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Study on the Temperature Field Change Characteristics of Coal Gangue Dumps under the Influence of Ambient Temperature in Heat Pipe Treatment

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Abstract: In order to investigate the influence of ambient temperature on the temperature field of coal gangue dumps governed by heat pipes (HPs), using self-developed heat pipe and intelligent cloud monitoring software, a 1-year field test was conducted in the spontaneous combustion coal gangue dump of Danao liang. This study analyzed the temperature distribution changes of a spontaneous combustion coal gangue dump under different ambient temperatures, as well as the temperature changes of the coal gangue at different time scales. Correlation analysis between ambient temperature and coal gangue temperature was conducted, and a quadratic regression model was established for goodness of fit and significance testing. The results show that ambient temperature affects the distribution of the temperature field of the spontaneous combustion coal gangue dump under the action of the HPs, and the cooling effect on the high-temperature zone is stronger in autumn and winter. The daily change in coal gangue temperature at each measurement point is similar, showing a peak-shaped curve of low at night and high during the day. The inter-day changes of each measuring point have seasonal characteristics: the cooling rate of the high-temperature zone measuring point is affected by the ambient temperature; the seasonal characteristics of the low-temperature zone measuring point are more obvious than the high-temperature zone, and its daily average temperature is affected by the ambient temperature. The ambient temperature and the internal temperature of the coal gangue dump are correlated, and the quadratic regression equation has a high degree of goodness of fit and meets the F-test, indicating that the quadratic regression model can be used for the empirical regression formula of the ambient temperature and the internal temperature of the coal gangue dump. The results of this study provide some references for the sustainable development of mining environments.

Keywords: coal gangue dumps; heat pipe; spot test; regression analysis; temperature distribution

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1. Introduction

Coal gangue is a solid waste generated during coal mining and processing, which is one of the largest industrial solid wastes in China [1]. Due to its low utilization rate, a large amount of coal gangue is dumped near mines [2]. Coal gangue has a certain amount of pyrite and carbon-containing substances and, after a long period of accumulation of heat accumulation, it is very prone to oxidization reactions, triggering spontaneous combustion [3]. Coal gangue spontaneous combustion, which can cause coal fires, is one of the serious threats facing coal mining areas [4]. Spontaneous combustion of coal gangue can release harmful gases (CO, SO_2, and H_2S) and trace elements (Pb, Hg, As, Se) and can even cause explosions, seriously affecting human health and safety and causing pollution to the global environment [5–11]. Therefore, study of the prevention and control of spontaneous combustion of coal gangue dumps is a prerequisite for the prevention of safety hazards and economic losses.

At present, the most common methods used for the prevention and control of spontaneous combustion in coal gangue dumps are traditional treatment methods from the perspective of creating an oxygen barrier, including the direct excavation method, surface sealing method, and grouting method [12–15]. Although these methods are effective in the short-term management of the spontaneous combustion coal gangue dump problem, there are numerous limitations in practice [16]. The direct excavation method is only applicable to areas with a low ignition source temperature and small fire area in the early stage of spontaneous combustion. The surface sealing method can isolate oxygen to achieve combustion control, but internal heat still exists. Once the sealing material is damaged, the coal gangue dump will continue to burn and release heat. The grouting method requires a large amount of caustic soda during the construction process, and the high cost of treatment also leads to the occurrence of reignition.

An heat pipe (HP) is an efficient heat transfer device, which has the advantages of high heat transfer efficiency, fast response, and no external energy supply [17]. HPs have been applied in the embankment of the Qinghai Tibet Railway, mine return air heating, electronic cooling, and solar collectors, demonstrating their excellent cooling and heat transfer capabilities [18–23]. In 2010, Schmidt et al. [24] conducted a cooling test on HPs in the fire area of the Wuda coalfield, verifying the feasibility of suppressing coal spontaneous combustion with HPs. Li Bei et al. [25] designed a coal–HP physical model that explored the heat transfer ability of HP in coal piles. Cheng Fangming et al. [26] established a physical and mathematical model of the action of HP on a coal pile, exploring the influence of the tilt angle of the HP on the internal temperature field of the coal pile. Meng Xi [27] built a coal spontaneous combustion gravity HP thermal energy extraction test bench to explore the impact of different coal pile temperatures and different types of HPs on the temperature field of coal piles. Sun Meihua [28] established a mathematical model for the transfer of heat and cooling of coal piles under the action of HPs, exploring the effects of HP insertion depth and angle on the internal temperature field of coal piles. Zhao Na et al. [29] conducted an HP test on the coal gangue dump in Yinying, exploring the temperature field distribution at different depths of the coal gangue dump. Zhao Bolin et al. [30] analyzed the effect of fin spacing on the heat transfer performance of heat pipes. Most scholars have explored the heat transfer performance of HPs and the influence of HP parameters on the temperature field.

Changes in the external ambient temperature directly affect the temperature difference that drives the working fluid properties and evaporation and condensation process of an HP, which is one of the important factors affecting the heat transfer performance of the HP [31]. Meanwhile, ambient temperature is the primary factor affecting the safety of coal gangue dumps [32]. Zhang Mingyi, Fan Yunlong et al. [33,34] pointed out that the HP of the Qinghai-Tibet highway roadbed cools down in the cold season and stops working in the warm season. Liu Renwei et al. [35] pointed out in a multi-year permafrost zone HP test that the external ambient temperature has a greater influence on the cooling effect of the HP, and ambient temperature conditions can be fully utilized in the cold season to realize the seasonal thawing and refreezing of a roadbed layer. The above research indicates that the ambient temperature in permafrost regions has a significant impact on the heat transfer characteristics of HPs. Coal gangue is a mixture of carbonaceous, muddy, and sandy shale [36,37]. Its thermophysical properties and heat transfer behavior are different from those of permafrost media in permafrost regions. Therefore, it is not appropriate to apply the conclusion about ambient temperature in permafrost regions to spontaneous combustion in coal gangue dumps. As mentioned above, there are currently almost no data on the impact of ambient temperature on the internal temperature field of spontaneous combustion coal gangue dump fire prevention engineering.

Therefore, this paper conducts an HP test in the Danao liang coal gangue dump, using a wireless temperature data acquisition and transmission cloud platform system, to study the influence of ambient temperature on the temperature field of a spontaneous combustion coal gangue dump and to further study the influence of the ambient environment on different gangue temperature zones under different time scales, and it establishes a regression model of the ambient temperature and the coal gangue temperature. Study of the characteristics and distribution of thermal phenomena is of key importance for solving the issue of solid waste disposal, and it provides a reliable theoretical basis for the prevention and control of the application of HPs in spontaneous combustion coal gangue dumps.

2. Test and Methodology

2.1. Test Background

The Danao liang coal gangue dump is located in Yangquan City, Shanxi Province, China. The coal gangue dump faces the air on three sides, the airside is windward, and the slope is steep on three sides; the height of the windward side is more than 10 m. The top of the coal gangue dump was selected as the test site, and the platform area is about 16,514.1 m^2, as shown in Figure 1. At present, part of the coal gangue dump has caught fire, a large amount of vegetation is withered and burned, the surface temperature is high, the smell in the air is pungent, and the covered soil is "white" or "yellow". Therefore, the study of coal gangue dump temperature distribution in order to find reasonable and effective treatment methods to solve the problem of spontaneous combustion of coal gangue dumps cannot be delayed.

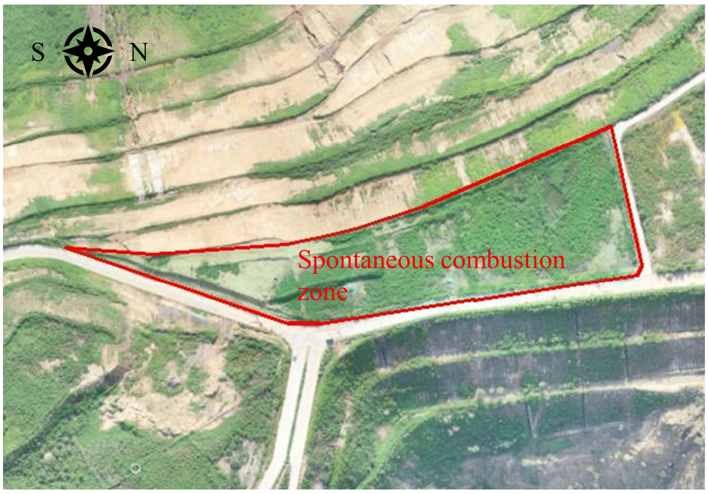


Figure 1. Location of the Danao liang coal gangue dump.

