ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20230306000405
Original scientific paper

Present Geothermal Field and Roadway Heat Damage Characteristics in Zhujidong Coal Mine Area of Huainan City, Anhui Province, China

Weijing YAO*, Jinxiu HAN, Yu LIU, Yongwen DENG, Jianyong PANG

Abstract: With the normalization of deep mining, the problem of mine thermal damage has been widely concerned. In this paper, 64 logging temperature data of surface boreholes of Zhujidong coalfield in Huainan City, Anhui Province, China, were summarized and sorted. The temperature data of 12 measuring points at the current main working level of −906 m and −965 m were measured. The ground temperature conditions of the vertical direction, horizontal direction, and main coal seam floor in the coalfield were analyzed. The characteristics of the present geothermal field and roadway heat damage, and its influencing factors were discussed. The results showed that the geothermal gradients of this area are between 1.7 °C/hm and 3.6 °C/hm, and the average geothermal gradient is 2.607 °C/hm. It shows the transmission of warming in the vertical direction and horizontal direction shows the ground temperature lowering from south to north, east to west. The geothermal field in this area is mainly affected by the geological structure, and the thermal physical properties of rocks, magmatic rocks and groundwater activities also have a certain effect. At present, most of the main work level has reached the first heat hazard area, and some are in the second heat hazard area, according to Chinese regulations. The working face temperature is keeping above 28 7 °C and the relative humidity is being maintained above 70% for a long time. The problem of heat damage is extremely serious. It is suggested to construct the thermal environment control measures combining active and passive ways.

Keywords: distribution characteristics; field measurement; geo-temperature field; heat damage; influential factors; Zhujidong coalfield

1 INTRODUCTION

The high ground temperature in mine seriously affects the mining conditions and workers' physical and mental health [1]. Thus, the study on the characteristics of coal mine geothermal field has received extensive attention in the world. For example, Dolezal et al. studied the primary rock temperature field in Czech and Polish part of upper Silesian Coal Basin [2]. Weydt et al. investigated geothermal reservoir of two regions in Alberta, Canada, and gave an assessment for geothermal utilization [3]. Raymond et al. proposed a ground coupled heat pump system in the waste rock pile environment, which appears attractive to heat and cool buildings of the mine to improve energy efficiency [4]. It can be seen that the exploration of geothermal field and rational utilization of geothermal energy are hot issues concerned by scholars at present. China is rich in coal reserves, and due to the complex geological structure, multiple coal forming conditions, multiple coal forming periods, coal metamorphism, etc. China's coal mining faces serious geological disasters [5]. With the normalization of deep mining in most mines in China, the problem of high-temperature heat damage becomes more and more serious, which has received extensive attention from engineers and technicians [6-7]. China's "Coal Mine Safety Regulations" stipulates that the temperature of excavation working face shall not exceed 26 °C, and the temperature of electromechanical equipment chamber shall not exceed 30 °C. According to the air-flow temperature of the excavation working face, it is divided into three heat damage grades: Grade I is 28 - 30 °C, Grade II is 30 - 32 °C, and Grade III is above 32 °C. According to the original rock temperature of the minefield, it is divided into two grades, Grade I is 31 - 37 °C, and Grade II is above 37 °C. High temperature not only aggravates the deformation and failure of the surrounding rock mass, induces the failure of supporting structure, spontaneous combustion of coal, reduces the equipment performance, but also seriously reduces the labor production efficiency [8-9]. It has an adverse effect on the physical and mental health of miners, making miners feel irritable, reducing alertness, increasing the accident rate, and even leading to the death of miners from heat stroke and heat exhaustion. According to the statistics of Lan et al., there are 34 Class I heat harm mines in deep mines in China, accounting for 24.64%, 26 Class II heat harm mines, accounting for 18.84%, and 9 Class III heat harm mines, accounting for 6.52%, mainly distributed in Anhui Province, Jiangsu Province, Shandong Province, Heilongjiang Province, Jilin Province, and Henan Province, China [10]. It can be seen that the heat damage mines in China are widely distributed and the heat damage problem is extremely serious. Huainan mining area is an important energy supply base in East of China, many mines reach −1000 m, and the average geothermal gradient in the area is 2.9 °C/hm [11]. According to this calculation, the average surrounding rock temperature in the area will be close to or even exceed 50 °C, facing extremely serious problems of high-temperature heat damage and thermal environment control in the roadways. In this paper, the logging temperature data of various surface boreholes in the Zhujidong coal mine, a typical kilometer high-temperature mine in the Huainan mining area, were systematically collected and sorted. Combined with the field measurement results of temperature and humidity in underground roadways and chambers, the present geothermal field distribution and the characteristics of thermal damage in boreholes in the research area were revealed. Finally, it is proposed to develop suitable underground thermal insulation shotcrete material to construct active thermal insulation lining layer, which has a positive significance for the control of heat damage in mine roadways. This paper has important reference significance for heat damage prevention and control of similar deep mines and the research of mine geothermal field distribution.

2 COAL FIELD OVERVIEW

Located in the north of Huainan coalfield, Anhui Province, China, Zhujidong coalfield is 12.5 km long from east to west, 3.5 km wide from south to north, covering an area of about 45.13 km^2. Its location is shown in Fig. 1. It is a large modern mine with a design capacity of 4.0 Mt/a, a service life of 80.2 years, coal resource reserves of 947 million tons and recoverable reserves of 449 million tons. The mine is located in the monsoon warm temperate sub-humid climate, with four distinct seasons, cold in winter and hot in summer. The annual average temperature is 15.1 °C, and the two extremes of temperature are 41.1 °C and −21.7 °C respectively [12].

