced from 26°C to 24°C. Considering the working face airflow rate and airflow state parameters, the calculated cooling load required to decrease the airflow temperature from 26°C to 24°C at a position 60m from the working face entrance is 79.93kW. Therefore, the first cooling system is installed at this location for refrigeration.

After the airflow temperature drops to 24°C, based on the airflow temperature rise rate, at a position 100m downstream of the first cooling system, the airflow temperature rises again to 26°C. At this location, the second cooling system is installed to reduce the airflow temperature from 26°C to 24°C. After passing through the second cooling equipment, the airflow temperature continues to rise as it flows along the working face. At a position 240m from the working face entrance, the airflow temperature reaches 26°C again, and the third cooling system is established at this location for cooling. During the production period of the working face, the positions for installing the three cooling systems are determined based on the different temperature rise rates of the airflow. The total cooling load for working face cooling during production is 239.79kW.

During the maintenance period of the working face, the airflow entering the initial section of the working face experiences a rapid temperature rise. At a distance of 60m from the intake, the airflow temperature rises to 26℃. At this position, the first set of cooling devices is installed to reduce the airflow temperature from 26℃ to 24℃. After passing through the first cooling system, the airflow continues to flow forward along the working face. After flowing for 70m, the airflow temperature rises again to 26℃. At this location, the second set of cooling devices is installed to cool the airflow. After passing through the second cooling system, the airflow continues to flow along the working face until the highest temperature in the return airway is below 26℃, meeting the thermal environmental requirements of the working face. During the maintenance period of the working face, a total of two sets of cooling devices are required to be installed, with a total cooling load of 159.86kW.

According to the cooling load and deployment of cooling devices during both production and maintenance periods on the working face, it is determined that three sets of cooling devices will be installed on the 2302N working face for cooling purposes. The first set will be placed at a distance of 65m from the working face intake, the second set at 140m, and the third set at 230m.

According to the working face during the production and cooling period of the need for cooling is not used, the principle of cooling economy for the principle of controlling the operation of the air cooler. During the production period, all three sets of cooling devices will be simultaneously activated to achieve cooling. However, during maintenance, only the first and second sets of air coolers will operate for cooling. Adjusting the operational status of the cooling systems based on the different states of the working face allows for better utilization of cooling capacity, enhancement of cooling efficiency, and reduction of cooling energy loss.



a. Cooling Load During Production Period

b. Cooling Load During Maintenance Period

Figure 11. Distribution of Cooling Load at Different Periods on the Working Face

5 Conclusion

In the deep coal mining process, the issue of heat damage caused by the influence of geothermal gradient on high-temperature surrounding rocks becomes increasingly severe. By understanding the temperature variation patterns of airflow along the working face during production and maintenance periods, and identifying the main causes of heat changes at different periods, this study determines the methods for cooling load and cooling device arrangement. Taking the 2302N fully mechanized mining face as an example, on-site experiments were conducted to obtain the temperature variation patterns of the working face airflow at different periods, cooling load, and the arrangement of cooling devices. The main conclusions are as follows:

(1) During the production period, the temperature of the airflow at the working face is distributed in a “V” shape, which is related to the heat dissipation from the freshly exposed coal wall, revealing the significant effect of the temperature difference between fluids and solids on the convective heat transfer efficiency. During the maintenance shift, the temperature increase of the airflow becomes slower because the working face is stationary, the temperature difference of the airflow is smaller, and the airflow is gradually stabilized after passing through the air cooler.

(2) In the air intake lane, the temperature of the wind flow experienced different degrees of cooling process. After passing through each air cooler, the airflow temperature showed a significant decrease, especially during the production shift, the air cooler had a more significant effect on the decrease of the airflow temperature. The temperature reduction between the temperature measurement point and the first air cooler was 1.4°C, while the subsequent air coolers further reduced the airflow temperature to ensure that the temperature at the entrance of the working face was stable.

(3) The temperature changes at different locations in the working face show a trend of gradual increase from top to bottom, and the changes of the airflow along the forward direction in the working face are not only affected by convective heat transfer, but also by humidity and water vapor pressure difference. The wet coal wall of the working face gradually increases the temperature of the wind flow through the mass transfer and latent heat exchange of the vapor. In addition, the frictional resistance in the working face slows down the wind flow velocity, leading to a reduction in the wind flow pressure, which further affects the exchange efficiency of heat and moisture, and thus accelerates the rise of the wind flow temperature at a later stage.

(4) According to the cold load demand in different areas, multiple sets of air coolers are distributed in the working face to control the airflow temperature within a safe range. During the production period, three air coolers were arranged at the working face according to the temperature rise rate of the wind stream to ensure that the temperature dropped from 26°C to 24°C. The cooling load was calculated accurately and adjusted according to the temperature rise rate of the wind stream. By accurately calculating the cooling load and adjusting the operating status of the cooling equipment, it is possible to optimize cooling efficiency and reduce energy loss. During maintenance, only the first two sets of air coolers are activated according to the temperature of the airflow, reducing energy consumption and ensuring that the temperature of the working surface meets safety standards.

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