2.2. Meteorological Characteristics

The study area has a temperate humid continental monsoon climate, which is characterized by long winters and summers, short springs and autumns, little rain in spring and dry and windy conditions [38]. The average annual precipitation is 450~550 mm, with a large proportion of precipitation in summer and the area is dry in winter [39]. The main wind directions throughout the year are west and east, with a multi-year average wind speed of 2 m/s [40]. The test started on 1 December 2020, and ended on 1 December 2021, lasting 366 days. Figure 2 shows the average external ambient temperature during the test period. Autumn and winter were from 1 December 2020 to 1 March 2021, and from 1 September 2021 to 1 December 2021. Spring and summer were from 1 March 2021 to 1 September 2021.

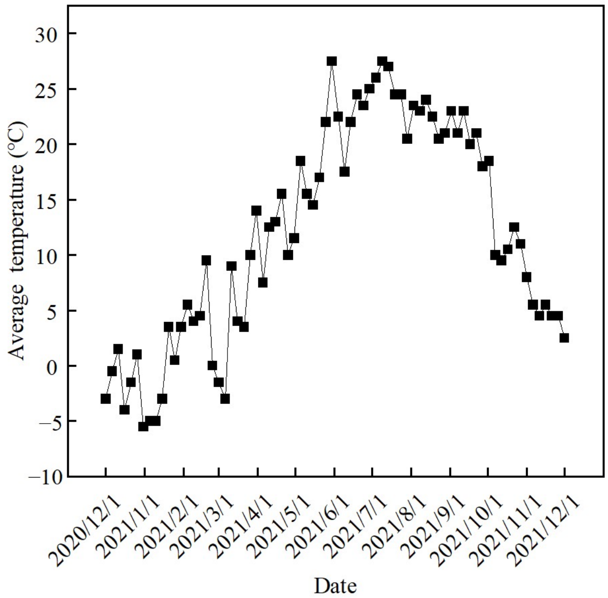


Figure 2. The average external ambient temperature.

3. Test Procedure

3.1. Layout of HPs

An HP is a heat transfer device that relies on the gravity of the medium to circulate on its own and can be divided into three parts: the evaporation section, the adiabatic section and the condensation section [41]. The working principle is shown in Figure 3a. The coal gangue dump comes into contact with the evaporation section and the air comes into contact with the condensation section to form a temperature difference, resulting in the evaporation of the internal mass of the HP, forming a gas. The gas travels to the condensation section where air and heat exchange to produce a liquid, which relies on gravity to flow back, so that the source of the coal gangue dump's internal heat is transferred into the atmosphere to reduce the internal temperature of the coal gangue dump [42].

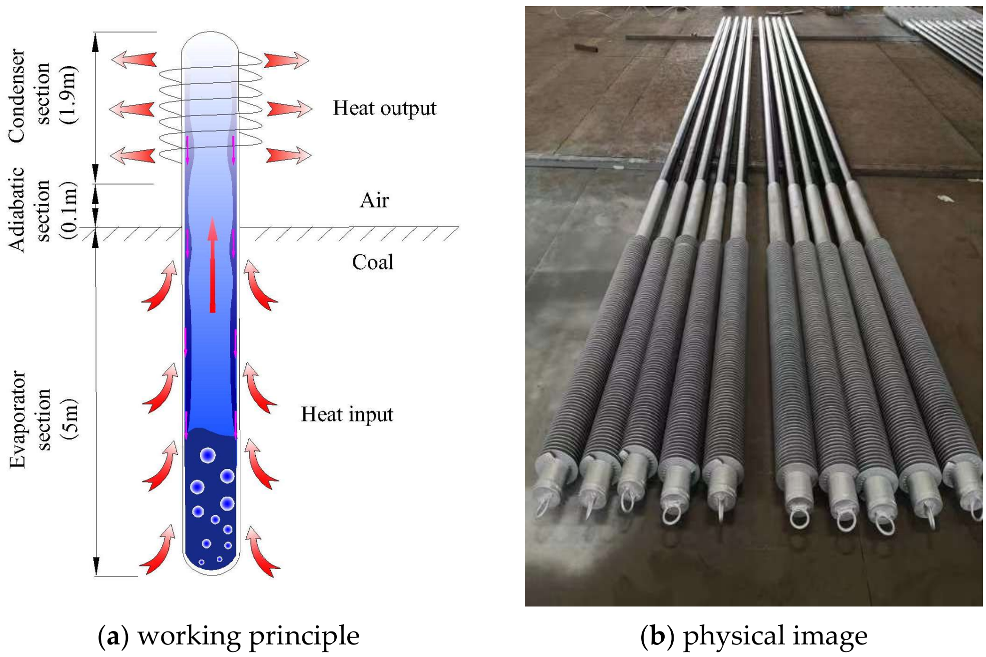


Figure 3. Working principle and physical image of the heat pipe (HP).

The physical image of the HP used in this test is shown in Figure 3b. The HP has an outer diameter of 89 mm, a wall thickness of 6 mm, and a total length of 7 m. The lengths of the evaporative, adiabatic and condensing sections are 5 m, 0.1 m and 1.9 m (1.2 m for the fin section and 0.7 m for the light tube section). The radial height, axial thickness and spacing of the fins are 25 mm, 1.5 mm and 15 mm. The shell is made of highly heat-resistant and corrosion-resistant materials with high thermal conductivity. The internal working medium is a water-based inorganic compound, and the working temperature is 50~800 °C.

Based on increasing the heat transfer surface area, improving the structural stability of the HP and improving the space utilization, the plum-blossom-shaped layout was used in this test. The height of the HP above the ground is 2 m. Considering the high temperature on the south side of the study area and the low temperature on the north side, and the limited influence range of a single gravity heat pipe (about 2–3 m) [43], the HP experiment in the high-temperature area was arranged at a spacing of 4 m, and a short pipe was inserted into the middle of the long pipe to strengthen shallow heat transfer. The HP test in the medium-temperature zone was arranged at a spacing of 5 m, and the arrangement was consistent with that in the high-temperature zone. The HP test in the low-temperature area was arranged at a spacing of 6 m. The temperature at the slope location is high and there is sufficient oxygen, with a fast heating rate. Spacings of 2, 2.5, and 3 m were used to strengthen the cooling effect at the slope location, and spraying measures were taken on the windward slope surface. After the HP test layout was completed, 0.5 m of loess was rolled and used as cover to reduce porosity, prevent oxygen from entering, and prevent harmful gas from overflowing. The layout of the HPs and on-site heat pipes are shown in Figures 4 and 5, with a total of 821 heat pipes.

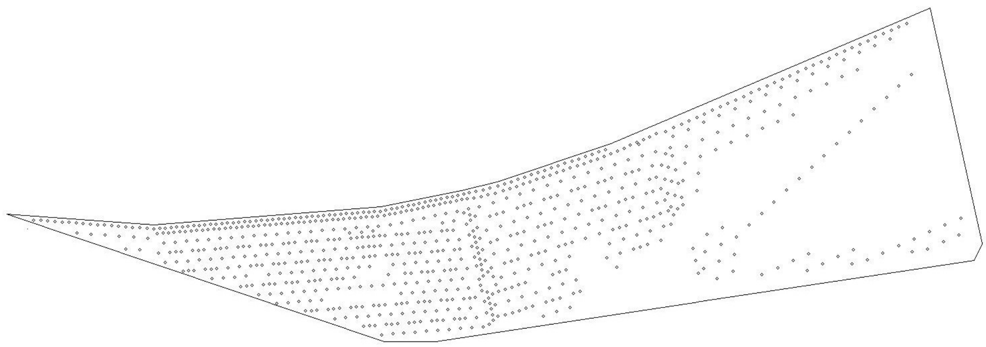


Figure 4. The arrangement and spacing of the HPs.