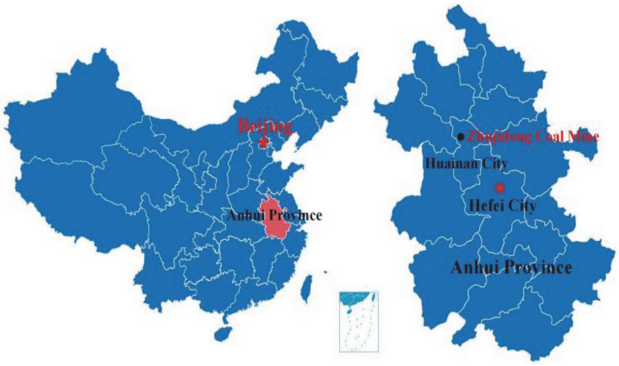


Figure 1 Zhujidong Coal Mine location

The exploration shows that the strata of Zhujidong coalfield include Ordovician, Carboniferous, Permian, Triassic, Paleogene, Neogene and Quaternary successively from old to new. The overall structure is a continuous northwest anticline and syncline, which is the secondary fold of the Huainan syncline. The south and north sides are northwest reverse faults. The north end of the west is the Zhuji-Tangji anticline, the south end is the Shangtang-Gengcunji syncline, and the east is a group of small wide and gentle anticlines, which is the natural extension of the Zhuji-Tangji anticline [13-14].

3 RESEARCH DATA AND FIELD TEST

3.1 Geo-Temperature Data Statistics

During the geological exploration of the Zhujidong coalmine, a total of 64 temperature measurement boreholes were constructed, of which 64 boreholes reached the −906 m and 30 boreholes reached the −1200 m. and 62 boreholes with well temperatures exceeding 31 °C. Among them, holes 7-2, 14-1 and 10-3 are approximate steady-state temperature measurement data. the temperature data was measured 72 hours after completion. The temperature of well fluid and rock has reached a balance, and the measured data can objectively reflect the real formation temperature. The remaining large number of borehole temperature measurement data were simple temperature measurements or instantaneous temperature measurements [15]. In this paper, the collected geothermal temperature data are classified and summarized into vertical ground temperature, horizontal geothermal temperature and main coal seam floor temperature for discussion and research.

3.2 Vertical Geothermal Distribution

According to the long-term geothermal observation hole data of the original Jiulonggang Coal Mine, it is determined that the depth of the constant temperature zone is 30 m, and the temperature is 16.8 °C [16]. According to the temperature measurement data of 64 boreholes, the average thickness of the loose layer is 279.40 m, and the temperature varied from 15.8 °C to 29.7 °C, with a mean temperature of 22.78 °C. The geothermal gradient of the whole stratum is 1.7 - 3.6 °C/hm, with an average value of 2.60 °C/hm. The geothermal gradient of bedrock is 2.2 - 3.8 °C/hm, with a mean value of 2.93 °C/hm. The approximate steady-state temperature measuring borehole was selected as the relationship curves between geothermal temperature and depth in Fig. 2, and the relationship curves between geothermal gradient and depth in Fig. 3. According to relevant literature [17], the formula for calculating geothermal gradient is as follows:

$$G=\frac{T-T_0}{h-h_0} \tag{1}$$

where, G is the average geothermal gradient of temperature measured borehole, °C/hm; T is the temperature of a certain point, °C; T_0 is the temperature of constant temperature zone, taken as 16.8 °C; h is the depth of a certain point, m; h_0 is the depth of constant temperature zone, taken as 30 m.

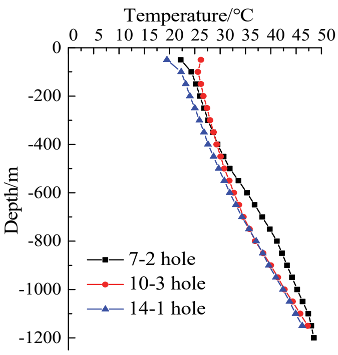


Figure 2 Relationship between temperature and depth of approximate steady-state temperature measurement borehole

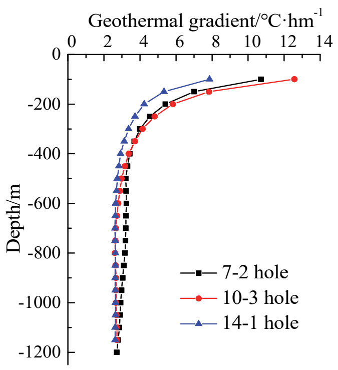


Figure 3 Relationship between geothermal gradient and depth of approximate steady-state temperature measurement borehole

As can be seen from Fig. 2, at the same depth, the temperature is the largest in hole 7-2 in the eastern part of the coalfield. In the vertical, the ground temperature gradually increases with the increase of the measured depth, showing a good linear relationship, which is characterized by conduction type warming. As can be seen from Fig. 3, the geothermal gradient decreases with the increase of depth and gradually tends to be consistent. At the depth of 400 m, the maximum geothermal gradient is 12.57 °C/hm, while the minimum is 2.92 °C/hm. The distribution is discrete and decreases rapidly with the increase of burial depth. When the depth reaches 400 m, the geothermal gradient changes little, ranging from 2.6 °C to 3.4 °C/hm, which is significantly lower than that at 400 m shallow.