(**a**) Flat ground HP (**b**) Slope HP

Figure 5. The site of HPs.

3.2. Layout of Monitoring Points

In the test area, 28 temperature monitoring points (numbered from T1 to T26, W1, and W2) were punched; monitoring points were arranged in the center of the equilateral triangle of the HPs, as shown in Figure 6. Two sets of temperature measuring equipment were installed at each location to measure the temperature at 3 m and 6 m, respectively. W1 and W2 represent the high-temperature zone and low-temperature zone without HPs in the case of coal gangue temperature monitoring points.

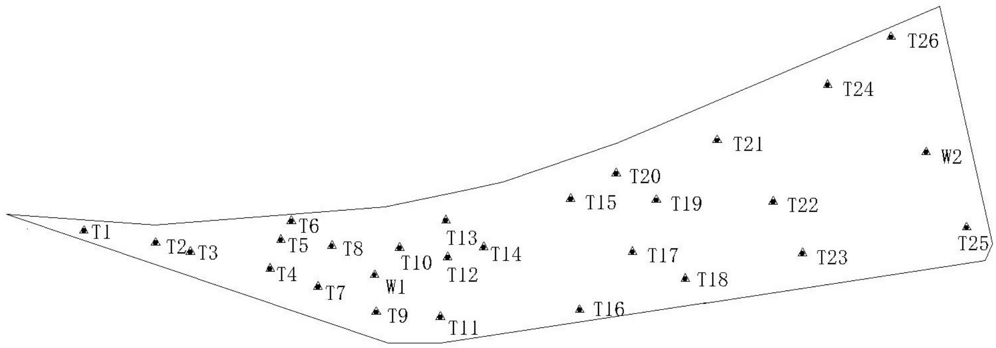


Figure 6. Distribution of temperature monitoring points (numbered from T1 to T26, W1, and W2).

3.3. Smart Dynamic Cloud Monitoring System

As shown in Figure 7, the smart dynamic cloud monitoring system includes a thermocouple, wireless module, transmitting and receiving device, and monitoring platform. A K-type high-temperature thermocouple sensor and wireless module were used for data monitoring and transmission, 4G gateway and a LORA (a kind of ultra-long-range wireless transmission based on spread spectrum technology) transmitter were used for data transmission, and the monitoring data were stored on the cloud platform for real-time viewing on a computer.

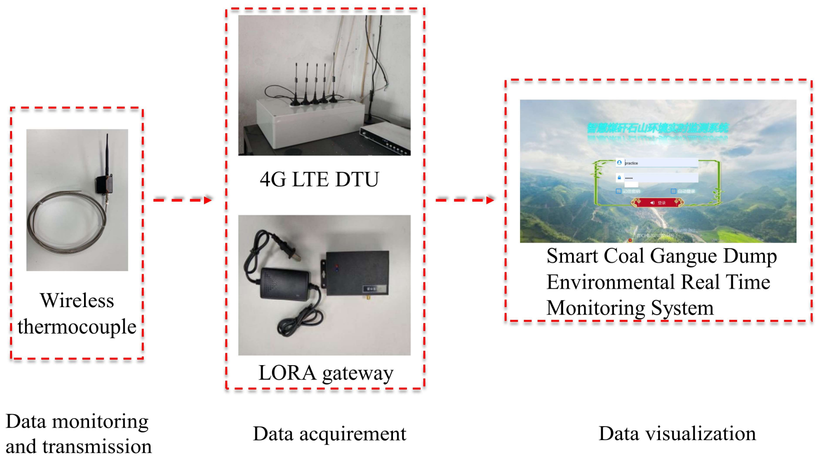


Figure 7. Smart dynamic cloud monitoring system.

4. Results and Discussion

4.1. Temperature Field Distribution Characteristics

4.1.1. Initial Temperature Field

Temperature is an important indicator to measure the degree of spontaneous combustion in coal gangue dumps. In order to clarify the initial temperature distribution of the coal gangue dump (monitored on 1 December 2020), a kriging interpolation method was used to draw shallow and deep level isothermal maps, respectively, as shown in Figure 8. According to the coal gangue spontaneous ignition point temperature (280 °C) and critical temperature (80 °C), the same depth of spontaneous coal gangue dump from west to east can be divided into a high-temperature zone, medium-temperature zone and low-temperature zone [44].

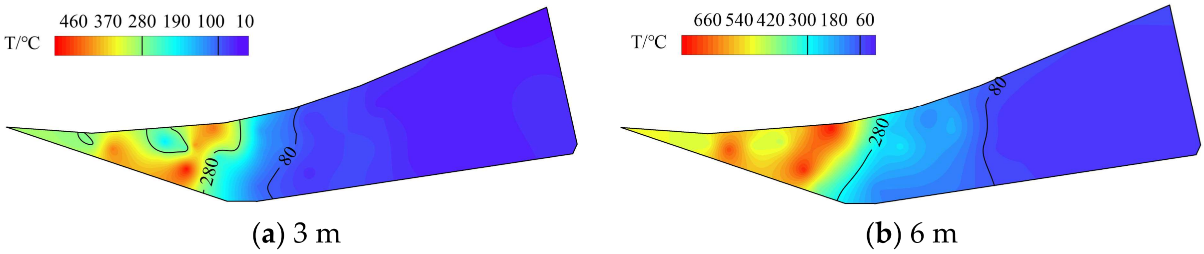


Figure 8. Initial temperature distribution of different depths of the coal gangue dump.

As shown in Figure 8, there is similarity and consistency in the contour plots at both depths, with similar temperature trends from south to north. From each contour temperature value, it can be concluded that the high-temperature zone in the two horizontal planes is mainly concentrated in the southern location. There are three temperature high value points in which the location is the same. Because the south side of the coal gangue dump is a windward surface, oxygen can easily enter the coal gangue dump inside, and the coal gangue dump is near the perennial west wind and east wind, so the windward slope location in the south near the sides appears to be a high-temperature point of spontaneous combustion in the coal gangue dump [43–45].

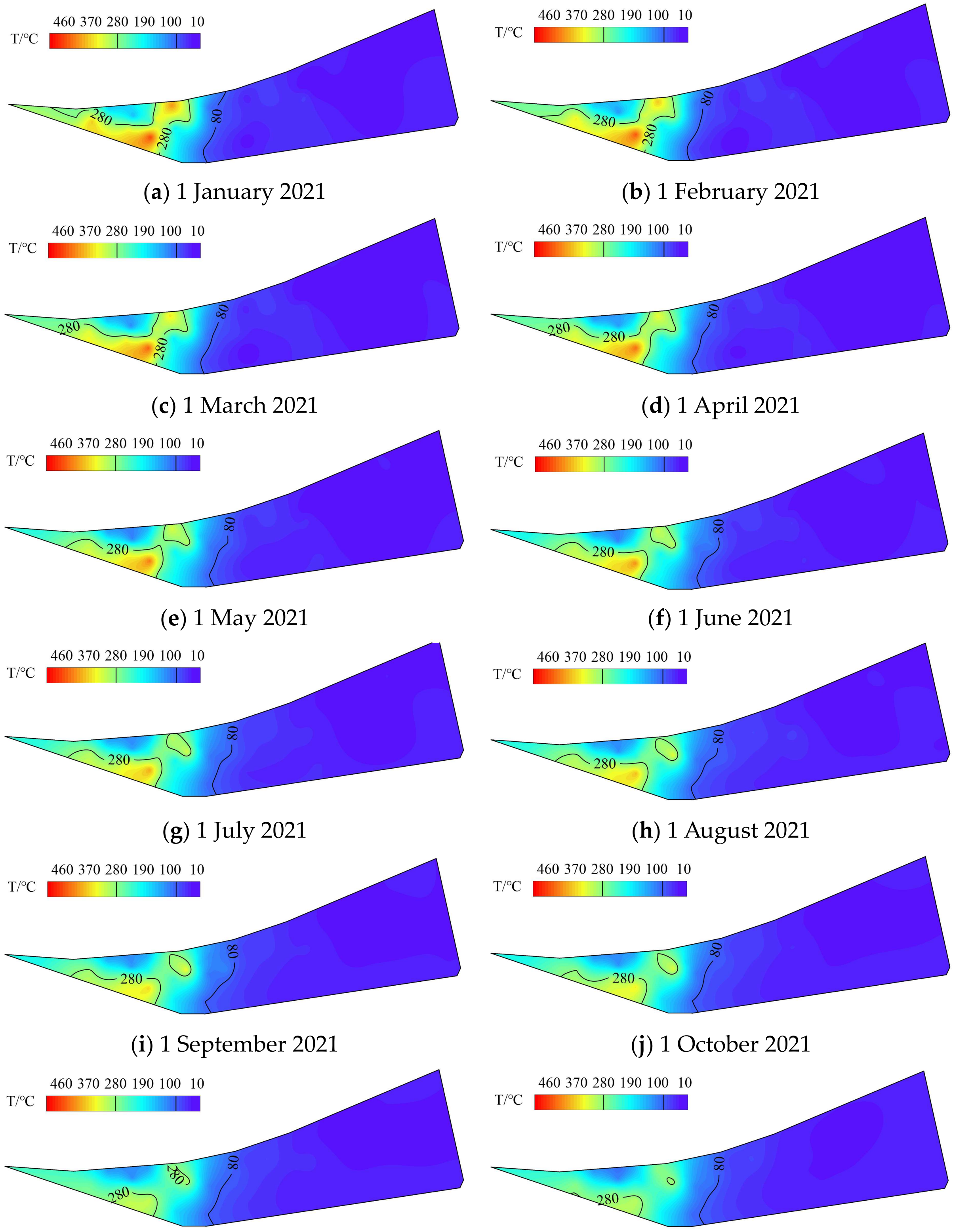
As shown in Figure 8, it can be seen that the temperature generally showed an increasing trend from 3 m to 6 m depth, and the temperatures at 3 m and 6 m depth ranged from 20 °C to 500 °C and from 40 °C to 740 °C, respectively. At 3 m depth, the highest temperature value was 498 °C; whereas, at the same position at 6 m depth, the maximum temperature value occurred, with a value of 740 °C. In the southern area where most of the temperature exceeded 280 °C, internal spontaneous combustion occurred, forming a high-temperature zone. With the increase in depth from 3 m to 6 m, the internal temperature increased significantly, and the high-temperature zone and the middle-temperature zone gradually spread to the north, and the trend of expanding the area of the middle-temperature zone was especially obvious. The main reason for this is that the heat cannot be dissipated with the increase in depth, so a better heat storage environment is formed and heat is transferred to the low-temperature zone, causing the internal temperature to spread and increase.

4.1.2. Temperature Field Evolution Trend

In order to clarify the changes in temperature field distribution in a spontaneous combustion coal gangue dump with time under the action of HPs, horizontal isotherms at different depths were plotted over a 1-month span, as shown in Figures 9 and 10.

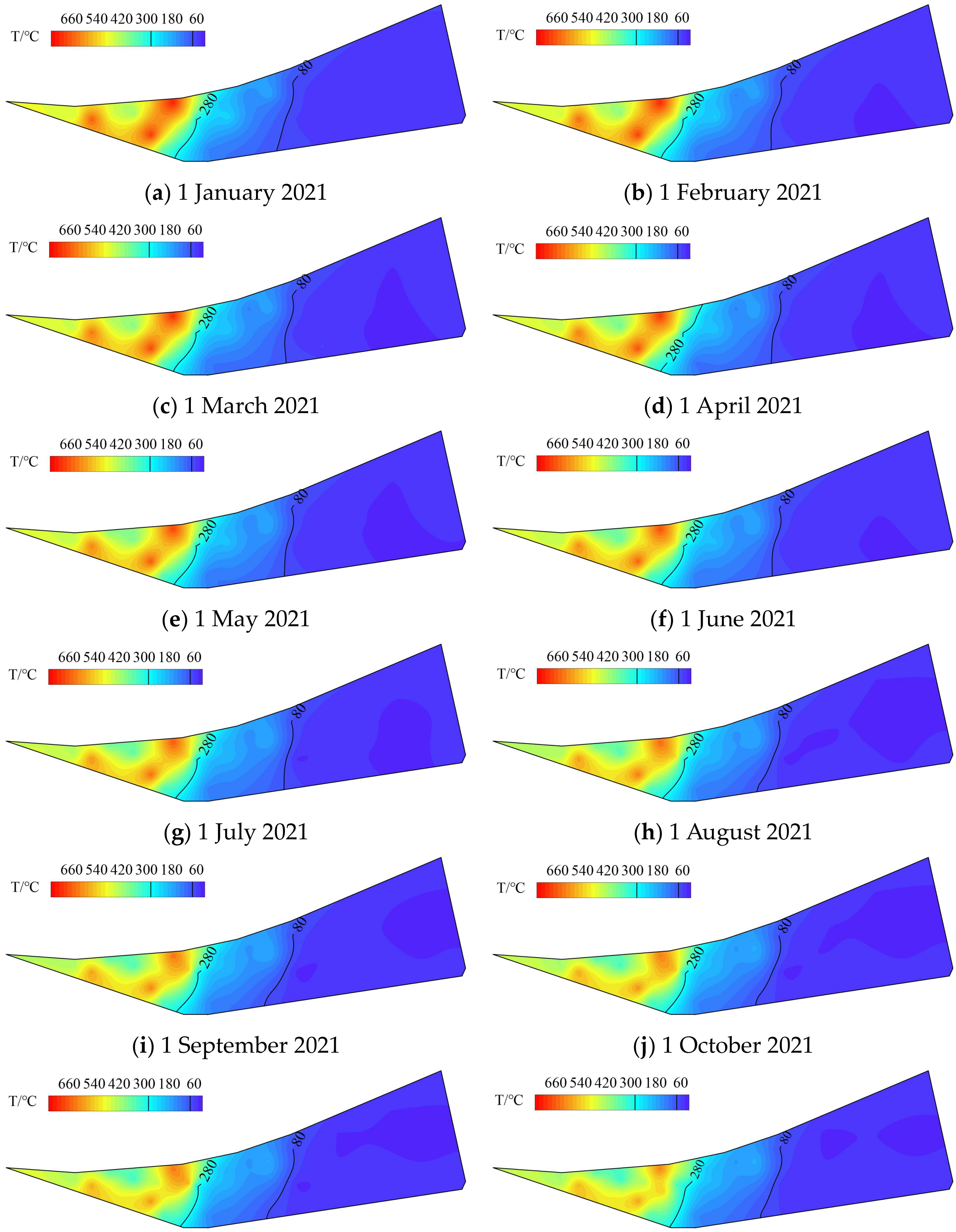
From Figure 9 and Table 1, it can be seen that the maximum temperature at a depth of 3 m decreased by 188 °C, the proportion of the high-temperature zone decreased by 12.10%, and the proportion of the medium- and low-temperature zone increased by 5.29% and 5.18%, respectively. This indicates that the presence of HPs in the horizontal direction can effectively suppress the spread of the high-temperature zone. The initial three high-temperature centers gradually evolved into two high-temperature centers within a year, and the internal temperature of the coal gangue at a depth of 3 m overall decreased.

From Figure 10 and Table 1, it can be seen that the maximum temperature at a depth of 6 m decreased by 116 °C, the proportion of the high-temperature zone decreased by 4.08%, the proportion of the medium-temperature zone decreased by 5.55%, and the proportion of the low-temperature zone increased by 3.69%. This indicates that the HPs can effectively control the increase in combustion temperature in the high-temperature zone, suppress the oxidation rate in the medium-temperature zone and prevent it from heating up, and effectively remove heat and dissipate it. At a depth of 6 m, the internal temperature of the coal gangue in the high-temperature zone is generally decreasing, and it still maintains three high-temperature centers.