3.3 Horizontal Geothermal Distribution

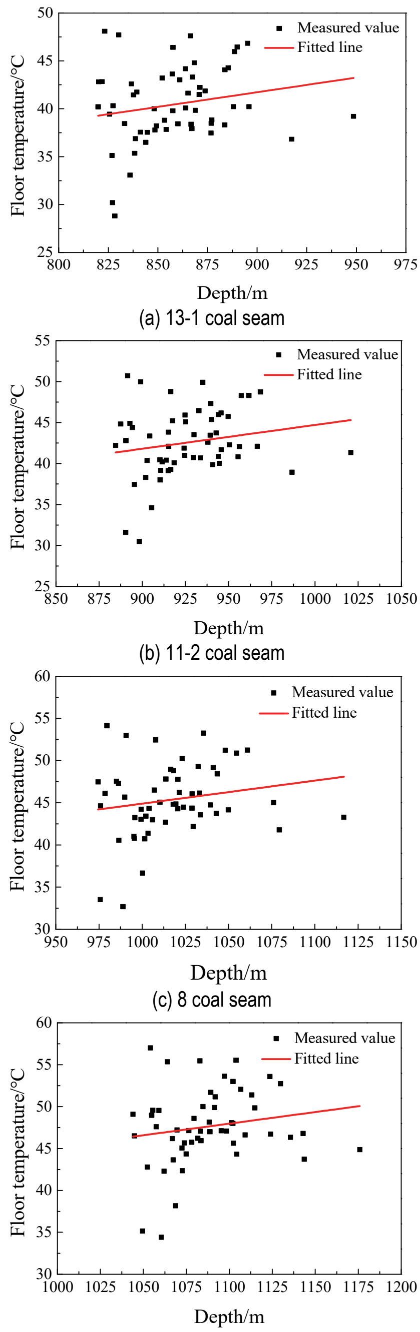
Based on the analysis and calculation of borehole temperature measurement data, taking the three main operation levels of −906 m, −1070 m and −1200 m as the research focus, it can be found that the ground temperature at −906 m ranges from 28.6 °C to 50.8 °C, and the average temperature is 39.69 °C. The horizontal ground temperature at −1070 m ranges from 32.5 °C to 55.9 °C, and the average temperature is 44.31 °C. The ground temperature at the −1200 m ranges from 39.5 °C to 56.6 °C, with an average temperature of 47.08 °C. It can be seen that the ground temperature gradually increases with the increase of buried depth. According to the regulations of "Coal Mine Safety Regulations" on the division of well field heat damage by rock temperature, the level of −1070 m generally reaches above the first level of the thermal damage zone, and the level of −1200 m generally reaches above the second level of the thermal damage zone, and the ground temperature at the same level in the coalfield is different. Taking the current main working level −906 m as an example, from the north to the south, the temperature in the central part of mine is low, which is the first-grade heat damage area, while the ground temperature in the north and south of mine is high, which is the second-grade heat damage area. From east to west, the temperature in the east is higher than that in the west. In general, the geothermal characteristics of Zhujidong coalfield are high in the north and south, low in the middle, high in the east and low in the west. In addition, according to the borehole temperature measurement data, it is determined that the starting and ending depths of mine level elevation in the 31 °C first-grade thermal damage area are −281.00 m and −919.00 m, and the average depth is −552.01 m. The starting and ending depths of mine level elevation in the second-grade thermal damage area at 37 °C are −490.00 m and −1134.00 m, and the average depth is −741.01 m. Now the main working level is −906 m and −965 m, which shows that the problem of high-temperature heat damage is extremely prominent and severe.

3.4 Temperature Distribution of Main Coal Seam Floor

According to the analysis and calculation of borehole temperature measurement data, the distribution range of geothermal temperature from shallow to deep in the main coal seam floor of the current well field is as follows: 13-1 coal seam elevation range is −819.89 - −948.57 m, and the distribution range of geothermal temperature is 28.80 - 48.09 °C. 11-2 coal seam elevation ranges are −884.56 - −1020.75 m, and the distribution range of geothermal temperature is 30.49 - 50.72 °C. 8 Coal seam elevation ranges from −974.50 - −1116.76 m, and ground temperature distribution ranges from 32.67 - 54.13 °C. The elevation range of the 4-1 coal seam is −1043.96 - −1175.91 m, and the ground temperature distribution range is 34.40 - 57.02 °C. The temperature change and depth of each main coal seam are fitted. The fitting relation is shown in Tab. 1, and the fitting situation is shown in Fig. 4.

Table 1 Relationship fitting between temperature and depth of main coal seam floor in Zhujidong coalfield

Coal seam	Fitting function ($y = a + bx$)		Fitting relationship	R^2
	a	b		
13-1	14.22	0.03056	T (°C) = 14.22 + 0.03056 H (m)	0.022
11-2	15.69	0.02901	T (°C) = 15.69 + 0.02901 H (m)	0.019
8	17.57	0.02731	T (°C) = 17.57 + 0.02731 H (m)	0.015
4-1	17.56	0.02764	T (°C) = 17.56 + 0.02764 H (m)	0.011



(a) 13-1 coal seam

(b) 11-2 coal seam

(c) 8 coal seam

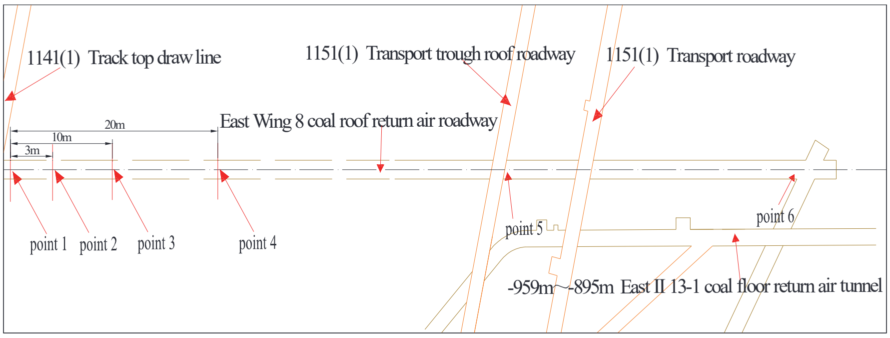
(d) 4-1 coal seam

Figure 4 Relationship fitting between temperature and depth of main coal seam floor in Zhujidong coalfield

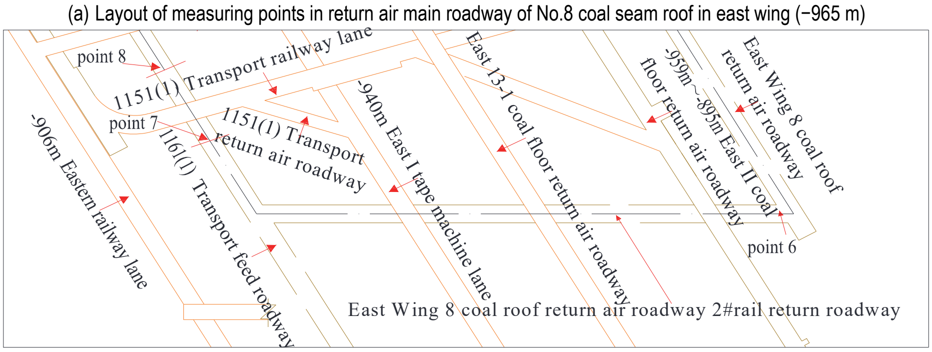
As shown in Fig. 4, combined with the temperature measurement data, it can be seen that the distribution range of the geothermal temperature of each coal seam is larger than 20 °C. However, the geothermal temperatures of the four coal seams are high, and the majority of the measured temperature data exceeds 30 °C, mainly 40 °C to 50 °C, further reflecting the serious heat damage problem faced by the Zhujidong coalfield.