(**a**) 1 January 2021
(**b**) 1 February 2021
(**c**) 1 March 2021
(**d**) 1 April 2021
(**e**) 1 May 2021
(**f**) 1 June 2021
(**g**) 1 July 2021
(**h**) 1 August 2021
(**i**) 1 September 2021
(**j**) 1 October 2021
(**k**) 1 November 2021
(**l**) 1 December 2021

Figure 9. Isothermal graph of 3 m depth at different times.



(**a**) 1 January 2021 (**b**) 1 February 2021

(**c**) 1 March 2021 (**d**) 1 April 2021

(**e**) 1 May 2021 (**f**) 1 June 2021

(**g**) 1 July 2021 (**h**) 1 August 2021

(**i**) 1 September 2021 (**j**) 1 October 2021

(**k**) 1 November 2021 (**l**) 1 December 2021

Figure 10. Isothermal graph of 6 m depth at different times.

Table 1. Different temperature zone change table.

Depth	Date	High-Temperature Zone (>280 °C)			Medium-Temperature Zone (80–280 °C)		Low-Temperature Zone (<80 °C)		
		Max. Value/°C	Area/m^2	Percentage/%	Area/m^2	Percentage/%	Area/m^2	Percentage/%	Min. Value/°C
3 m	1 December 2020	498.00	2461.75	14.91	2174.47	13.16	11,877.88	71.93	22.00
	1 March 2021	446.00	1498.70	9.08	2566.50	15.54	12,448.90	75.38	18.00
	1 June 2021	416.00	1121.60	6.79	2790.30	16.90	12,602.20	76.31	18.00
	1 September 2021	368.00	1084.55	6.57	2899.08	17.55	12,530.47	75.88	22.00
	1 December 2021	310.00	731.83	4.43	3047.90	18.46	12,734.37	77.11	27.00
6 m	1 December 2020	740.00	3412.26	20.66	3385.47	20.50	9716.37	58.84	48.00
	1 March 2021	714.00	3328.07	20.15	2891.53	17.51	10,294.50	62.34	36.00
	1 June 2021	678.00	3335.10	20.20	2892.93	17.51	10,286.07	62.29	38.00
	1 September 2021	638.00	3364.92	20.38	2635.41	15.95	10,513.77	63.67	32.00
	1 December 2021	624.00	3322.55	20.12	2865.62	17.35	10,325.93	62.53	36.00

Horizontally, the ambient temperature has little impact on the overall cooling trend of the temperature field of the coal gangue dump from south to north, mainly affecting the distribution of various temperature zones. In the vertical direction, the influence of ambient temperature on the temperature field distribution of the coal gangue dump at a depth of 3 m is greater than that at a depth of 6 m. From Figures 8–10, and Table 1, it can be seen that at a depth of 3 m, the proportion of the high-temperature zone in autumn and winter decreased by 5.83% and 2.14%, respectively, whereas the proportion of the high-temperature zone in spring and summer decreased by 2.29% and 0.22%, respectively. At a depth of 6 m, the proportion of the high-temperature zone in autumn and winter decreased by 4.05% and 0.26% respectively, whereas the proportion of the high-temperature zone in spring and summer increased by 0.05% and 0.18% respectively. This indicates that the proportion of each area changes relatively significantly in autumn and winter, which affects the distribution of the temperature field in the coal gangue dump. Spring and summer have a relatively small impact on the temperature field distribution of the coal gangue dump.

In the horizontal direction, the cooling value of the high-temperature zone is significantly higher than that of the medium-temperature zone and the low-temperature zone. There are two main reasons for this, one of which is that the cooling capacity of the HPs increases with a reduction in their spacing, which makes the cooling effect in the high-temperature zone better, the other is that the evaporation of the work material is accelerated with an increase in the heat source temperature, and the temperature difference between the condensing section of the HPs and the ambient temperature increases, which accelerates the heat dissipation and cooling. From the west-to-east direction, the coal gangue dump side slope location cooling value is obviously higher, which is mainly because the HP spacing in the side slope location has a small influence.

In the vertical direction, the temperature change at a depth of 6 m is relatively small compared to a depth of 3 m, mainly due to two reasons: Firstly, the insertion depth of the HPs is 5 m, and there is a certain distance from the evaporation section of the HPs at a depth of 6 m. The thermal conductivity of the coal gangue is low, the heat conduction is limited, and the cooling efficiency of the HPs is reduced; Secondly, as the depth gradually increases, the temperature of the gangue dump increases, and the internal heat continuously replenishes, resulting in relatively weakened cooling in the high-temperature zone at a depth of 6 m.

4.2. Trend of Coal Gangue Dump Temperature Change under Different Time Scale

4.2.1. Intraday Temperature Variation Pattern

Monitoring points T6 and T21 were selected in the high-temperature zone and low-temperature zone, respectively, to analyze the intraday variation monitoring results of the coal gangue dump on 11 October 2021. Figure 11 shows the hourly temperature changes at 3 m and 6 m depth in different locations of the coal gangue dump.

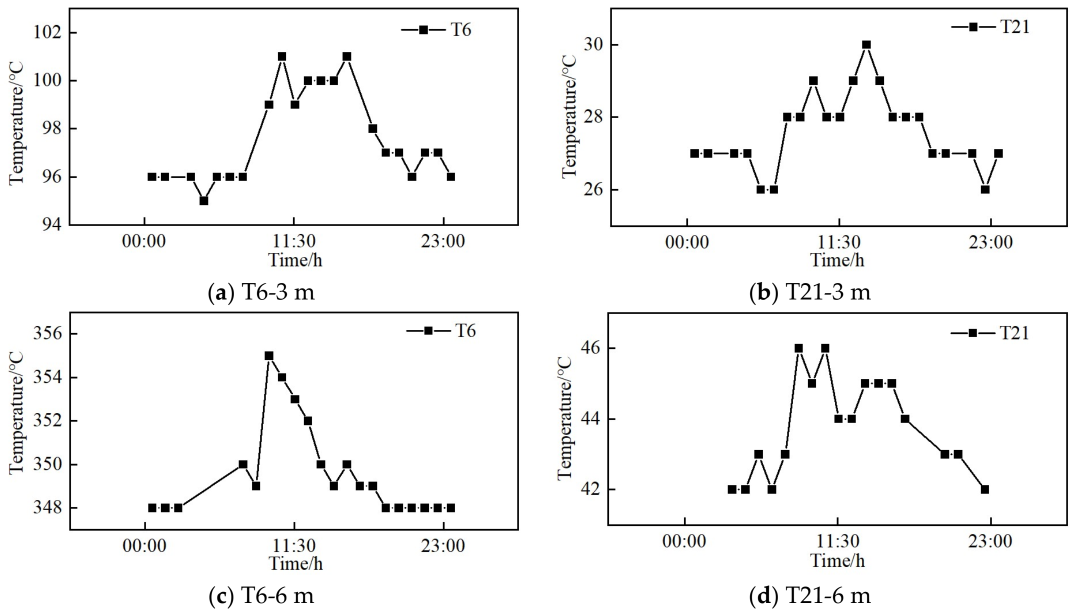


Figure 11. Intraday variation of coal gangue dump at different locations.