3.5 Roadway Temperature and Humidity Test

Twelve typical measuring points were selected for Zhujidong roadway, which was as follows. Measuring point 1 is the excavation working face (−965 m) of the east wing 8 coal roof return air roadway. Measuring point 2 is 3 m away from the excavation working face (−965 m) of the east wing 8 coal roof return air roadway. Measuring point 3 is 10 m away from the excavation working (−965 m) face of the east wing 8 coal roof return air roadway. Measuring point 4 is 20 m away from the excavation working face (−965 m) of the east wing 8 coal roof return air roadway. Measuring point 5 is the east wing 8 coal seam roof return air roadway I (−965 m). Measuring point 6 is the east wing 8 coal seam roof return air roadway II (−965 m). Measuring point 7 is the east wing north of panel track lane I (−965 m). Measuring point 8 is the east wing of north panel track lane II (−965 m). Measuring point 9 is the east wing of north panel track lane III (−965 m). Measuring point 10 is the east wing of north panel track lane IV (−965 m). Measuring point 11 is the south of track lane on the east wing (−906 m). Measuring point 12 is the main waiting chamber (−906 m). The relative positions of some measuring points are listed in Fig. 5.



(a) Layout of measuring points in return air main roadway of No.8 coal seam roof in east wing (−965 m)

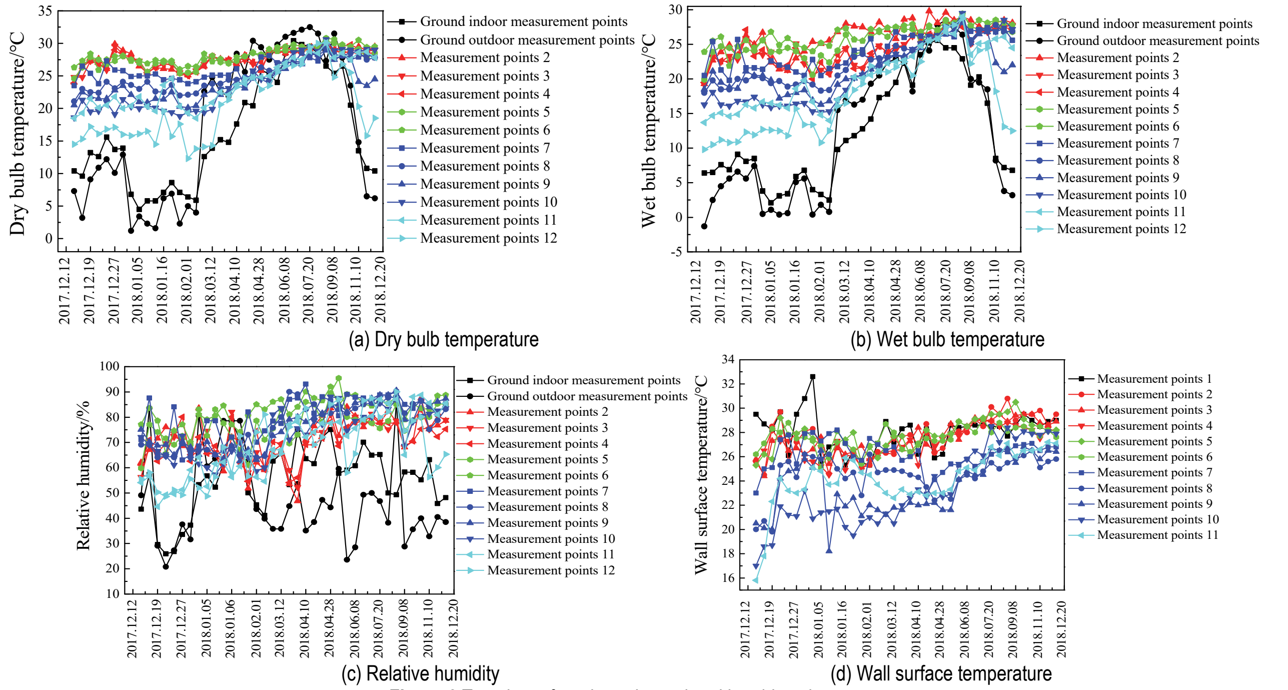


(b) Layout of measuring points for other roadways (−965 m)

Figure 5 Layout of measuring points of roadway thermal environment

Industrial digital thermometers and non-contact infrared thermometers were used to monitor the thermal and humid environment for one year (from December 2017 to December 2018), including the dry bulb temperature, the wet bulb temperature, relative humidity and wall temperature at each measuring point, and compared with the indoor and outdoor temperature on the ground. The test results are shown in Fig. 6. As shown in Fig. 6, the building environment indicators such as dry bulb temperature, wet bulb temperature and relative humidity have the same regularity, the indoor and outdoor dry bulb temperatures are much lower than the mine environment. The four seasons are distinct in Huainan city, winter is cold and dry, the temperature is stable at 1 - 13 °C, and the relative humidity is lower than 60%. Summer is hot and humid, the outdoor temperature is close to 30 °C, the relative humidity is between 30 - 80%. For the mine environment, it is less affected by seasonality. The dry bulb temperature is generally between 20 – 30 °C, the wet bulb temperature is between 18 – 28 °C, and relative humidity is between 60 - 90%. Both surface and mine dry and wet bulb temperatures show a sinusoidal curve with time, which is related to seasonality [18-19]. However, farther away from the wellbore or vent, the average temperature gradually increases, and the change curve is not obvious. Monitoring of mine thermal and humid environment. The thermal and humid environment of long-term used roadways such as the waiting chamber and main track roadway is stable, while the thermal and humid environment of the excavation working face and roadway is worse. In the case of Zhujidong coal mine, the temperature of −906 m chamber and track roadway change seasonally because of the ground factors. The temperature is 10 - 15 °C in winter and 20 - 30 °C in summer, but the relative humidity is low, maintained between 50 - 90%. Due to long-term use, each measuring point of −965 m roadway has a good ventilation effect. Although the temperature is higher than that of a −906 m roadway, the temperature is generally lower than

25 °C and the relative humidity is between 60% and 90%, which is suitable for normal work of the human body. For the excavation roadway without ventilation measures, the closer it is to the working face, the temperature and humidity of the roadway continue to rise. The temperature of the roadways 20 m away from the working face remains above 27 °C for a long time, the wall temperature mostly exceeds 27.5 °C, and the relative humidity remains above 70%. Temperature monitoring of roadway excavation working face. The temperature of the working face is generally about 28.0 °C, and even exceeds 30.0 °C at the maximum. The farther away from the working face, the lower the temperature is, but is generally greater than 27 °C. After ventilation and cooling measures, the wall temperature is generally 26.0 - 29.0 °C. In addition, the excavation working face and its surrounding roadway's hot and humid environment are complex, and there are many influencing factors of the test, including various construction processes, charge blasting, temporary support, drilling, shotcrete support, as well as the use of all kinds of mechanical equipment, human body heat dissipation, air flow, etc., all have different degrees of influence.



(a) Dry bulb temperature (b) Wet bulb temperature

(c) Relative humidity (d) Wall surface temperature

Figure 6 Test data of roadway thermal and humid environment

4 CURRENT GEOTHERMAL DISTRIBUTION CHARACTERISTICS AND INFLUENCING FACTORS

The distribution of the geothermal field is controlled and affected by many factors. Generally, the geothermal field distribution is mainly influenced by the geological structure; in addition, different thermophysical properties of rocks, magmatic rock action, and groundwater activities also affect the temperature distribution in local areas. Taking Zhujidong Coal Mine as an example, the detailed analysis is as follows.

4.1 Geological Structure

Basement undulation and fold. Tectonic movement makes the crust fold and fracture, forming depressions and uplifts, which lead to changes in the thermal conductivity of rocks horizontally and vertically, resulting in the redistribution of heat flow in rock strata. Specifically, the ancient rock series located in the uplift area have dense lithology and high thermal conductivity, while the rocks in the subsidence area have low thermal conductivity. Therefore, the heat flow flows towards the anticline axis of the uplift area, which is characterized by higher geothermal temperature, geothermal gradient, and heat flow in the upper part of the uplift area, and the depression area is relatively low [20-21]. As shown in Fig. 7, the influence of the Panji-Chenqiao anticline on the geothermal field is manifested in the Huainan mining area. The high-temperature abnormal area is distributed in pieces and continuously from east to west, consistent with the anticline trend. The upward transfer of deep heat flow causes the variation of the geothermal field. Therefore, the geothermal gradient is higher in the anticline axis area, which is 3.5 - 4.5 °C/hm and decreases to below 3.5 - 3.0 °C/hm along the inclined direction.

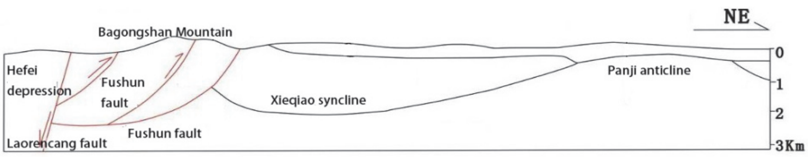


Figure 7 Schematic diagram of Huainan coalfield structure [7]

The Zhujidong coalfield is located in the northern wing of the Panji anticline, its southern boundary is separated by the Panbei mine and is parallel to the back slope axis, and thus is influenced by the thermal concentration of the anticline axis and exhibits a high geothermal gradient to the south and low to the north. The overall structure of the coalfield is a northwest-trending broad anticline, with the south forming a northwest-trending Shangtang-Gengcun slope parallel to the anticline axis. The eastern part of the mine is influenced by the Panji anticline and Zhuji-Tangji anticline, and is significantly higher than the normal section, with ground temperature gradients greater than 3.0 ℃/hm in many places, and greater than 3.6 ℃/hm in some areas, such as 4-2, 5-6, 6-1, 7-4, 8+1, 8-2, 8-4, 9+1 9-1, 10+1, 11-1, 11-2, 14-4, 20-1 and other holes. The western part of the mine is influenced by the Zhuji-Tangji anticline and the Shangtang-Gengcun slope, which have no high-temperature anomalies. As a result, the geothermal gradient of the mine is generally high in the east and low in the west. Fault. Faults can both block and facilitate the transfer of heat flow, thus affecting areas of high temperature formed by anticline tectonics. It can also form conduits for groundwater and magmatic intrusion, so high geothermal anomaly areas often appear nearby faults [22]. The fault zone in the Zhujidong coal mine becomes the channel for deep heat flow upwards, which shows the higher geothermal temperature and larger geothermal temperature gradient at the fault and its vicinity, such as boreholes 4-2, 7-9, 8-4, 9+1, 10-1, 12-1, 14-1, 15-1, and 21-2, which are all located in the fault zone, and their geothermal and geothermal gradient are significantly higher than those in the normal section.

4.2 Thermophysical Properties of Rocks

Different rocks have different thermal conductivities, heat conduction, heat aggregation and dispersion performance, thus affecting the geothermal field. Among them, the thermal conductivity of sandstone is the highest, followed by mudstone, and coal is the lowest. The upper Cenozoic strata in Zhujidong coalfield and even Huainan mining area are composed of fine sand, clay, and gravel with low thermal conductivity, while the lower Permian coal measures are mainly composed of sandstone and mudstone with high thermal conductivity. Deep heat flow will be refracted and redistributed when it is transmitted to the overlying loose layer with low thermal conductivity, thus resulting in the shallow loose layer with low thermal conductivity forming the covering layer with a heat preservation cover effect. Meanwhile, the loose layer also contains a certain amount of heat generating elements, so the loose layer is also a warming layer [23], and its warming is related to the heat preservation effect and the size of the thickness. The Zhujidong coalfield shows the effect of insulation and impedes heat flow conduction and heat dissipation, so the geothermal gradient is higher in the shallow area of 400 m, while the deep coal strata with good heat conduction performance make the heat flow transfer rapidly, showing a gradient decrease in the geothermal with the increase of depth [24]. As shown in Fig. 3, the decreasing relationship of geothermal gradient value with increasing depth indicates that the shallow rock with low thermal conductivity hinders the heat transfer, resulting in a significantly higher geothermal gradient than deep rocks with high thermal conductivity.