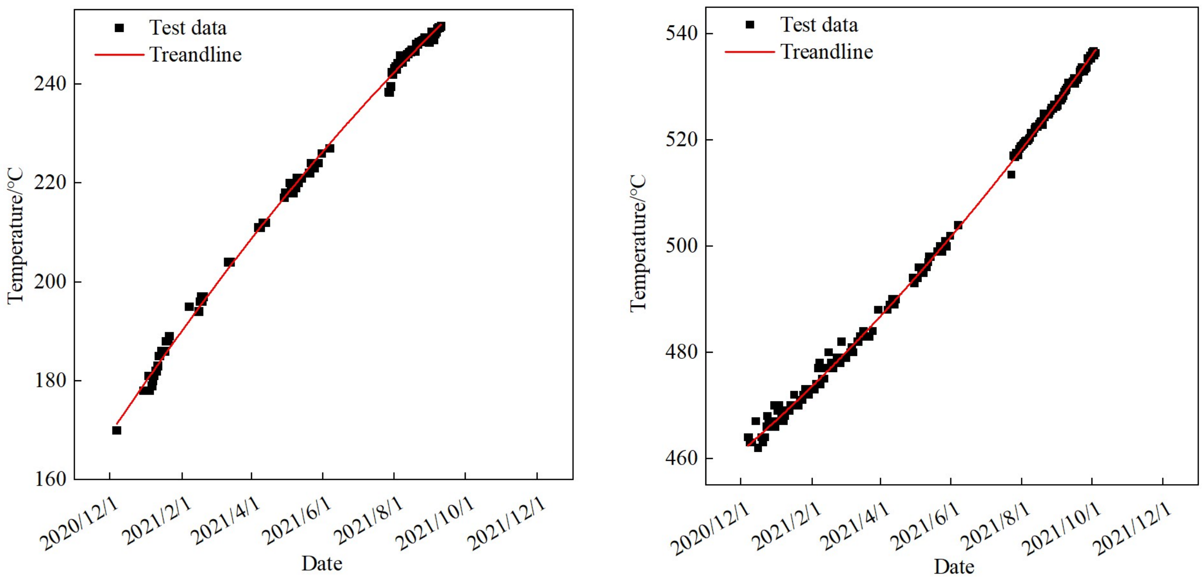
As shown in Figure 11, it can be seen that for the maximum value of coal gangue dump temperature at different depths of the same monitoring point and its occurrence of time points, the magnitude of change is similar. The maximum value of temperature at 3 m depth appeared in the time period of 10:35~15:35, and the maximum value of temperature at 6 m depth appeared in the time period of 8:35~10:35. From the viewpoint of temperature variation, 3 m depth is between 4 and 6 °C, 6 m depth is between 4 and 7 °C, and 6 m depth temperature variation is larger than 3 m depth. Each monitoring point of the coal gangue dump showed similar intraday temperature changes with nightly lows and daily highs in a peak-shaped curve. This is because energy is transferred from the atmosphere to the coal gangue, and with the increase in solar radiation, the atmosphere temperature rises, so the coal gangue temperature rises gradually and reaches its highest value around noon; therefore, when the solar radiation changes, the coal gangue temperature changes.

4.2.2. Daily Temperature Variation Characteristics

The T6 monitoring point in the high-temperature zone was selected to explore the daily variation characteristics of coal gangue temperature. Figure 12 is the temperature change curve of coal gangue temperature in the W1 monitoring point that is without a heat pipe for comparison, and Figure 13 is the temperature change curve of T6 at different depths from 1 December 2020 to 1 December 2021.

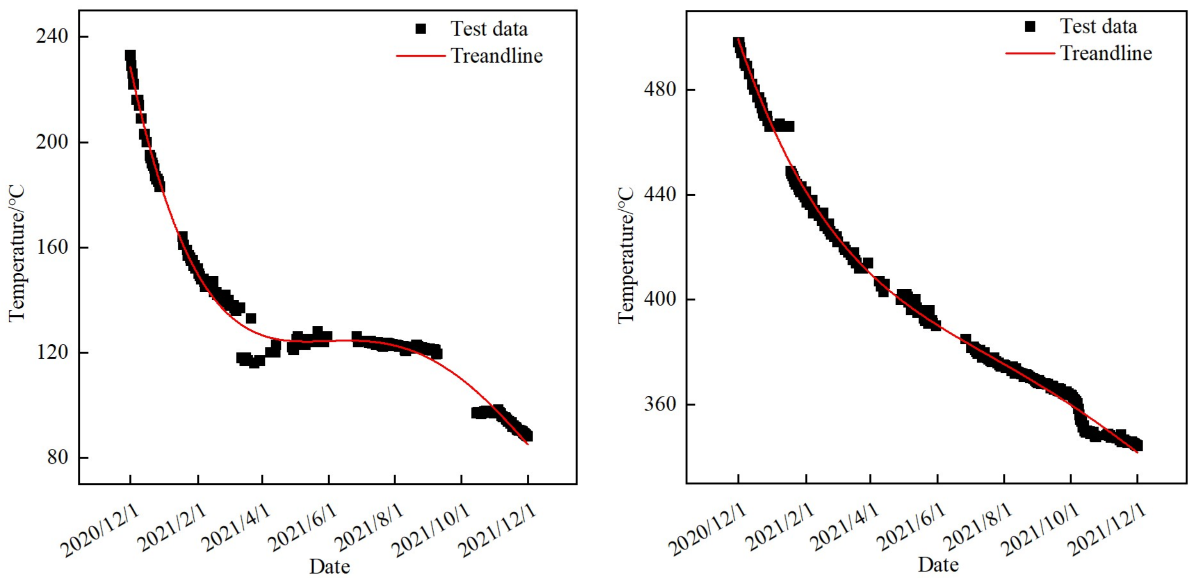
As shown in Figure 12, the temperature difference of the control group at 3 m depth is 81.69 °C, and the ratio is 48.05%. The temperature difference of the control group at 6 m depth is 72.43 °C, and the ratio is 15.61%. It can be seen that the internal part of the coal gangue dump firing area is in a burning state when there is no heat pipe, and the temperature continues to rise.

As shown in Figure 13, the cooling amplitude of the temperature at a depth of 3 m at the T6 measurement point is 144.81 °C, and the cooling ratio is 62.15%. The cooling amplitude of the temperature at a depth of 6 m is 153.54 °C, and the cooling ratio is 30.83%. It can be seen that the HPs can efficiently transfer the internal heat to the outside in the high-temperature zone, and they can continuously destroy the heat storage conditions and continuously and significantly reduce the internal temperature of the coal gangue dump, with significant cooling effect, which confirms the superiority of the HPs in managing the spontaneous combustion coal gangue dump.



(**a**) 3 m (**b**) 6 m

Figure 12. Daily variation in temperature at monitoring point W1.

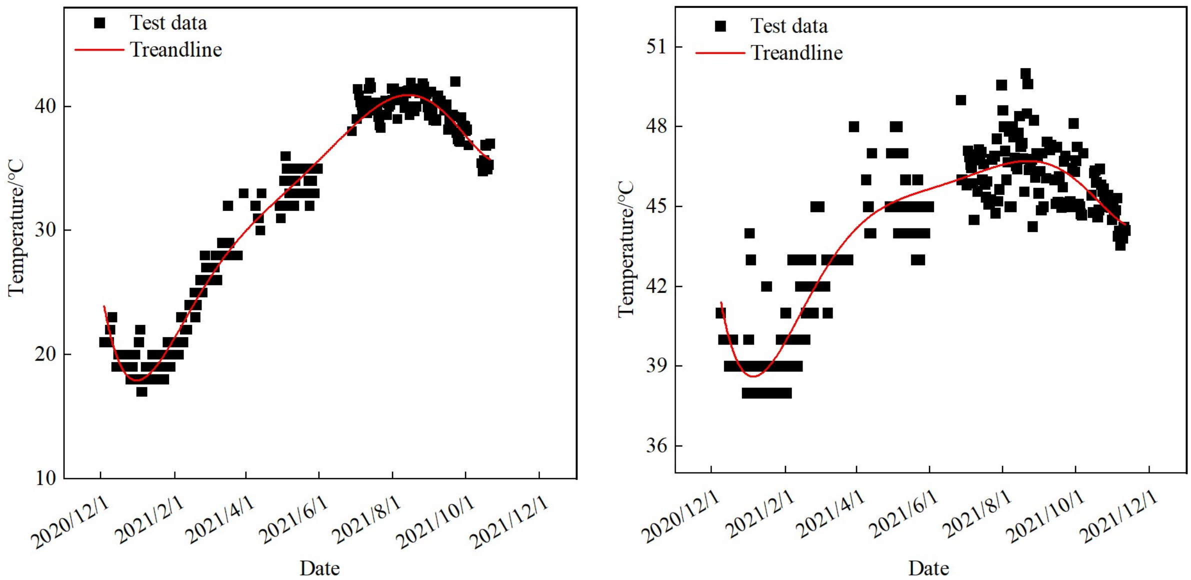


(**a**) 3 m (**b**) 6 m

Figure 13. Daily variation in temperature at monitoring point T6.