4.3 Magmatic Rocks Activities

Most areas of Zhujidong coalfield are eroded by magmatic rocks, but the intrusion time is Yanshan period according to the measured data, the intrusion time is far away, and the residual heat is dissipated. However, according to the geological data, there are still some borehole data that can reflect the rising effect of magmatic rock intrusion on the geothermal temperature and geothermal gradients, such as boreholes 10-1, 11-1 and 12-1 in the 13-1 coal seam suffered magmatic rock intrusion. Boreholes 12-3, 13-2-1, 14-1, 16-1 and 15+1 in the 8 coal seam invaded by magmatic rock. Boreholes 9-1, 9-2, 8+1, 10-3, 11-1, 12-1, 12-3, 13-2-1 and 14-1 in the 4-1 coal seam invaded by magmatic rock have higher geothermal temperature and geothermal gradient than normal section.

4.4 Groundwater

Groundwater is the most active geological factor because of its easy flow, large heat flow and wide distribution. It has an important influence on the temperature field of the surrounding rock. When cold water flows from shallow to deep, it takes away the heat of surrounding rock and plays a cooling role. When the fracture zone becomes the channel for deep high temperature hot water to migrate upward, it will heat the surrounding rock and increase the temperature. In addition, due to the high specific heat capacity of water, it also plays a thermostatic role. Generally, the vertical movement of groundwater has a more obvious influence on the temperature field of rockstrata than the horizontal movement. There are several normal faults with a large drop and long extension in the Zhujidong coalfield, which become the channels for deep high pressure hot water to migrate upward along the fracture, resulting in the formation of high-temperature anomaly areas near the fracture channels and the rise of geothermal gradient [16, 25].

5 ROADWAY HEAT DAMAGE CHARCTERISTICS AND TREATMENT SUGGESTION

5.1 Roadway Heat Damage Characteristics and Influencing Factors

According to the above geo-temperature measurement and data analysis, it can be seen that the geothermal temperature is generally higher in Zhujidong coalfield, and the problem of heat damage in the roadway is significant. As can be seen from Fig. 6, the air temperature of the excavation working face in the east wing 8 coal roof return air roadway is above 28 ℃, which has already exceeded the operating regulations of "Coal Mine Safety Regulations". The main heat source that causes heat damage in the roadway is surrounding rock heat release, which can account for more than 40% of the mine heat source [26]. Secondly, it is the heat release of mechanical and electrical equipment in the process of tunneling operation, most of the heat is transferred to the airflow, resulting in extreme heat on the working face. Other heat sources include air compression heat release, ore and rock transport heat release, roadway organic oxide heat production, underground water gushing, fissure water heat release, etc. In addition, the temperature of the roadway is also affected by the surface seasonal climate. According to the statistics and calculation of technical personnel of Zhujidong coal mine, the inlet air temperature leading to the fully mechanized mining transportation roadway in summer is 30 °C, the humidity is 95%, and the inlet air volume is 2500 - 3000 m^3/min. Under the condition of no cooling measures, the temperature from the beginning to the end of the mining face gradually increases from 31 °C to 34 °C, with humidity up to 96 - 100%. The design air supply of the excavation working face is 900 – 1000 m^3/min, the temperature from the beginning to the end of the comprehensive excavation face increases gradually from 30.5 °C to 33 °C, and the humidity reaches 96 - 100%. It can be seen the influence of seasonal climate on the temperature and humidity environment of the roadway [19].

5.2 Treatment Suggestions

In the Zhujidong coal mine, mechanical refrigeration type mine air conditioning cooling measures were adopted, which were put into use from June to October, and achieved a certain cooling effect, but also brought high operation and maintenance costs. At present, the Zhujidong coal mine and even Huainan mining area are in a transition stage from shallow to deep. The authors think that the current prevention and control idea of thermal damage is as follows: In middle or shallow buried high-temperature mines, priority shall be given to the development of non-mechanical refrigeration technology, while in deep buried high-temperature mines, mechanical refrigeration is the main cooling technology, supplemented by non-mechanical refrigeration comprehensive prevention and control technology [27]. It is necessary to know that the fundamental of mine heat harm control is to ensure that the heat emission is greater than the amount of heat generated, so controlling the heat source and increasing the heat emission are two major ways. Therefore, some scholars have proposed the method of active heat insulation and temperature reduction, for example, applying a thermal insulation spray layer in the roadway of high geothermal rock strata to isolate the spread of geothermal temperature into the roadway, which is an active temperature reduction method. The basic idea is to cover the surrounding rock with heat insulation materials to construct a heat insulation structure to hinder the spread of mine geothermal heat in the roadway, and then take away the heat in time by strengthening ventilation and other measures, which is an ideal measure of combining prevention and treatment [28]. Based on this idea, the authors developed a new type of thermal insulation material suitable for mine slurry spraying. Taking the east wing 8 coal roof return air roadway of Zhujidong coal mine as a typical high-temperature roadway, completed an industrial test of thermal insulation slurry spraying with 100 m to test the thermal insulation effect of the slurry layer in blocking the heat of surrounding rocks, which provided a beneficial reference for the thermal damage prevention and control idea of combining active and passive in the roadway. For the research and practical experience in this area, readers can refer to the author’s other relevant literature [6, 27, 29-30]. In addition, some scholars have proposed the idea of geothermal energy from mines, for example, an open loop ground source heat pump was put forward [31], phase change energy storage material was used to store heat [32]. However, the above method is still in the experimental research stage and has not been widely applied.

6 CONCLUSION

In this paper, the data of 64 temperature measuring boreholes in Zhujidong coalfield were collected and sorted, including 3 approximately steady-state temperature-measuring boreholes. The temperature and humidity data of 12 measuring points at −965 m and −906 m were measured on-site. The current geothermal field condition and characteristic of Zhujidong coalfield were analyzed, and the following conclusions were obtained.

(1) The geothermal gradient in Zhujidong coalfield is between 1.7 °C/hm and 3.6 °C/hm, with an average value of 2.60 °C/hm. The geothermal gradient is relatively high as a whole. In the vertical direction, the geothermal temperature increases linearly with the increase of depth, showing conductive warming. In the horizontal direction, the geothermal temperature is high in the south and low in the north, high in the east and low in the west.

(2) The average depth of the first-grade thermal damage zone at 31 °C is −552.01 m, and the average depth of the second-grade thermal damage zone at 37 °C is −741.01 m. At present, the main working levels of −906 m and −965 m mostly reach the first-grade thermal damage zone, and some are in the second-grade thermal damage zone, most of the further developed −1070 m and −1200 m levels are second-grade thermal damage areas.

(3) The present geothermal field in Zhujidong coalfield is mainly controlled by geological structure, and the thermophysical properties of rocks, magmatic rocks and groundwater activities also have certain effects on the distribution of the geothermal field.

(4) The monitoring of the heat and humidity environment in the mine roadway shows that the problem of high-temperature heat damage is serious, the temperature of the excavation working face keeps above 28 °C for a long time, and the relative humidity is maintained above 70%. At present, the cooling method of mechanical mine air conditioning is adopted, and the proposal of thermal environment control measures combining active and passive is put forward. The industrial test is completed in the east wing 8 coal roof return air roadway of the mine, and the effect is good.

(5) It is proposed forming combined heat damage treatment technology system of underground coal mine cooling technology, included thermal insulation support, support structure and artificial refrigeration. This is an effective idea to solve the problem of high temperature thermal damage in underground roadways of high temperature rock. The development of long-term effective thermal insulation materials, effective utilization of geothermal energy are future research hotspots.

Acknowledgements

This research was supported by the Open Fund of Anhui Key Laboratory of Mining Construction Engineering (No. GXZDSYS2022106), Science and Technology Plan Project of Huainan City, China (No. 2023A313), Housing Urban and Rural Construction and Technology Project of Anhui Province, China (No. 2023-YF048), and Graduate Innovation Fund Project of Anhui University of Science and Technology (No. 2023CX2041).

7 REFERENCES

[1] Donoghue, A. M. (2004). Heat illness in the U.S. Mining Industry. *American Journal of Industrial Medicine*, *45*, 351-356.

[2] Doleżal, L., Knechtel J., Taufer, A., & Travnićek, L. (2013). Primary rock temperature fields in Czech and Polish part of the upper of the upper Silesian coal basin. *Archives of Mining Sciences*, *58*(1), 55-72. https://doi.org/10.2478/amsc-2013-0004

[3] Weydt, L. M., Heldmann, C. D. J., Machel, H. G., & Sass, I. (2018). From oil field geothermal reservoir: assessment for geothermal utilization of two regionally extensive Devonian carbonate aquifers in Alberta. Canada. *Solid Earth*, *9*, 953-983. https://doi.org/10.5194/se-9-953-2018

[4] Raymond, J., Therrien, R., Gosselin, L., & Lefebvre, R. (2011). Numerical simulation of geothermal energy transfer beneath exothermic waste rock piles. *HVAC & R Research*, *17*(6): 1115-1128. https://doi.org/10.1080/10789669.2011.589747

[5] Wu, B., Wang, J. X., Zhong, M. Y., Xu, C. C., & Qu, B. L. (2023). Multidimensional analysis of coal mine safety accident in China - 70 years review. *Mining, Metallurgy & Exploration*, *40*, 253-262. https://doi.org/10.1007/s42461-022-00722-w

[6] Yao, W. J., Pang, J. Y., Ma, Q. Y., & Lyimo, H. (2021). Influence and sensitivity analysis of thermal parameters on temperature field distribution of active thermal insulated roadway in high temperature mine. *International Journal of Coal Science and Technology*, *8*(1), 47-63. https://doi.org/10.1007/s40789-020-00343-y

[7] Zhang, W., Wang, T. Y., Zhang, D. S., Tang, J. J., & Duan, X. (2020). A comprehensive set of cooling measures for the overall control and reduction of high temperature-induced thermal damage in oversize deep mines: a case study. *Sustainability*, *12*, 2489. https://doi:10.3390/su12062489

[8] Wang, G., Xie, J., Xue, S., & Wang, H. Y. (2015). Laboratory study on low-temperature coal spontaneous combustion in the air of reduced oxygen and low methane concentration. *Tehnicki Vjesnik-Technical Gazette*, *22*(5), 1319-1325. https://doi.org/10.17559/TV-20150225022245

[9] Guo, Z. B., Zhang, L., Wang, H. H., Yin, S. Y., & Kuai, X. H. (2018). Failure mechanism of bolts and countermeasures in swelling soft rock support. *Tehnicki Vjesnik-Technical Gazette*, *25*(5), 1447-1456. https://doi.org/10.17559/TV-20180925162917

[10] Lan, H., Chen, D. K., & Mao, D. B. (2016). Current status of deep mining and disaster prevention in China. *Coal Science and Technology*, *44*(1), 39-46.

[11] Ren, Z. Q., Peng, T., Shen, S. H., Zhang, H. C., Xu, S. P., & Wu, J. W. (2015). The distribution characteristics of current geothermal field in Huainan Coalfield. *Geological Journal of China University*, *21*(1), 147-154.

[12] Hu, J. T. (2015). Measurement and rule analysis of underground temperature parameters of Zhuji Colliery. *Coal Mining Technology*, *20*(4), 136-139.

[13] Chen, L. S. (2011). Analysis on the rationality of development mode design of Zhujidong Mine. *Coal Engineering*, (10), 8-9.