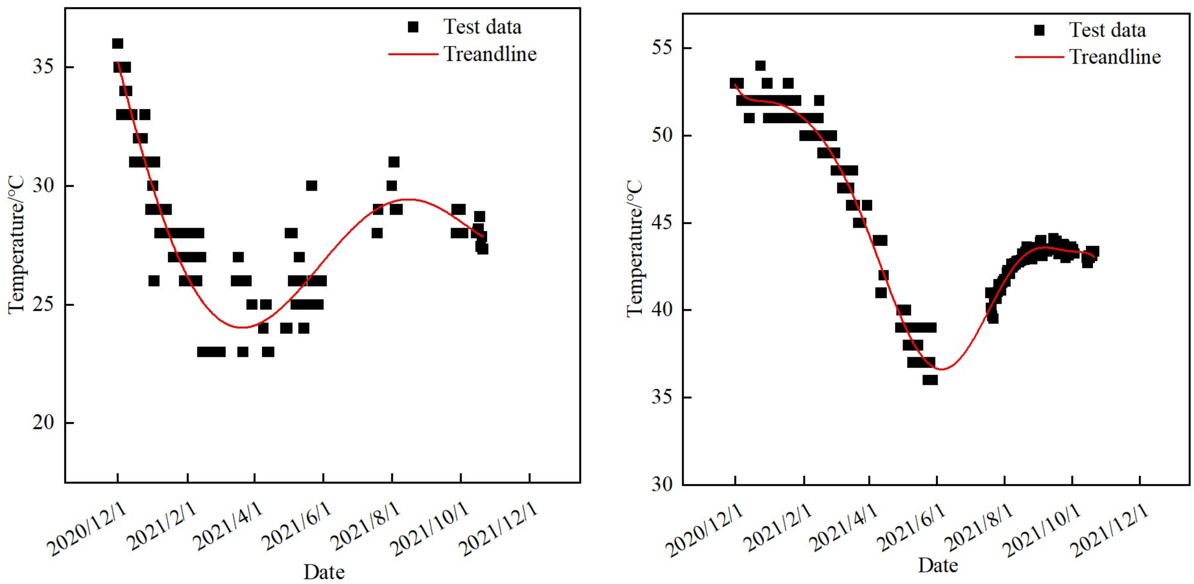
In contrast to Figure 13a,b, the temperature change trend of different depth monitoring points is shown to be faster in the early cooling stage, whereas the later cooling trend is more gentle. Combined with Figure 2, it can be seen that the trend of ambient temperature and cooling rate are correlated, and the cooling rate is larger when the ambient temperature is lower. But the ambient temperature and cooling rate is not a single inverse relationship because wind speed, moisture and other factors also have a certain impact on the internal temperature of the spontaneous combustion coal gangue dump.

The low-temperature zone T21 monitoring point was selected to explore the daily variation characteristics of coal gangue temperature. Figure 14 shows no heat pipe temperature change curve for the W2 monitoring point for comparison. Figure 15 shows the temperature change curve for T21 at different depths from 1 December 2020 to 1 December 2021.



(**a**) 3 m (**b**) 6 m

Figure 14. Daily variation in temperature at monitoring point W2.



(**a**) 3 m (**b**) 6 m

Figure 15. Daily variation in temperature at monitoring point T21.

As shown in Figure 14, the temperature at the W1 measuring point at 3 m decreased from 21 °C to 18 °C within more than a month and then continued to rise until reaching its peak of 41.9 °C in August. Afterwards, the temperature decreased to 34.78 °C. The temperature at 6 m decreased from 41 °C to 38 °C within more than a month, then continued to rise until reaching its peak of 50 °C in mid-August, and then decreased to 43.55 °C. When no heat pipe is laid, the internal heat storage area of the coal gangue dump is not burned, and the internal temperature of the coal gangue dump is subject to the joint action of heat accumulation, ambient temperature and moisture and other factors. Combined with Figure 1, it can be seen that the temperature of the monitoring point in the heat storage area changes with the ambient temperature, indicating that its internal temperature is influenced by the ambient temperature.

As shown in Figure 15, the temperature at the 3 m depth of the T21 monitoring point decreased from 36 °C to 21 °C from December to mid-March, increased to 31 °C from April to August, and decreased to 27.33 °C from September to December. The temperature at the 6 m depth of the T21 monitoring point decreased from 53 °C to 36 °C from December to mid-May, increased to 44 °C from June to August, and decreased to 42.71 °C from September to December. The overall trend of first cooling, then warming, and then cooling changed. The internal temperature of the low-temperature zone of the spontaneous combustion coal gangue dump is obviously affected by the ambient temperature, and the temperature of the monitoring point changes with the ambient temperature, but the cooling range is greater compared with that of the heatless tube, and the maximum value does not exceed the initial temperature after the temperature rebound. Overall, the deployment of the HPs in the low-temperature zone does not form an obvious cooling effect, but mainly plays the role of preventing a large amount of heat accumulation and inhibiting the speed of oxidation, and can implement dynamic monitoring of temperature, monitoring the internal temperature changes in the heat storage area, and timely prevention, control and management.

For a coal gangue dump with HPs, there are two main ways in which the external ambient temperature affects the internal temperature evolution. Firstly, the ambient temperature directly affects the temperature of the condensation section of the HPs. By controlling the temperature difference between the evaporation section and the condensation section of the HPs, the heat transfer efficiency of the HPs is affected, thereby affecting the internal temperature evolution of the coal gangue. Secondly, the direct convective heat transfer of ambient temperature changes the temperature of the surface layer of the coal gangue dump, which in turn affects the temperature at different positions within the coal gangue dump due to the same medium-heat conduction within the coal gangue.

4.3. Correlation Analysis

To investigate whether there is a correlation between ambient temperature and the internal temperature of the coal gangue dump, as well as the strength of the statistical relationship, correlation analysis was conducted, correlation coefficients were calculated, and significance tests were conducted. Due to the non-monotonic nature of environmental temperature, the environmental temperature curve was divided from the highest point of 27.5 °C into a heating stage (1 December 2020 to 9 July 2021) and a cooling stage (10 July 2021 to 1 December 2021) for correlation analysis. The calculation results are listed in Table 2.

Table 2. Correlation between monitoring points temperature and ambient temperature.

	Ambient Temperature	
	The Heating Stage	**The Cooling Stage**
W1-3 m	0.92 **	0.93 **
W1-6 m	0.94 **	0.94 **
T6-3 m	−0.72 **	−0.97 **
T6-6 m	−0.86 **	−0.94 **
W2-3 m	0.93 **	0.96 **
W2-6 m	0.88 **	0.95 **
T21-3 m	−0.23	−0.91 **
T21-6 m	−0.93 **	−0.77 **

** indicates that the correlation is significant at the 0.01 level.

There are varying degrees of correlation between temperature at different monitoring points and ambient temperature, indicating a statistical relationship between ambient temperature and coal gangue temperature, with varying degrees of strength. The correlation between the W measurement point and the ambient temperature is significantly positive, and between the T measurement point and the ambient temperature, the correlation is significantly negative. After inserting the HPs, the correlation between the coal gangue temperature and ambient temperature changed from positive to negative; it is presumed that after inserting the HPs, the heat conduction between the HPs and the coal gangue is dominant, the convective heat transfer between the coal gangue and the ambient temperature is relatively weakened, and the coal gangue temperature is changed from the original rise to a decline.

4.4. Regressive Analysis

In order to reveal the relationship between ambient temperature and the internal temperature of the coal gangue dump, a regression equation was established, and significance testing was conducted. The results are shown in Figure 16.

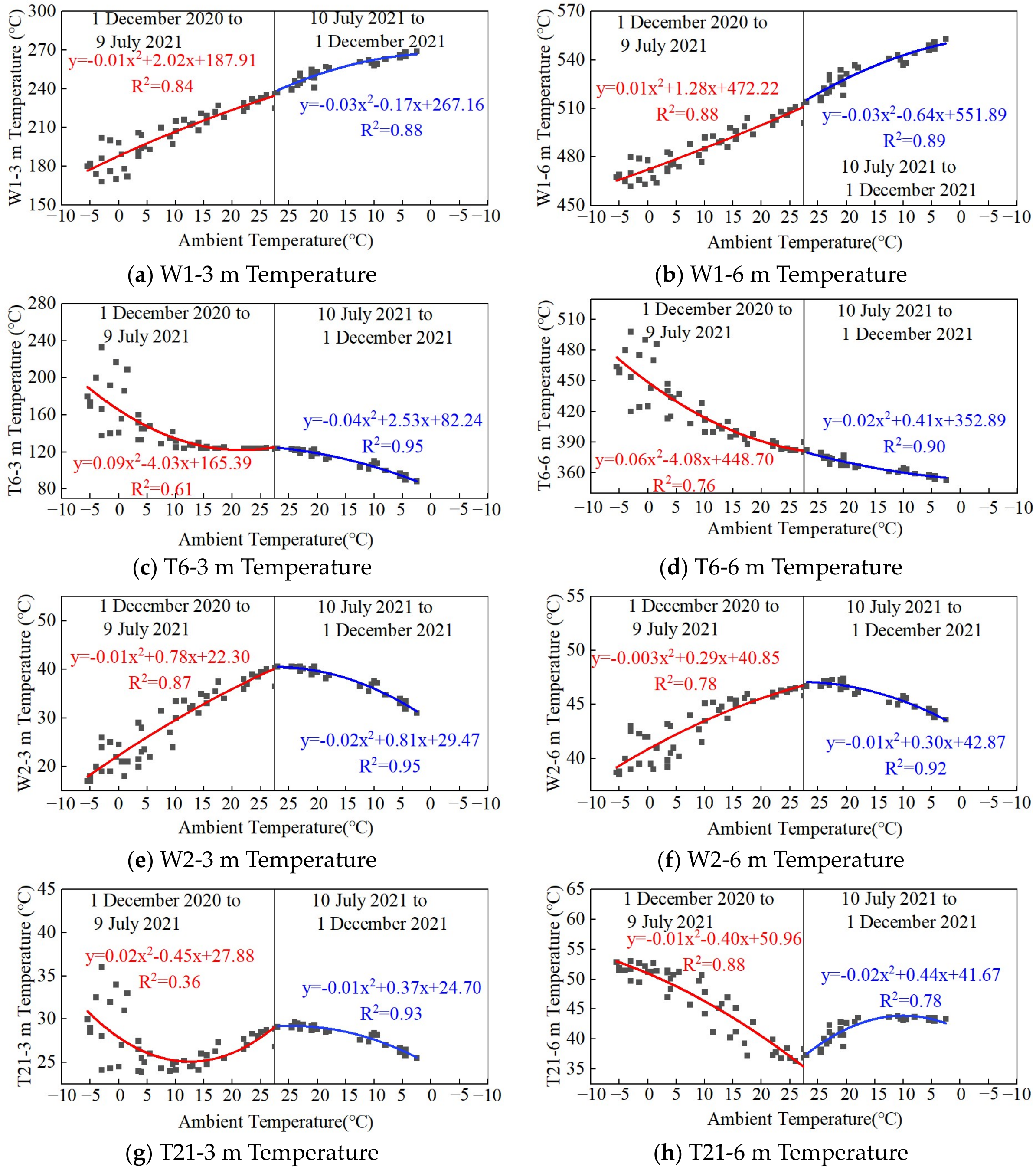


Figure 16. Results of temperature fitting.

From Figure 16, the results of fitting the ambient temperature to the temperature of each monitoring point are in good agreement, and the goodness of fit of the quadratic curve is in the range from 0.36 to 0.95. To determine whether the fitted regression coefficients can accurately represent the ambient temperature, it is still necessary to carry out a test of significance for the fitted equations. Using the F test, the F values of each regression model were obtained, as shown in Table 3.

Table 3. Results of significance tests.

Fitted Models	F-Value	
	1 December 2020 to 9 July 2021	10 July 2021 to 1 December 2021
Ambient Temperature and W1-3 m Temperature	110.94	96.09
Ambient Temperature and W1-6 m Temperature	156.88	100.04
Ambient Temperature and T6-3 m Temperature	32.22	267.45
Ambient Temperature and T6-6 m Temperature	68.00	115.78
Ambient Temperature and W2-3 m Temperature	140.77	266.14
Ambient Temperature and W2-6 m Temperature	76.14	155.59
Ambient Temperature and T21-3 m Temperature	11.63	163.65
Ambient Temperature and T21-6 m Temperature	147.90	45.18

Find the critical value $F_\alpha(2,\ n-3)$ by checking the F-distribution table:

$$\text{1 December 2020 to 9 July 2021},\ F_\alpha(2,\ n-3) = \begin{cases} F_{0.01}(2,42) = 5.15 \\ F_{0.05}(2,42) = 3.22 \end{cases} \quad (1)$$

$$\text{10 July 2021 to 1 December 2021},\ F_\alpha(2,\ n-3) = \begin{cases} F_{0.01}(2,26) = 5.53 \\ F_{0.05}(2,26) = 3.37 \end{cases} \quad (2)$$

Comparing the F-statistics in Table 3 with the critical values of different significance levels obtained from the F-distribution table, it can be seen that the regression model has $F > F_{0.01}(2,\ n-3)$, indicating that the fitted regression equations are highly significant with the test requirements, indicating that the choice of the quadratic model is reasonable.

4.5. Discussion

From tests, we have confirmed the variation law of the coal gangue dump temperature field under the influence of ambient temperature. Subsequently, we investigated the influence of ambient temperature on coal gangue temperature at hourly and daily scales. Finally, we proposed a fitting model of ambient temperature and coal gangue temperature. The results showed that HPs can effectively reduce the temperature of the coal gangue dump and control the spread of the high-temperature area. Zhao [29] found that HPs make the temperature distribution in the coal gangue dump more uneven, accelerating the heat dissipation rate. Meng [27] studied the variation law of the temperature field in coal piles under the action of HP and found the same conclusion. Those results showed that HPs can effectively prevent the problem of spontaneous combustion of solid waste accumulation. The results also showed that ambient temperature has a greater influence on the cooling effect of the HP and the cooling rate of coal gangue temperature, which is faster in winter and slower in summer. Liu [46] found that the variation pattern of soil temperature in the hot-rod section of the roadbed is similar to atmospheric temperature, with cooling in the cold season and warming in the warm season. The variation trend of the temperature was different from the results of this study, which might be due to the difference in the average temperature of frozen soil and the cooling effect of heat pipes.

The limitation of this study is the absence of a long series of monitoring data to explore the effect of multi-year ambient temperatures on the temperature field of coal gangue dumps. The impact of wind speed and rainfall in the external environment on the temperature field of the coal gangue dump needs further research in the future.

5. Conclusions

In this study, it was found that HP technology can effectively reduce the temperature of a spontaneous combustion coal gangue dump, while also being affected by external ambient temperature. Therefore, this article analyzed the changes in the temperature field of a coal gangue dump under the influence of environmental temperature on spatial and temporal scales and conducted a correlation analysis between ambient temperature and gangue temperature. The results of this study provide a reference for the sustainable development of mining environments. Some conclusions are drawn as follows:

(1) The impact of environmental temperature changes on the internal temperature distribution of gangue varies. On the horizontal plane, the impact on high temperature is greater than that on a low-temperature zone; in the vertical direction, the impact on the shallow layer is more significant than that on the deep layer.
(2) The internal temperature of the coal gangue has a consistent trend with the ambient temperature, which means that the cooling effect of heat pipe technology is inversely proportional to the ambient temperature. On an hourly scale, the intraday changes in the coal gangue temperature present a peak-shaped curve of low at night and high during the day. On a daily scale, the daily variation in coal gangue temperature has seasonal characteristics, indicating that the cooling effect is good in winter and poor in summer.
(3) There is correlation between ambient temperature and the temperature of the coal gangue. The use of quadratic polynomial fitting was effective, and the regression equation met the F-test requirements for significance level. The quadratic regression model can be used as a regression model between ambient temperature and the internal temperature of the coal gangue dump.

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