[14] Xu, D. S., Man, J., Liu, X. H., & Li, Y. (2019). Hydrochemical characteristics and multivariate statistical analysis of groundwater in loose aquifer: a case study from Zhujidong Coalmine. *Journal of Hebei North University* (*Natural Science Edition*), *35*(1), 17-21.

[15] Yu, H. C., Deng, X., & Chen, B. W. (1991). *Mine geothermal and heat damage control*. China Coal Industry Publishing House.

[16] Su, Y. R. & Zhang, Q. G. (2000). A preliminary analysis of the geo temperature situation of the panxie mine in the Huainan Coalfield. *Geology of Anhui*, *10*(2), 124-129.

[17] Waston, S. M. & Westaway, R. (2020). Borehole temperature log from the Glasgow geothermal energy research field site: a record of past changes to ground surface temperature caused by urban development. *Scottish Journal of Geology*, *56*, 134-152. https://doi.org/10.1144/sjg2019-033

[18] Fang, L. C., Chen, Y. C., An, S. K., Xu, Y. F., Zhao, Y. J., Wang, N., Li, Z. H., & Zhao, P. (2021). Temporal and spatial evolution of surface thermal environment in Huainan mining area in the last decade. *Coal Geology & Exploration*, *49*(4), 260-268.

[19] Yi, X., Wang, Z. P., Song, X. M., Feng, X. P., & Sun, Q. F. (2015). Study on governance technology of seasonal heat hazard in the mine. *Industrial Safety and Environmental Protection*, *41*(8), 63-66.

[20] Peng, T., Ren, Z. Q., Wu, J. W., & Zhang, H. M. (2017). Distribution characteristics of the present-day geothermal field and its structural controls in deep part of Panji mining area. *Geological Journal of China Universities*, *23*(1), 157-164.

[21] Peng, T., Wu, J. W., Ren, Z. Q., Xu, S. P., & Zhang, H. C. (2015). Distribution of terrestrial heat flow and structural control in Huainan-Huaibei Coalfield. *Chinese Journal of Geophysics*, *58*(7), 2391-2401.

[22] Jiang, B. (1993). Thrust imbricate fan tectonic system of Huainan coal field. *Coal Geology & Exploration*, *21*(6), 13-17.

[23] Tan, J. Q., Ju, Y. W., Hou, Q. L., Zhang, W. Y., & Tan, Y. J. (2009). Distribution characteristics and influence factors of present geo-temperature field in Su-Lin mine area, Huaibei coalfield. *Chinese Journal of Geophysics*, *52*(3), 732-739.

[24] Xu, S. P. (2014). *Study on the distribution law and control mode of geothermal field in Huainan-Huaibei coalfield*. Doctoral dissertation of Anhui University of Science and Technology.

[25] Xu, G. Q., Wang, W. N., & Zhang, H. T. (2009). The deep thermal damage analysis in Huainan mining area and research on resource utilization of geothermal water. *China Coal*, *35*(10), 114-116, 132.

[26] Yuan, L. (2007). Theoretical analysis and practical application of coal mine cooling in Huainan mining area. *Journal of Mining & Safety Engineering*, *24*(3), 298-301.

[27] Yao, W. J., Lyimo, H., & Pang, J. Y. (2021). Evolution regularity of temperature field of active heat insulation roadway consider thermal insulation spraying and grouting: a case study of Zhujidong Coal Mine, China. *High Temperature and Processes*, *40*, 151-170. https://doi.org/10.1515/htmp-2021-0023

[28] Zhang, Y. (2013). *Transient temperature field of surrounding rock of the high geothermal roadway and its heat control mechanism by heat insulation*. Doctoral dissertation of China University of Mining and Technology.

[29] Yao, W. J. (2019). *Research and application of thermal insulation concrete spray layer support technology for deep and high temperature rock roadways*. Doctoral dissertation of Anhui University of Science and Technology.

[30] Yao, W. J. (2022). *Study on temperature field evolution regularity and application for high geothermal active thermal insulation roadways*. China University of Mining and Technology Press.

[31] Athresh, A. P., Al-Habaibeh, A., & Parker, K. (2016). The design and evaluation of an open loop ground source heat pump operating in an ochre-rich coal mine water environment. *International Journal of Coal Geology*, *164*(S1), 69-76. https://doi.org/10.1016/j.coal.2016.04.015

[32] Liu, H. F., Alfonso, R. D., Zhang, J. X., Zhou, N., Wang, Y. J., Sun, Q., & Zhang, L. B. (2022). A new method for exploiting mine geothermal energy by using functional cemented paste backfill material for phase change heat storage: design and experimental study. *Journal of Energy Storage*, *54*, 105292. https://doi.org/10.1016/j.est.2022.105292

Contact information:

Weijing YAO, associate professor, PhD, post-doctor, master supervisor
(Corresponding author)
Anhui Key Laboratory of Mining Construction Engineering,
Anhui University of Science and Technology,
Huainan 232001, Anhui Province, China
School of Civil Engineering and Architecture,
Anhui University of Science and Technology,
Huainan 232002, Anhui Province, China
Wuhu Surveying and Mapping Design Institute Co., Ltd,
Wuhu 241000, Anhui Province, China
E-mail: yaoweijing0713@163.com

Jinxiu HAN, master degree candidate
School of Civil Engineering and Architecture,
Anhui University of Science and Technology,
Huainan 232002, Anhui Province, China
E-mail: hjx12342022@163.com

Yu LIU, master degree candidate
School of Civil Engineering and Architecture,
Anhui University of Science and Technology,
Huainan 232002, Anhui Province, China
E-mail: liuyu_cn1998@163.com

Yongwen DENG, senior engineering
Zhujidong Coal Mine, Huainan Mining Group Co., Ltd,
Huainan 232002, Anhui Province, China
E-mail: 448284414@qq.com

Jianyong PANG, professor, PhD, doctor supervisor
Anhui Key Laboratory of Mining Construction Engineering,
Anhui University of Science and Technology,
Huainan 232001, Anhui Province, China
School of Civil Engineering and Architecture,
Anhui University of Science and Technology,
Huainan 232002, Anhui Province, China
E-mail: pangjyong@163.com